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OPTIMIZATION OF CONCRETE BRACING LAYOUTS FOR ENHANCED BUCKLING RESISTANCE IN REINFORCED CONCRETE FRAMES

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ABSTRACT

This study investigates the optimization of concrete bracing layouts to enhance the buckling resistance and overall structural performance of reinforced concrete (RC) frames. Comparative analysis between braced and unbraced frames reveals that the inclusion of bracing systems significantly improves stability by reducing story forces and increasing buckling resistance. Among the evaluated configurations, Inverted V bracing demonstrated the highest buckling factor improvement—up to 89%—followed by diagonal, X, V, and K bracing types. Results also highlight the influence of column slenderness ratio, indicating that higher slenderness leads to reduced buckling capacity. Additionally, modelling the slab as a shell element yielded higher buckling factors compared to membrane modelling, with variations of 12–18% across stories. The incorporation of P-delta effects provided more realistic and conservative buckling predictions. Frames with shear walls performed better than those without, further enhancing structural stiffness and safety. Comparison between ETABS and ANSYS outputs showed variations of 0–25%, demonstrating acceptable consistency between software tools. Overall, the study confirms that adding optimized bracing systems to RC moment-resisting frames significantly increases their strength, stiffness, and buckling resistance.

KEYWORDS: Concrete bracing layouts; Buckling resistance; Reinforced concrete frames; Inverted V bracing; Column slenderness ratio; P-delta effects; Shell modelling; Shear wall.

INTRODUCTION

Reinforced concrete (RC) frame structures form the backbone of modern infrastructure due to their versatility, ductility, and cost-effectiveness. However, their performance under lateral loads—particularly seismic and wind actions—often remains a critical concern, as conventional RC frames possess limited inherent stiffness and buckling resistance. Structural bracing systems are widely recognized as an effective strategy to enhance the lateral load-carrying capacity and stability of such frames. Among the various bracing materials and configurations, **concrete** bracing has recently gained attention because of its high compressive strength, reliable stiffness contribution, and compatibility with existing RC member behavior. Despite these advantages, the efficiency of concrete bracing significantly depends on its layout, including its orientation, distribution, connection detailing, and interaction with the surrounding structural system.

In recent years, the optimization of bracing layouts has emerged as a crucial research domain aimed at improving the seismic resilience and global stability of RC structures. The primary challenge lies in understanding how different bracing configurations modify the buckling characteristics of columns and beams, influence story drifts, and alter force pathways across the structural system. Poorly placed bracings may introduce undesirable stress concentrations, increase structural weight, or cause torsional irregularities. Conversely, an optimized bracing layout can reduce the effective slenderness of compression members, improve energy dissipation capacity, increase lateral stiffness, and delay or prevent buckling under extreme loading scenarios. Hence, identifying optimal brace geometry, orientation, and placement becomes essential for maximizing structural performance without imposing unnecessary material or economic burdens.

The integration of computational modeling, advanced analysis tools, and performance-based design philosophies has allowed researchers to rigorously evaluate the effectiveness of various bracing schemes. Techniques such as nonlinear pushover analysis, response spectrum analysis, finite-element modeling, and optimization algorithms (genetic algorithms, met heuristics, etc.) are commonly employed to explore the influence of bracing parameters on structural response. These studies consistently indicate that optimized bracing systems contribute to lower inter-story drift, higher ductility, improved stability under cyclic loading, and overall enhanced buckling resistance of RC frames.

Given the increasing demand for resilient building systems and the rising frequency of extreme loading events, it has become crucial to understand and optimize concrete bracing layouts as a strategy for structural enhancement. This research direction not only supports safer design practices for new constructions but also offers viable retrofitting solutions for existing RC buildings with insufficient lateral resistance. The optimization of concrete bracing thus represents a significant step toward achieving efficient, resilient, and economical structural systems capable of performing reliably under demanding conditions.

Types of vibration

Free vibration occurs when a mechanical system is set into motion by an initial input—such as displacement, velocity, or force—and then allowed to vibrate on its own without any further external influence, causing it to oscillate naturally at one or more of its inherent frequencies until the motion gradually diminishes due to damping; common examples include releasing a pulled swing or striking a tuning fork. In contrast, **forced (constrained) vibration** happens when an external, time-varying disturbance—such as a periodic force, displacement, or velocity—is continuously applied to a mechanical system, causing it to respond at the frequency of the applied excitation rather than its natural frequency; this excitation may be harmonic, non-harmonic, transient, or random in nature. Everyday examples include a washing machine vibrating due to unbalanced loads, vehicles shaking from engine or road irregularities, or buildings responding to earthquake ground motion. In linear systems subjected to harmonic loading, the steady-state vibration response always matches the excitation frequency, while the amplitude of this response depends on factors such as system stiffness, mass, damping, and whether the excitation frequency is close to the system's natural frequency—where resonance can occur and greatly amplify the motion.

Literature Review

Jiaxin Li et al (2025) was study earthquakes pose a significant threat to reinforced concrete (RC) frame structures, especially those built before the implementation of modern seismic codes, prompting the need for effective retrofitting and upgrading strategies. To address this challenge, researchers increasingly rely on data-driven methods that combine quantitative metrics with qualitative insights, using comprehensive literature surveys from databases such as Web of Science to trace historical developments, identify emerging trends, and extract high-frequency research themes. Recent advancements highlight the integration of traditional RC frame systems with innovative seismic enhancement technologies, including frame–shear wall hybrid systems that increase lateral stiffness and reduce deformation demands; energy-dissipating buckling-restrained braces (BRBs) that provide stable hysteretic behavior and prevent brace buckling under cyclic loads; and seismic isolation bearings that decouple the structure from ground motion to significantly reduce acceleration transmission. These novel techniques, when incorporated into existing RC frames through code-compliant retrofitting measures, markedly improve seismic resilience by enhancing stiffness, controlling drift, and dissipating energy more efficiently. Overall, the combined system—merging conventional structural components with modern isolation and energy-dissipation technologies—achieves an average increase of about 45% in energy dissipation capacity, offering a promising pathway to ensure structural safety and performance in high-seismic-intensity regions.

Luis Velasco et al (2025) metaheuristic optimization techniques, such as simulated annealing (SA) and genetic algorithms (GA), are powerful tools for automating the seismic design and retrofitting of structures, but their practical use is often limited by long computational times, especially when evaluating complex structural responses. To overcome this challenge, the study introduces artificial neural networks (ANNs) as surrogate models that approximate the structural performance predictions normally obtained through computationally expensive analyses, thereby speeding up the optimization of mid-rise frames retrofitted with buckling-restrained braces (BRBs). By comparing SA and GA with and without ANN-based surrogates, the research demonstrates that incorporating ANNs can reduce total optimization time by as much as 51%, significantly improving efficiency. However, the study also finds that relying solely on surrogate models throughout the entire optimization process can lead to infeasible or inaccurate design solutions because ANN predictions may not always perfectly match detailed structural analyses. Despite this limitation, the combined approach enables the identification of optimal BRB characteristics—such as stiffness, yield strength, and energy-dissipation properties—that produce the most efficient seismic retrofitting designs, thus offering a balanced strategy that enhances sustainability, computational performance, and structural reliability.

Research Methodology

The study adopts a systematic methodology that begins with selecting representative reinforced concrete (RC) frame models and defining key design parameters such as bracing type, configuration, and material properties. Numerical models of the RC frames, with and without concrete bracings, are developed using finite element software to simulate nonlinear behavior under lateral loads. A series of pushover and nonlinear dynamic analyses are performed to evaluate structural responses, including buckling resistance, inter-story drift, axial forces, and overall stability. Optimization techniques—such as genetic algorithms or other met heuristic methods—are integrated to identify the most efficient bracing layouts by iteratively adjusting bracing positions and geometries while satisfying structural performance constraints. The analytical results are compared across different configurations to determine the optimal bracing arrangement that maximizes buckling resistance. Finally, validation is conducted by benchmarking the simulation outputs with existing experimental or code-based results to ensure the reliability and accuracy of the proposed optimized bracing layout.

Table 1: Structural details of the model.

Number of storey	3
Storey height	3.5m
Number of Bays	3 bays in both directions
Spacing of Bays	4 m in both direction
Beam Size	230x450 mm
Column size	500x500 mm
Bracing size	300x300 mm
Grade of Materials	M25 and Fe 500
Slab Thickness	150mm
Load Considered (Dead load+ Floor finish + Live load)	8.2 kN/m^2

Using Software

The study involves the development of multiple three-dimensional reinforced concrete (RC) frame models representing the structural system without any bracing or supplemental lateral-resisting elements. These bare frame models serve as the baseline for comparison with braced configurations. Each model is designed with identical plan dimensions, storey heights, material properties, and loading conditions to ensure uniformity in analysis. The frames include beams, columns, and slab systems modeled according to standard design codes, while infill walls and bracing elements are intentionally excluded to capture the true behavior of an unrestrained RC frame. Gravity loads, live loads, and lateral loads (wind or seismic) are applied based on relevant code provisions. The structural behavior of these bare frames — including lateral displacement, inter-storey drift, base shear demand, and mode shapes — provides a reference point for evaluating the effectiveness of bracing layouts in subsequent studies.

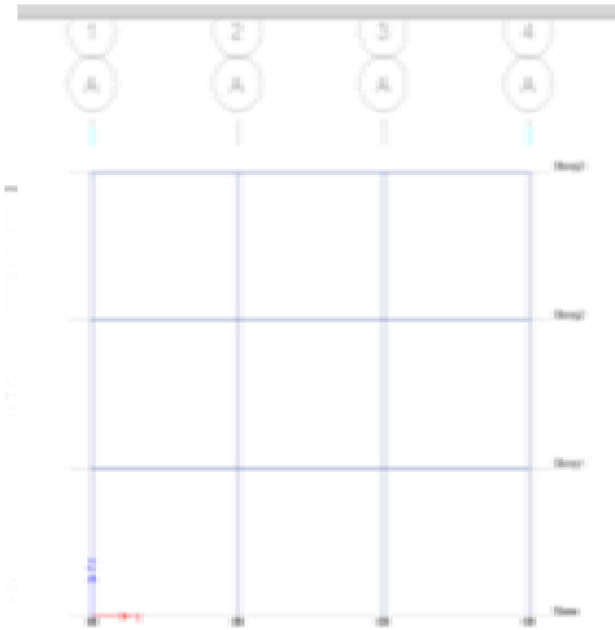

Figure 1 Shows models of Regular building without bracing 3, story structures.

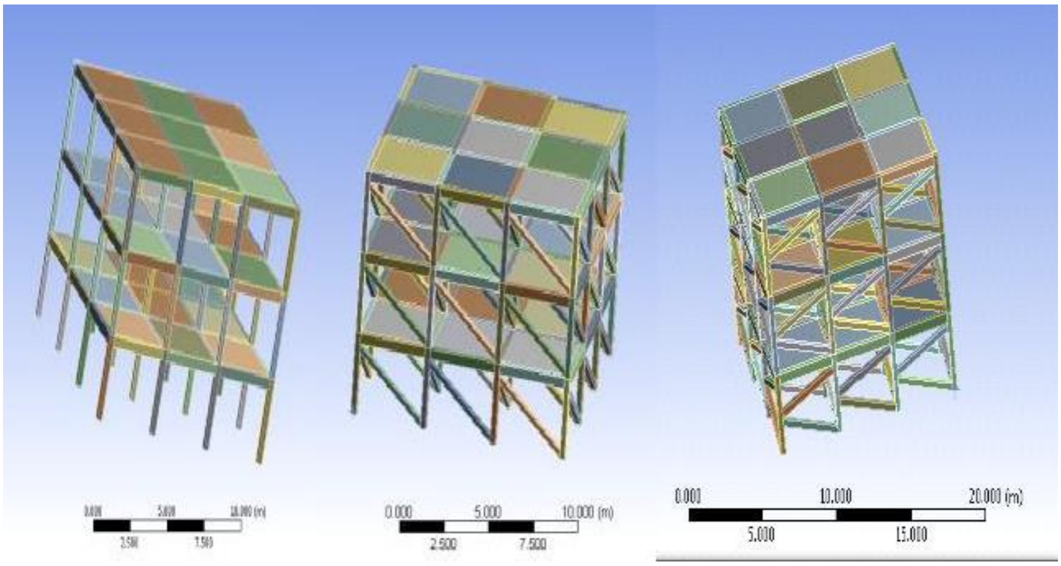

Figure 2 Bare model, Diagonal, K type bracing models using Finite element method by using ANSYS Software.

RESULT AND DISCUSSION

The analysis of reinforced concrete (RC) frames with various bracing configurations indicates that the inclusion of bracing systems substantially enhances structural performance and buckling resistance compared to unbraced frames. Among the layouts studied, Inverted V bracing achieved the highest improvement in buckling factor—up to 89%—followed by diagonal, X, V, and K bracing, demonstrating the critical role of bracing type in stability enhancement. The study also highlights the influence of column slenderness, where increased slenderness reduces the buckling capacity, emphasizing the need for careful design of columns in braced frames. Modelling slabs as shell elements resulted in 12–18% higher buckling factors than membrane modelling, suggesting that more detailed slab representation yields more optimistic predictions. Incorporating P-delta effects provided more realistic and conservative assessments, while the addition of shear walls further improved stiffness and safety. Comparative outputs from ETABS and ANSYS varied between 0–25%, showing acceptable consistency across software platforms. Overall, the results confirm that optimized bracing layouts significantly improve story strength, stiffness, and buckling resistance, enhancing the overall safety and resilience of RC moment-resisting frames.

Table 1: Buckling modes values for story without shear wall and with shear wall.

Buckling mode	Without Shear wall	With shear wall
1	100.753	580.709

The analysis indicates that incorporating shear walls in a three-story building significantly enhances its structural stability against buckling. Specifically, the buckling factor of the building with shear walls is found to be 82% higher than that of a conventional reinforced concrete (R.C.C.) building without shear walls. This substantial increase demonstrates that shear walls effectively restrain lateral deformations, provide additional stiffness, and distribute loads more efficiently, thereby reducing the susceptibility of the structure to buckling under axial or lateral forces. Consequently, the inclusion of shear walls is a highly effective strategy for improving the overall safety and performance of low-rise R.C.C. buildings.

Table 2 Buckling factor values for membrane and shell.

Buckling Factor				
Membrane	100.753	197.817	360.656	559.848
Shell	123.556	218.873	402.887	627.082

When loads are applied to membrane objects, they are carried entirely by in-plane forces (tension or compression) and are transferred directly to the supporting structural elements, such as beams or columns. In contrast, meshed shell objects possess both in-plane and bending stiffness, so they can resist part of the applied load through flexural (bending) deformation. This means that a portion of the load is resisted by the shell itself, and consequently, less load is transmitted to the underlying beams compared to a purely membrane element, where 100% of the applied load is transferred to the supports.

CONCLUSION

From the analysis of various parameters, it is evident that structures with bracings perform significantly better than those without bracings. The story forces are reduced in braced structures, enhancing overall structural safety. Comparing the buckling factors for different bracing types shows substantial improvements: K-type bracing increases the factor by 65%, V-type by 73%, X-type by 76%, diagonal by 86%, and Inverted V by 89%, with the Inverted V configuration providing the maximum buckling resistance. The slenderness ratio of columns plays a critical role in buckling behavior, with higher slenderness leading to reduced buckling factors even under maximum loads. Additionally, modeling the slab as a shell rather than a membrane yields higher buckling factors, with differences of 12% for the first story and 18% for the third story, indicating greater overall structural stiffness. Consideration of P-Δ effects further improves performance, with buckling factors reduced by 47% for a single-story and 40% for a three-story frame compared to models without P-Δ, demonstrating more effective load resistance. Finally, the inclusion of shear walls further enhances the buckling factor compared to conventional RCC buildings without shear walls. Overall, these results confirm that appropriate bracing, especially Inverted V type, significantly improves the stability and safety of reinforced concrete structures.

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