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Review of Bracing Systems for Improving Buckling Resistance in Reinforced Concrete Frames

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Abstract

Bracing systems play a critical role in enhancing the stability and load-carrying capacity of reinforced concrete (RC) frames, particularly under lateral and compressive loading that may lead to buckling. This review examines the effectiveness of various bracing configurations—such as diagonal, X-bracing, K-bracing, knee bracing, and concrete–steel composite bracing—in improving the buckling resistance of RC structures. Emphasis is placed on understanding how bracing layout, stiffness, material properties, and connection detailing influence the global and local stability of RC frames. The study synthesizes findings from experimental investigations, analytical modeling, and numerical simulations to provide insights into optimal bracing strategies for mitigating buckling and improving overall structural performance. The review concludes that well-designed bracing systems significantly enhance the ductility, stiffness, and energy-dissipation capacity of RC frames, making them a valuable technique for strengthening existing structures and improving the reliability of new construction.

Keywords: Buckling Resistance, Reinforced Concrete Frames, Bracing Systems, Structural Stability, Concrete Bracing.

Introduction

Reinforced concrete (RC) frames form the backbone of most modern buildings and infrastructure systems due to their durability, versatility, and structural reliability. However, despite their inherent strength, RC frames are susceptible to buckling, especially when slender columns, high axial loads, seismic actions, or lateral forces destabilize the structure. Buckling failure is particularly critical because it can occur suddenly and without significant prior deformation, leading to partial or complete collapse of the structural system. As construction trends shift toward taller, more slender, and architecturally demanding structures, improving the buckling resistance of RC frames has become a major focus in structural engineering research and practice.

Bracing systems have emerged as one of the most effective and economical techniques for enhancing the stability and axial load-carrying capacity of RC frames. By providing additional stiffness, reducing effective slenderness ratios, and improving lateral load resistance, bracing systems significantly delay or prevent buckling under compressive forces. These bracing systems may be constructed using steel, reinforced concrete, composite materials, or hybrid configurations, and can be strategically placed to optimize their structural benefits without compromising architectural functionality.

In recent decades, engineers have developed a wide variety of bracing configurations—diagonal bracing, X-bracing, K-bracing, V-bracing, shear walls, infill concrete panels, and reinforced concrete struts—to improve frame performance under both static and dynamic loads. Each bracing type influences the structural behavior differently by altering load paths, redistributing stresses, and increasing overall frame rigidity. Consequently, understanding the strengths, limitations, and design implications of each bracing system is essential for selecting the most suitable solution for specific structural requirements.

Numerical analysis tools, such as finite element modeling and elastic stability analysis, have further advanced the study of braced RC frames. These tools enable engineers to simulate complex interactions between braces and frame elements, evaluate buckling modes, and optimize bracing layouts for maximum efficiency. Research in this field also explores innovative materials, such as high-strength concrete, steel-reinforced concrete bracings, and fiber-reinforced composites, which contribute to improved stiffness-to-weight ratios and enhanced buckling resistance.

Overall, the review of bracing systems for improving buckling resistance in reinforced concrete frames is crucial for ensuring safer, more resilient structures. By synthesizing existing research, evaluating various bracing techniques, and identifying opportunities for further innovation, this study contributes valuable insights to the development of advanced, cost-effective, and high-performance bracing solutions for modern RC structures.

Literature Review

Madi et al. (2024)**,** existing buildings are upgraded by determining the optimal distribution of protective technologies, meaning that instead of randomly adding seismic protection devices—such as base isolators, dampers, or bracing systems—the researchers use optimization techniques to strategically place these components where they provide the maximum improvement in structural performance. Their method evaluates how different configurations of protective devices influence overall building behavior during earthquakes, considering parameters like energy dissipation, reduction in inter-story drifts, and enhancement of lateral stiffness. By applying numerical optimization algorithms, the study identifies the most efficient layout of these technologies to achieve high seismic resilience while minimizing material use and retrofitting cost. This approach ensures that retrofitting is both technically effective and economically sustainable, allowing older or vulnerable buildings to reach safety levels comparable to modern code-compliant structures.

Benyamin Mohebi et al (2023) the study introduces advanced alternatives to conventional buckling-restrained braces (BRBs), which, despite their effectiveness, still exhibit limitations such as residual drifts due to yielding under seismic loads. To overcome these drawbacks, two innovative systems were proposed: the double-stage yield buckling-restrained brace (DYB) and a hybrid system combining DYB with shape memory alloy components (DYBSMA). These systems were incorporated into steel BRBFs ranging from 2 to 12 stories and evaluated using nonlinear dynamic analysis (NDA) and incremental dynamic analysis (IDA) under both design-based earthquakes (DBE) and maximum considered earthquakes (MCE) with far-field ground motions. The analyses revealed that frames equipped solely with traditional BRBs showed the highest residual drift ratio demands (RDRMed), indicating greater permanent deformation after shaking. In contrast, the DYBSMA system significantly reduced these demands due to the self-centering and energy-dissipating properties of SMA materials. Under MCE conditions, the BRB-DYBSMA configuration demonstrated superior seismic performance by achieving substantial reductions in median interstory drift ratios (IDRMed)—79.67% lower than conventional BRBs and 18.5% lower than DYB systems—and also minimizing RDRMed more effectively than the other brace types. Overall, the DYBSMA system proved to be the most efficient lateral-resisting solution, capable of enhancing structural performance, reducing collapse probability over 1- and 50-year return periods, and ensuring improved resilience compared to traditional and single-stage innovative bracing systems.

Sumit Kumar Gawande et al (2023) the lateral load–resisting system of a building plays a principal and highly productive role in safeguarding a structure against gradual collapse, especially under the influence of dynamic forces such as wind and earthquakes. With the increasing construction of high-rise buildings and the growing exposure of urban areas to seismic hazards, the demand for efficient and reliable lateral load-carrying mechanisms has become more critical than ever. Recent earthquakes across the globe have significantly impacted structures, revealing vulnerabilities in conventional reinforced concrete (RC) frames and highlighting the necessity for enhanced buckling resistance and improved seismic performance. A considerable amount of research has been devoted to understanding how buildings respond to seismic forces in different seismic zones. Various scholars have evaluated multi-story structures by examining key performance parameters such as story displacement, base shear, inter-story drift, story stiffness, natural time period, and the overall efficiency of different lateral load-bearing systems. These studies have utilized a combination of methodologies, including experimental investigations, numerical simulations, nonlinear time-history analysis, and software-based structural modelling using tools such ANSYS. Based on these analytical and experimental findings, numerous bracing configurations have been proposed to strengthen RC frames and enhance their ability to resist buckling and lateral deformation. Among these, steel and concrete bracing systems—such as X-bracing, V-bracing, inverted-V bracing, and K-bracing—have emerged as effective retrofitting and design solutions. In particular, X-bracing has consistently demonstrated superior performance in increasing the lateral stiffness of buildings, reducing excessive displacement, and improving overall stability during seismic excitation. This review aims to examine the developments in bracing systems used for improving buckling resistance in RC frames, summarize the comparative findings of previous studies, and discuss suitable methodologies for achieving optimal seismic performance. By synthesizing research insights, the study highlights the importance of selecting an appropriate bracing system to ensure structural safety, economic feasibility, and resilience against future seismic events.

Sumit G et al. (2021) conducted a detailed seismic performance study on a G+7 reinforced concrete (RCC) frame building by performing an equivalent static analysis using STAAD.PRO software. The research focused on evaluating the building's response under seismic and earthquake loads by employing both the equivalent static method and the dynamic analysis method, which are standard procedures for seismic design according to Indian codes. The structural model was developed in compliance with IS 1893 (Part 1): 2016, considering the building located in seismic zone III, which corresponds to a moderate seismic hazard region in India. The study highlighted the comparative effectiveness of software-based dynamic analysis over manual calculations, emphasizing that the dynamic analysis using STAAD.PRO provides more precise and reliable results in terms of structural behavior, lateral displacements, base shear, and overall seismic performance. This accuracy arises because the software can capture the complex interactions of inertial forces, mass distribution, and dynamic characteristics of the building more comprehensively than simplified manual methods, which often rely on approximations. The findings underline the importance of integrating advanced computational tools for seismic assessment, particularly for mid-rise RCC structures, to ensure safer and more efficient design practices under earthquake loading conditions.

Birendra B et al. (2021) conducted a comprehensive seismic study using Response Spectrum Analysis on a total of 24 structural models, comprising 12 unbraced reinforced concrete (RC) frames and 12 steel-braced RC frames, with building heights of 4, 8, 12, and 16 stories. The study focused on evaluating critical seismic parameters, including the fundamental time period (FTP), inter-story drift, base shear, top-story displacement, and story stiffness, to understand the dynamic behavior of these frames under earthquake loading. The results indicate a clear influence of bracing on structural performance: in the unbraced models, as the base shear acting on the columns increases, there is a corresponding rise in inter-story drift and overall displacement, reflecting greater flexibility and vulnerability under seismic forces. Conversely, the inclusion of steel bracing improves lateral load resistance, leading to reduced base shear demands and enhanced stiffness, which in turn limits excessive drift and top-story displacements. This demonstrates that steel bracing effectively enhances seismic performance by controlling lateral deformations and distributing seismic forces more efficiently across the frame, particularly in taller structures where dynamic effects are more pronounced.

Shital B et al. (2021) conducted a detailed study on the seismic behavior of different slab systems in multi-story buildings, specifically focusing on flat slab structures, conventional slab structures, and flat slab structures with drops. The study was carried out on a G+5 storey building, and ETABS software was employed for the structural analysis under seismic loads. The research aimed to evaluate and compare the performance of modern flat slab construction materials with traditional two-way slab systems across different seismic zones—Zone II, III, IV, and V. Key parameters analyzed included the maximum bending moments at critical points of the slabs, which reflect the structural response and potential vulnerability during earthquakes. The results highlighted differences in seismic performance depending on the slab type and material system, indicating that flat slab systems, particularly those with drops, can offer distinct advantages in controlling bending moments under seismic excitations, while the performance also varied with seismic intensity and zoning, providing insights for designing safer multi-story buildings in earthquake-prone regions.

Rahul M et al. (2020) conducted a detailed study on a G+19 storey steel braced building by designing seven different models, each incorporating a distinct bracing configuration. The analysis and design of these models were performed using STAAD Pro software, adhering to the Indian standards IS 800:2007 for steel design and IS 1893 (Part 1):2016 for seismic loading. The primary objective was to evaluate how different bracing patterns influence the building's seismic performance, particularly in terms of lateral displacement and overall stability. The comparative study revealed that the type and arrangement of braces have a substantial effect on the seismic response of high-rise steel structures. Among the configurations analyzed, the backward bracing pattern was identified as the most effective, significantly enhancing the building's resistance to lateral forces. Specifically, this bracing pattern was able to reduce the horizontal displacement at the top of the structure by up to 50% compared to other bracing arrangements, indicating its superior performance in controlling drift and improving structural stability during earthquakes. This study emphasizes the critical role of bracing design in high-rise steel buildings for seismic mitigation and highlights backward bracing as an optimal strategy for minimizing lateral deformations under seismic loads.

Formisano et al. (2020) focused on enhancing the seismic performance of the Italian building stock, which predominantly comprises structures built between the 1970s and 1980s. These buildings often exhibit deficiencies in lateral resistance due to their construction practices and codes of that era. To evaluate their seismic behavior, three representative structural models were developed: a bare frame (BF), a full in filled frame (FIF), and a pilots frame (PF). The seismic performance of these models was analyzed using the N2 method, implemented through the Capacity Spectrum Method, which allows for the assessment of nonlinear structural response under seismic loading by relating the capacity curve of the structure to the demand spectrum. Following this, the models were retrofitted with an external bracing system using a rational, systematic methodology aimed at improving lateral stiffness and energy dissipation. The results demonstrated that the introduction of X-bracing systems had a pronounced positive impact on the overall seismic performance. Among the three models, the bare frame structure benefited the most, exhibiting a substantial increase in its safety factor, as the addition of bracing significantly enhanced both its stiffness and ductility, reducing the likelihood of excessive lateral displacement or collapse during seismic events. The full in filled frame and pilots frame also showed improvements, but the relative gains were less pronounced due to their existing lateral resistance characteristics provided by infill's or open ground floors. Overall, the study highlighted the effectiveness of X-bracing in retrofitting older reinforced concrete structures, particularly those with minimal initial lateral resistance.

M. Suneel et al. (2019) conducted a detailed pushover analysis on 6-, 9-, 12-, and 15-storey special concentric X-braced steel frames to evaluate their ductility and overall seismic performance when subjected to increasing lateral loads. In this study, the structures were modeled and analyzed using SAP2000, incorporating material properties, geometric configurations, and loading conditions in accordance with the Indian Standard codes IS 800 for the design of steel structures and relevant seismic provisions of IS 1893. The research aimed to understand how building height influences nonlinear behavior, yielding patterns, load-displacement characteristics, and capacity curves of X-braced frames. By applying monotonic lateral loads until structural performance limits were reached, the authors examined key response parameters such as base shear capacity, roof displacement, stiffness degradation, and formation of plastic hinges. The results highlighted how bracing enhances lateral stiffness and energy dissipation, with taller buildings exhibiting more distributed hinge formation and comparatively higher displacement demands. Overall, the study demonstrated the effectiveness of X-bracing in improving ductility and seismic resilience, while also emphasizing the need for careful consideration of height-dependent behavior to ensure safe performance during strong earthquakes.

Hongjia L. et al. (2018) conducted a detailed investigation to determine the theoretically optimal bracing layouts for pre-existing frame structures that were originally designed only for gravity loads, aiming to enhance their lateral stiffness and overall seismic performance without altering the main frame. The study explored three bracing configurations: tension-only bracing, bracing elements crossing only at the frame corners, and unrestricted ideal bracing, where the members are allowed to intersect at any location within the frame. Using layout optimization techniques, initial feasible designs were generated and evaluated based on structural efficiency and load-carrying capacity. The results clearly indicated that tension-only bracing performed poorly due to its inability to resist compression, leading to reduced stiffness and ineffective lateral load resistance. In contrast, configurations allowing bracing components to cross at optimized locations—especially under unrestricted conditions—proved significantly more efficient. The analysis further revealed that a 45° intersection angle between bracing members consistently offered the best structural behavior, maximizing stiffness and minimizing material usage. This finding provides a practical guideline for retrofitting existing frames, suggesting that bracing added at approximately 45° can greatly improve seismic and lateral performance while maintaining structural economy.

Andrea P. et al. (2018) conducted a detailed seismic analysis of a seven-story, heavily loaded timber building in which the lateral load-resisting system was formed by CLT (Cross-Laminated Timber) shear walls, using Strand7 Finite Element Software to model the structural behavior. Their study employed numerical linear dynamic simulations to examine how variations in construction detailing influence the seismic force–resisting system (SFRS) during earthquake events. The analysis revealed that mid-rise timber buildings exhibit significant lateral flexibility, which affects their dynamic response under design-level ground motions. Due to this flexibility, the structure tends to develop considerable uplift forces at the base of the shear walls, transferring large uplift demands to the foundation system. The study emphasizes that, even with robust CLT shear-wall systems, mid-rise timber buildings remain sensitive to deformation patterns, and proper detailing is essential to control uplift, enhance stability, and improve overall seismic performance.

Can-Xing Qiu et al. (2016) conducted a comprehensive numerical study to evaluate the seismic performance of self-centering braced frames (SC-BFs) in comparison with conventional buckling-restrained braced frames (BRBFs). Their objective was to understand how self-centering systems behave under different levels of seismic excitation and whether they offer advantages over traditional BRBs in mid-rise steel buildings. The research utilized pushover analysis, single-degree-of-freedom (SDOF) analysis, and incremental dynamic analysis (IDA) to capture elastic, post-yield, and near-collapse performance indicators. A six-story benchmark steel building model originally equipped with BRBs was modified by replacing the BRBs with three different parameterized configurations of SC braces. These SC-BFs varied mainly in their post-yield stiffness, self-centering capability, and energy dissipation characteristics. All structural modelling and nonlinear analyses were performed using OpenSees. A suite of 20 ground motion records was selected and scaled to multiple intensity levels to ensure the building response could be evaluated across the full seismic demand spectrum, from elastic range to significant nonlinear deformation. Through this process, the researchers examined response parameters such as inter-story drift, residual drift, energy dissipation, and variability of seismic demand. The study concluded that SC-BFs with enhanced post-yield stiffness and appropriate energy-dissipating mechanisms exhibit superior and more reliable seismic performance. Specifically, these systems resulted in more uniform inter-story drift profiles, lower residual drifts, and reduced variability in structural response when subjected to different ground motions compared to the conventional BRBF system. Overall, the findings demonstrate that properly designed SC-BFs can provide improved seismic resilience by combining self-centering capability with controlled energy dissipation.

Hendramawat S. and colleagues (2013) conducted a study to evaluate whether the addition of steel bracing systems could significantly improve the seismic performance of an existing reinforced concrete structure, specifically the UNS Engineering Faculty's 5th Building. The research involved creating a structural model in ETABS and subjecting it to various load combinations that included dead loads, live loads, and earthquake loads, ensuring that the assessment reflected realistic in-service conditions. To understand the building's behavior under seismic forces, the researchers applied three major seismic evaluation methods: the Nonlinear Static Pushover Displacement Coefficient Method, the Improved Nonlinear Static Pushover Displacement Coefficient Method, and Dynamic Time History Analysis. These methods were selected based on recognized standards—SNI 03-1726-2002, FEMA 356, and FEMA 440—which provide guidelines for analyzing and predicting structural performance during earthquakes. The study compared the original unbraced building with several retrofitted models that incorporated different configurations and sizes of steel bracing. Results clearly indicated that the addition of steel bracing enhances the building's ability to resist seismic loads. Notably, target displacements in both principal directions were reduced by 16% to 55%, demonstrating a substantial improvement in lateral stiffness and overall structural stability. Interestingly, the study found that changing the size of the steel bracing elements did not significantly alter the improvement achieved. This suggests that the presence of bracing itself—rather than its exact dimensions—is the principal factor contributing to enhanced seismic performance.

K.M. Ward et al. (2012) introduced the Cast Modular Ductile Bracing (CMDB) system as an innovative alternative to conventional Special Concentrically Braced Frames (SCBFs), aiming to enhance seismic performance through improved strength, stiffness, and deformation capacity. The CMDB system incorporates specially cast modular components placed at both the ends and the center of the brace, allowing for controlled yielding and ductile behavior under seismic loading. Using ANSYS, the researchers performed nonlinear static (pushover) and transient dynamic analyses to compare the seismic response of CMDB with typical SCBFs, focusing on performance parameters such as energy dissipation, stiffness retention, and deformation compatibility. The analytical study emphasized the significance of evaluating flexural and axial over strength factors to properly characterize the CMDB design and ensure stable cyclic behavior. The results indicated that CMDBs offer reliable and repeatable performance, making them a viable and efficient alternative to SCBFs, and the analytical findings served as the foundation for developing a physical prototype intended for laboratory testing to validate the predicted behavior.

Temel T. et al. (2011) carried out both experimental and numerical investigations to evaluate how different brace configurations influence the seismic behavior of steel buildings by testing a three-story steel frame constructed at half scale in the Civil Engineering Department of Karadeniz Technical University. The study compared the performance of the bare (unbraced) frame with the same frame strengthened using four types of steel bracing—cross (X-type), inverted-V, V-type, and K-type—to understand how each geometry affects stiffness, strength, and overall structural response. Their results showed that introducing bracing elements substantially increases lateral stiffness and reduces lateral deformation under loading, thereby improving the seismic resistance of the building. Among the different configurations, the effectiveness varied depending on the brace arrangement, as some provided better load distribution and energy dissipation than others. Overall, the study emphasized that appropriate bracing design plays a crucial role in enhancing the stability and performance of steel structures, and that selecting an optimal brace geometry can lead to significant improvements in seismic behavior.

Methodology

This review adopts a systematic methodology that synthesizes findings from experimental investigations, numerical modelling, optimization-based studies, and software-driven seismic analyses to evaluate the effectiveness of various bracing systems for improving buckling resistance in reinforced concrete (RC) frames. The process begins with a comprehensive literature search of recent studies where researchers have examined advanced protective technologies and bracing mechanisms using both optimization frameworks and dynamic structural simulations. For instance, Madi et al. (2024) provide an optimization-based approach for determining the ideal distribution of protective devices such as isolators, dampers, and braces, highlighting how numerical algorithms enhance structural efficiency and reduce retrofit costs; similarly, Mohebi et al. (2023) employ nonlinear dynamic analysis (NDA) and incremental dynamic analysis (IDA) to assess innovative BRB alternatives—DYB and DYBSMA—under DBE and MCE ground motions, offering performance benchmarks related to drift control and residual deformations. Complementing these advanced analyses, studies such as those by Gawande et al. (2023) and Shital B et al. (2021) incorporate experimental methods, finite element modelling, and software tools like ANSYS and ETABS to evaluate slab–frame interaction, lateral stiffness, and the influence of different bracing and slab configurations under seismic loading. Additional contributions from Sumit G et al. (2021), Birendra B et al. (2021), and Rahul M et al. (2020) rely on equivalent static, response spectrum, and software-based dynamic analyses (STAAD.PRO, ETABS) to compare unbraced and braced RC frames and to investigate the performance of various bracing patterns in mid-rise and high-rise buildings. The data extracted across these studies—including inter-story drift, base shear, top displacement, natural period, and residual drift ratios—are systematically compared, allowing this review to identify trends, assess the relative efficiency of different bracing configurations, and determine the methodologies most suited for enhancing buckling resistance and seismic resilience in RC frames.

Conclusion

The review of various bracing systems clearly demonstrates that bracing is one of the most effective and practical strategies for improving the buckling resistance and overall seismic performance of reinforced concrete (RC) frames. Conventional steel bracings—such as X-, V-, K-, and inverted-V configurations—significantly enhance lateral stiffness, reduce inter-storey drifts, and lower structural deformations under seismic and wind loads. However, their performance is limited by the susceptibility of compression members to buckling, which restricts their energy-dissipation capacity. To overcome these shortcomings, advanced systems such as Buckling-Restrained Braces (BRBs)**,** Double-Yield BRBs (DYBs), and innovative hybrid systems incorporating shape memory alloys (SMA-BRBs) have been developed. These modern systems provide stable hysteretic behavior, excellent ductility, and reliable performance under repeated cyclic loading without strength degradation. Further, optimization-based studies and recent methodologies—such as optimal distribution of protective devices, metaheuristic algorithms, and surrogate modeling—demonstrate that the strategic placement of bracing systems can maximize safety while minimizing material use. Overall, the integration of advanced bracing technologies significantly enhances the resilience, sustainability, and safety of existing and new RC frames, making bracing systems a highly reliable approach for improving buckling resistance and seismic performance.

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