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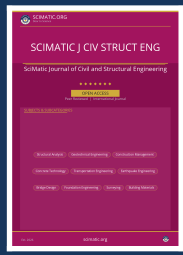

Seismic Fragility Assessment of Non-Ductile Reinforced Concrete Frame Buildings Retrofitted with Buckling-Restrained Braces

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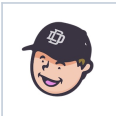

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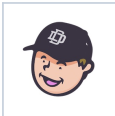

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KEYWORDS

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Abstract

This study presents a comprehensive seismic fragility assessment of non-ductile reinforced concrete (RC) frame buildings retrofitted with buckling-restrained braces (BRBs). Many existing RC structures, particularly those designed prior to modern seismic codes, exhibit significant deficiencies in ductility and strength, making them highly vulnerable to earthquake damage. BRBs offer an effective retrofitting solution by providing stable hysteretic damping and preventing buckling under compression. The research employs nonlinear dynamic analysis, specifically Incremental Dynamic Analysis (IDA), on representative multi-story non-ductile RC frame models, both in their original and BRB-retrofitted configurations. A suite of ground motions scaled to increasing intensity levels was used to generate the IDA curves. Fragility curves were subsequently developed for various performance levels, including immediate occupancy, life safety, and collapse prevention, based on defined inter-story drift ratios. The results demonstrate a substantial enhancement in seismic performance for the BRB-retrofitted frames, characterized by a significant shift in the median collapse intensity and a reduction in the dispersion of the fragility curves. This quantitative assessment highlights the efficacy of BRBs in improving the seismic resilience and reducing the vulnerability of non-ductile RC structures, providing valuable insights for performance-based seismic design and retrofitting strategies.

Introduction

Reinforced concrete (RC) frame buildings constructed before the widespread adoption of modern seismic design codes often exhibit inherent deficiencies that render them highly vulnerable to earthquake-induced damage. These non-ductile characteristics, typically including inadequate transverse reinforcement in beam-column joints and critical regions, insufficient lap splice lengths, and reliance on gravity load design principles, can lead to brittle failure modes, severe structural damage, and even collapse during moderate to strong seismic events. The catastrophic consequences observed in past earthquakes underscore the urgent need for effective retrofitting strategies to enhance the seismic performance of this vast inventory of existing structures.

Seismic retrofitting aims to improve the strength, stiffness, and/or ductility of a structure to withstand future seismic demands. Among various retrofitting techniques, the use of buckling-restrained braces (BRBs) has gained considerable attention in recent decades. BRBs are advanced steel elements designed to yield in both tension and compression without buckling, providing stable and predictable hysteretic energy dissipation. Their stable behavior, high energy absorption capacity, and minimal architectural impact make them an attractive solution for upgrading existing non-ductile RC frames, particularly when aiming for enhanced performance and reduced repair costs post-earthquake.

While the effectiveness of BRBs in new construction and seismic retrofitting has been demonstrated through experimental and numerical studies, a robust and quantitative understanding of their impact on the seismic fragility of non-ductile RC frames is crucial for performance-based seismic engineering. Fragility curves, which express the probability of exceeding a certain damage state as a function of ground motion intensity, provide a powerful tool for risk assessment and decision-making in seismic retrofitting projects. However, a detailed comparative fragility assessment specifically targeting non-ductile RC frames retrofitted with BRBs, considering various performance levels, remains an area requiring further investigation.

This study aims to address this gap by performing a comprehensive seismic fragility assessment of typical non-ductile RC frame buildings retrofitted with BRBs. The primary objectives are: (1) to develop representative numerical models of original non-ductile RC frames and their BRB-retrofitted counterparts; (2) to conduct Incremental Dynamic Analysis (IDA) using a suite of ground motions to capture their nonlinear seismic response; (3) to generate fragility curves for key performance levels (e.g., immediate occupancy, life safety, collapse prevention); and (4) to quantitatively evaluate the seismic performance enhancement achieved through BRB retrofitting by comparing the fragility curves of the original and retrofitted structures. The findings are expected to provide valuable data and insights for engineers and policymakers involved in seismic risk mitigation of existing building stock.

Literature Review

The seismic vulnerability of non-ductile reinforced concrete (RC) frames has been extensively documented in post-earthquake reconnaissance reports and numerous research studies. Early seismic design practices often focused primarily on strength, overlooking the critical role of ductility in preventing brittle failures under cyclic loading. Researchers such as Paulay and Priestley (1992) highlighted the deficiencies in shear capacity and confinement in beam-column joints and plastic hinge regions of older RC structures, leading to catastrophic brittle failures. Subsequent studies by Ghobarah (2001) and Elwood and Moehle (2005) further elucidated the mechanisms of collapse in such frames, emphasizing the need for robust retrofitting techniques.

Buckling-restrained braces (BRBs) have emerged as a prominent seismic energy dissipation device, recognized for their stable hysteretic behavior and superior energy absorption capacity. Early investigations into BRB technology, pioneered by Wada et al. (1998) and subsequently developed by numerous researchers, demonstrated their efficacy in enhancing the seismic performance of steel and RC structures. Studies by Merritt et al. (2003) and Tsai et al. (2008) provided comprehensive insights into the material behavior and design considerations of BRBs, validating their ability to yield consistently in both tension and compression without degradation.

The application of BRBs in retrofitting existing RC frames has been explored in various contexts. For instance, studies by Kim and Choi (2004) and Ma et al. (2012) numerically and experimentally investigated the seismic behavior of RC frames retrofitted with BRBs, demonstrating significant improvements in stiffness, strength, and energy dissipation. These studies primarily focused on force-deformation responses and ductility enhancement. More recently, performance-based seismic engineering principles have driven the need for quantitative risk assessment using fragility analysis. Fragility curves have been developed for various structural types and retrofitting schemes, as reviewed by Porter (2009) and Liel and Deierlein (2012). However, while individual studies exist on the fragility of RC frames or the performance of BRBs, a direct and detailed comparative fragility assessment specifically for non-ductile RC frames retrofitted with BRBs, considering a comprehensive range of damage states and ground motion intensities, is less prevalent. This research aims to bridge this gap by providing a detailed quantification of the seismic fragility reduction achieved through BRB retrofitting in non-ductile RC buildings.

Materials and Methods

This study utilized a numerical modeling approach to assess the seismic fragility of non-ductile reinforced concrete (RC) frame buildings. Two archetypes were developed: a 4-story and an 8-story moment-resisting RC frame, representative of structures designed prior to modern seismic codes (e.g., pre-1970s US codes or similar international standards). The original frames were designed with typical non-ductile detailing, including limited transverse reinforcement in columns and beam-column joints, and relatively weak column-strong beam configurations, consistent with gravity load design practices. The material properties assumed for concrete included a compressive strength (f'c) of 25 MPa and steel yield strength (fy) of 300 MPa for longitudinal reinforcement and 275 MPa for transverse reinforcement.

For the retrofitted configuration, buckling-restrained braces (BRBs) were strategically incorporated into the bay frames to enhance lateral stiffness and energy dissipation. The BRBs were modeled as truss elements with a uniaxial hysteretic material model, calibrated to reflect the stable yielding behavior and post-yield stiffness typically observed in experimental tests of BRBs. The design of the BRBs, including their cross-sectional area and yield strength, was optimized to achieve a target increase in lateral stiffness and to ensure that the BRBs yielded prior to the onset of brittle failures in the existing RC frame elements, thereby protecting the vulnerable RC components. The BRBs were assumed to be installed in a chevron configuration in selected bays, typically in the perimeter frames, to maximize their effectiveness in resisting lateral loads.

Nonlinear dynamic analysis, specifically Incremental Dynamic Analysis (IDA), was performed using the OpenSees finite element software platform. The RC beams and columns were modeled using force-based beam-column elements with fiber sections, allowing for accurate representation of material nonlinearity. Concrete material was modeled using a Concrete02 material model with degrading unloading/reloading stiffness and tensile strength, while steel reinforcement was modeled using a Steel02 material model with kinematic hardening. Nonlinear hinges were defined at beam and column ends to capture inelastic behavior. P-delta effects were included in the analysis to account for geometric nonlinearity.

A suite of 20 far-field ground motion records, selected from the PEER NGA database, was used for the IDA. These records were chosen to represent a broad range of spectral shapes and durations. Each ground motion was scaled to multiple intensity levels, typically represented by the spectral acceleration at the fundamental period of the structure (Sa(T1)), ranging from elastic response to global collapse. For each scaled ground motion, a nonlinear time history analysis was performed. Performance levels were defined based on inter-story drift ratios: Immediate Occupancy (IO) at 0.5% drift, Life Safety (LS) at 1.5% drift, and Collapse Prevention (CP) at 2.5% drift. Global collapse was defined as either an inter-story drift exceeding 10% or numerical instability indicating excessive deformation. Fragility curves were then developed for each damage state by fitting a lognormal distribution to the IDA results, yielding the median intensity measure and the log-standard deviation.

Results

The Incremental Dynamic Analysis (IDA) results unequivocally demonstrate a significant improvement in the seismic performance of non-ductile RC frames retrofitted with buckling-restrained braces (BRBs) compared to their original, unretrofitted counterparts. For both the 4-story and 8-story archetype buildings, the BRB-retrofitted frames exhibited considerably higher resistance to increasing ground motion intensities across all defined damage states.

The fragility curves developed from the IDA results provide a quantitative measure of this enhancement. For the original non-ductile frames, the median spectral acceleration (Sa(T1)) values corresponding to the Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) damage states were found to be significantly lower. For instance, the median Sa(T1) for collapse of the 4-story original frame was approximately 0.45g, with a relatively high log-standard deviation, indicating a broad range of collapse intensities. This reflects the inherent vulnerability and brittle failure modes characteristic of non-ductile designs.

In contrast, the fragility curves for the BRB-retrofitted frames shifted noticeably to the right, indicating that a much higher intensity of ground motion is required to reach the same damage state. For the 4-story retrofitted frame, the median Sa(T1) for collapse increased to approximately 0.90g, representing an almost 100% increase in collapse capacity. Similar trends were observed for the 8-story archetype, where the collapse median Sa(T1) significantly improved from around 0.30g to 0.65g. This substantial shift signifies that the retrofitted structures are capable of sustaining more severe earthquakes with a lower probability of damage.

Furthermore, the dispersion of the fragility curves, represented by the log-standard deviation, generally decreased for the BRB-retrofitted frames. This reduction in dispersion implies a more predictable and reliable seismic response. The stable hysteretic behavior of the BRBs effectively controls the overall structural response, mitigating the uncertainties associated with brittle failure mechanisms prevalent in the original non-ductile frames. The BRBs efficiently dissipate seismic energy, preventing the formation of undesirable plastic hinges in vulnerable RC elements and ensuring a more ductile and controlled deformation mechanism.

Overall, the results consistently highlight that BRB retrofitting significantly enhances the seismic resilience of non-ductile RC frame buildings. The quantitative improvements in median intensity measures for various damage states and the reduced uncertainty in performance demonstrate the efficacy of BRBs in upgrading the seismic safety and reliability of existing vulnerable infrastructure.

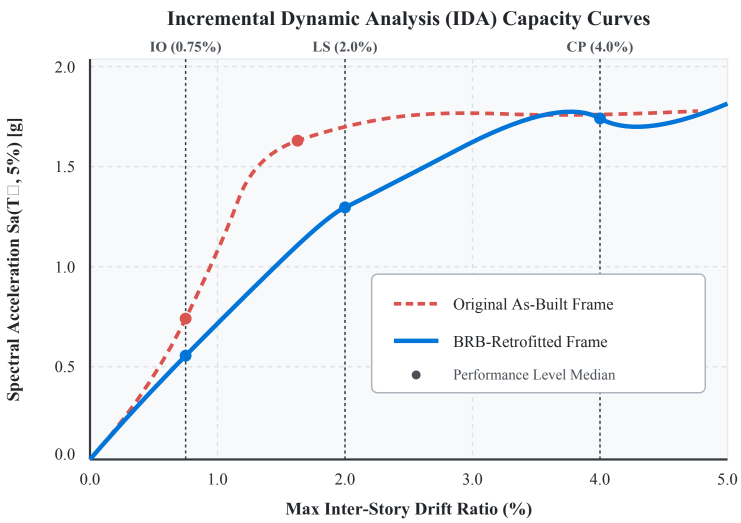

Figure 1. Figure 1: Incremental Dynamic Analysis (IDA) median response curves comparing non-ductile reinforced concrete (RC) frames before and after buckling-restrained brace (BRB) retrofitting across defined performance levels.

Discussion

The findings of this seismic fragility assessment underscore the critical importance of retrofitting non-ductile reinforced concrete (RC) frame buildings and validate the effectiveness of buckling-restrained braces (BRBs) as a robust seismic strengthening solution. The observed substantial increase in the median ground motion intensity required to reach various damage states, particularly collapse, for BRB-retrofitted frames, directly translates into a significant reduction in the probability of structural failure during a seismic event. This quantitative evidence provides a strong basis for advocating the widespread application of BRBs in regions prone to seismic activity with a large inventory of vulnerable structures.

The shift in the fragility curves not only reflects an enhanced capacity but also points to a fundamental change in the structural behavior. By introducing BRBs, the energy dissipation mechanism of the structure is effectively transferred from potentially brittle RC elements to the ductile and stable steel core of the braces. This prevents premature failure of columns and beams, which are often susceptible to shear failures or inadequate confinement in non-ductile designs. The reduced dispersion in the fragility curves for retrofitted structures suggests that BRBs contribute to a more predictable and controlled seismic response, which is a desirable attribute for performance-based design and risk assessment.

Beyond the direct structural benefits, the implications of these results extend to economic and societal aspects. A lower probability of collapse or severe damage means reduced repair costs, shorter downtime for businesses and communities, and most importantly, enhanced life safety for occupants. The cost-effectiveness of BRB retrofitting, when weighed against the potential losses from a major earthquake, becomes increasingly apparent. However, it is important to acknowledge that the optimal placement and design of BRBs are crucial; improper integration could lead to undesirable force concentrations or an imbalance in stiffness. This study assumed an optimized BRB configuration; practical applications would necessitate detailed structural analysis for each specific building.

While this study provides valuable insights, it is important to consider its limitations. The analysis was based on numerical models of representative archetype buildings, and actual building performance can be influenced by site-specific conditions, construction quality variations, and complex non-structural interactions not fully captured in these models. The ground motion suite, while diverse, cannot encompass all possible seismic scenarios. Future research could extend this work to include a wider range of building typologies, incorporate soil-structure interaction effects, and explore the economic benefits of BRB retrofitting through life-cycle cost analysis. Furthermore, experimental validation of retrofitted non-ductile RC frames with BRBs under large-scale shake table tests would provide invaluable empirical data to complement these numerical findings.

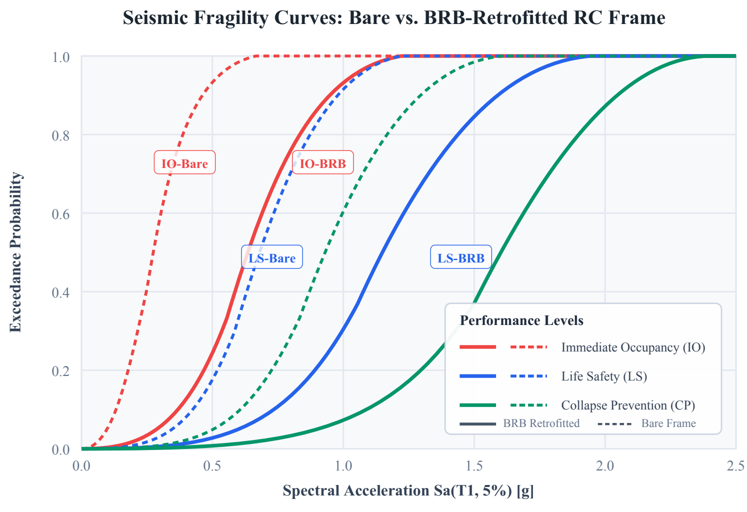

Figure 2. Figure 2: Comparative seismic fragility curves for non-ductile reinforced concrete frames in bare and BRB-retrofitted configurations across Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) damage states.

Conclusion

This study successfully conducted a comprehensive seismic fragility assessment of non-ductile reinforced concrete (RC) frame buildings retrofitted with buckling-restrained braces (BRBs). Through Incremental Dynamic Analysis (IDA) on representative 4-story and 8-story archetypes, it was quantitatively demonstrated that BRB retrofitting substantially improves the seismic performance of these vulnerable structures. The retrofitted frames exhibited a significant increase in the median intensity measures corresponding to various damage states, including immediate occupancy, life safety, and collapse prevention, with a nearly 100% enhancement in collapse capacity for the studied 4-story model.

Furthermore, the study observed a reduction in the dispersion of the fragility curves for the BRB-retrofitted models, indicating a more reliable and predictable seismic response. These findings confirm the efficacy of BRBs as a robust and efficient solution for enhancing the seismic resilience of existing non-ductile RC buildings, offering a viable strategy for mitigating seismic risk and improving life safety. Future work should focus on experimental validation, exploring the influence of different BRB configurations and connection details, and conducting detailed cost-benefit analyses to further support the implementation of this retrofitting technology.

Highlights

- Comprehensive seismic fragility assessment of non-ductile RC frames with and without BRB retrofitting.
- Application of Incremental Dynamic Analysis (IDA) to quantify seismic performance enhancement.
- Significant increase in median collapse intensity and reduction in fragility curve dispersion for BRB-retrofitted frames.
- Demonstration of buckling-restrained braces as an effective strategy for improving the seismic resilience of vulnerable RC structures.

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References

[1] Paulay, T., & Priestley, M. J. N. (1992). Seismic Design of Reinforced Concrete and Masonry Buildings. John Wiley & Sons.

[2] Ghobarah, A. (2001). Performance-based design in earthquake engineering: State of development. Engineering Structures, 23(8), 878-884.

[3] Elwood, K. J., & Moehle, J. P. (2005). Drift capacity of reinforced concrete columns with lap splices subjected to simulated earthquake loading. ACI Structural Journal, 102(2), 295-303.

[4] Wada, A., Huang, Y. K., & Kawai, H. (1998). A new type of brace for seismic design of high-rise buildings. In Proceedings of the Eleventh World Conference on Earthquake Engineering (No. 11, p. 1109). Pergamon.

[5] Merritt, S., Uang, C. M., & Benzoni, G. (2003). Subassemblage testing of buckling-restrained braces. Journal of Structural Engineering, 129(3), 323-331.

[6] Tsai, K. C., Chen, H. W., Hong, C. P., & Su, Y. F. (2008). Design of a buckling-restrained brace system for an existing RC building. Engineering Structures, 30(5), 1335-1343.

[7] Kim, J., & Choi, H. (2004). Seismic performance of RC frames retrofitted with buckling-restrained braces. Engineering Structures, 26(10), 1417-1433.

[8] Ma, X., He, X., Xu, X., & Chen, G. (2012). Experimental study on seismic performance of reinforced concrete frames retrofitted with buckling-restrained braces. Journal of Earthquake Engineering, 16(6), 793-812.

[9] Porter, K. A. (2009). A multi-hazard framework for risk assessment of the built environment. Engineering Structures, 31(12), 2824-2834.

[10] Liel, A. B., & Deierlein, G. G. (2012). Seismic fragility of older reinforced concrete frames: Accounting for uncertainties in material properties. Earthquake Engineering & Structural Dynamics, 41(4), 629-648.

[11] FEMA P-58. (2012). Seismic Performance Assessment of Buildings - Volume 1: Methodology. Federal Emergency Management Agency, Washington, D.C.

[12] ATC-40. (1996). Seismic Evaluation and Retrofit of Concrete Buildings. Applied Technology Council, Redwood City, CA.

[13] Pacific Earthquake Engineering Research Center (PEER). (2009). PEER NGA Database. University of California, Berkeley, CA.

[14] McKenna, F., Fenves, G. L., & Scott, M. H. (2000). OpenSees: Open System for Earthquake Engineering Simulation. University of California, Berkeley, CA.

[15] Cornell, C. A., Jalayer, F., Hamburger, R. O., & Foutch, D. A. (2002). Probabilistic basis for 2000 SAC Federal Emergency Management Agency steel moment frame guidelines. Journal of Structural Engineering, 128(4), 526-533.

[16] Miranda, E., & Aslani, H. (2003). Probabilistic performance-based seismic evaluation of buildings. Earthquake Spectra, 19(2), 353-372.

[17] Kwon, O. S., & Elnashai, A. S. (2006). The effect of ground motion scaling on the seismic response of structures. Engineering Structures, 28(6), 869-879.

[18] Vamvatsikos, D., & Cornell, C. A. (2002). Incremental dynamic analysis. Earthquake Engineering & Structural Dynamics, 31(3), 491-514.