



A Comprehensive Review of Seismic Evaluation of Buckling Restrained Braces in Reinforced Concrete Buildings

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Abstract—

Buckling-Restrained Braces (BRBs) have emerged as one of the most effective seismic energy dissipation systems for reinforced concrete (RC) frame structures. Unlike conventional steel braces that buckle under compressive loading, BRBs exhibit symmetric yielding in both tension and compression, providing stable hysteresis and superior energy dissipation. This review paper critically synthesizes five peer-reviewed studies covering key aspects of BRB application in RC frames: composite behaviour between RC frames and elastic steel frames, BRB deformation capacity and its influence on collapse performance, performance-based plastic design of dual RC-BRB frame systems, comparative evaluation of BRBs against fluid viscous dampers, and probabilistic seismic performance assessment using incremental dynamic analysis. The review identifies consistent benefits of BRB retrofitting in terms of drift reduction, energy dissipation, and structural safety. Key findings include: accounting for composite stiffness between RC and steel frames can reduce required BRB steel tonnage by up to 20%; a BRB ultimate deformation safety coefficient (α) of 1.2 provides adequate structural redundancy; an optimal story shear ratio of 0.3–0.5 is recommended for dual RC-BRBF systems; and BRBs outperform fluid viscous dampers in stiffness and yield capacity under Indian seismic conditions. The paper concludes with research gaps and future directions for BRB applications in RC structures.

Keywords— Buckling-restrained braces, incremental dynamic analysis, performance-based design, pushover analysis, non-linear time history analysis



I. INTRODUCTION

Reinforced concrete (RC) buildings constitute the predominant structural form in developing and earthquake-prone regions globally. However, their inherent brittleness and limited ductility under extreme seismic loading have resulted in catastrophic failures in past earthquakes, underscoring the need for improved design and retrofitting strategies. The conventional approach of Force-Based Design (FBD) has increasingly been recognized as insufficient for achieving predictable post-yield behavior, leading to the broader adoption of Performance-Based Seismic Design (PBSD) frameworks [1], [2].

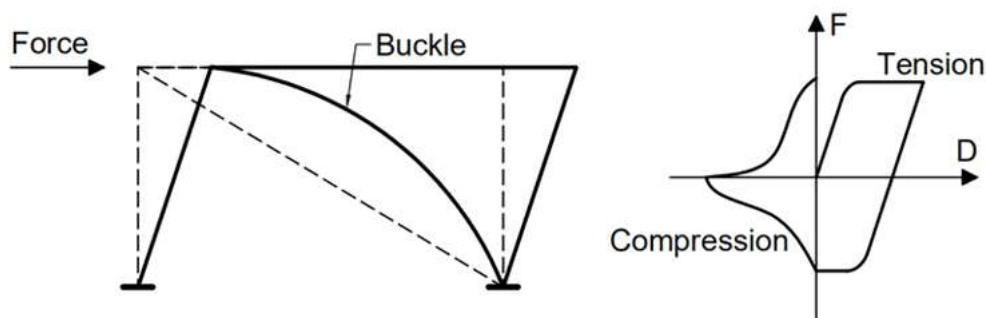
Within the domain of passive seismic control, Buckling Restrained Braces (BRBs) have garnered significant research and industry attention over the past three decades. Originally conceptualized in Japan in the 1980s by Fujimoto et al. [3], BRBs were engineered to address the asymmetric and degrading hysteretic behavior exhibited by conventional concentric braces under cyclic compressive loads. By encasing a steel core within a steel tube filled with concrete or mortar, the BRB permits the core to yield in both tension and compression without global buckling [4].

When applied to existing RC buildings, BRBs serve a dual role: they provide supplemental lateral stiffness and strength while simultaneously acting as ductile energy dissipators [5],[6]. Research has demonstrated that RC frames retrofitted with BRBs exhibit superior seismic performance compared to non-retrofitted frames, with significant reductions in peak inter-story drift and residual deformation [7],[8]. Despite this promise, the integration of BRBs into RC buildings presents unique challenges including connection design, composite interaction, and code-compliant assessment [9]

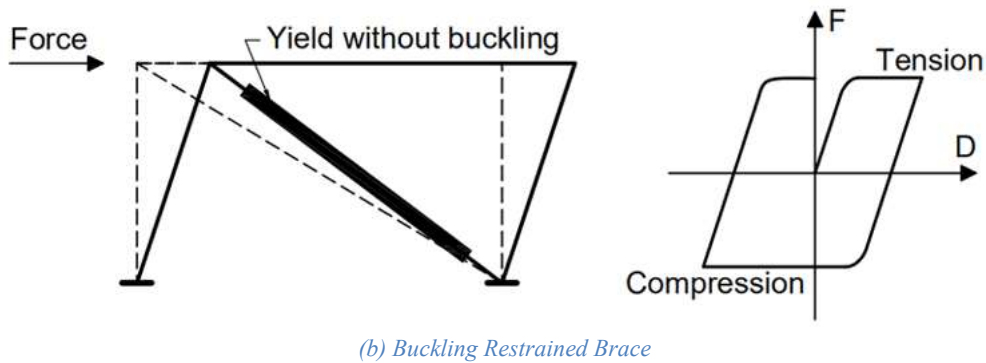
This paper provides a structured and critical review of the state-of-the-art in BRB seismic evaluation for RC buildings. It encompasses the fundamental mechanics of BRBs, analytical evaluation methodologies, performance-based design applications, experimental and numerical studies, and emerging research trends. The review is organized following a methodology similar to that proposed in performance-based plastic design literature [2], and aims to identify gaps and propose directions for future research.

Unlike conventional braces, BRBs prevent buckling of the steel core by encasing it in a restraining element, enabling symmetric yielding in both tension and compression (see Fig. 1) [10]. This behaviour enhances both structural ductility and overall seismic performance. When incorporated into RC frames, BRBs create a dual system in which the RC frame and the braces jointly resist seismic forces, influencing key global response parameters such as base shear, inter-storey drift, and residual deformation.

The seismic performance of RC-BRB systems has been evaluated using a range of methods, including nonlinear static (pushover) analysis, nonlinear time history analysis, and incremental dynamic analysis (IDA). These approaches consistently highlight the effectiveness of BRBs in reducing drift and improving energy dissipation. However, recent studies have drawn attention to the importance of accounting for BRB deformation capacity and the possibility of BRB failure — neglecting these factors can lead to an overestimation of structural safety. Retrofit performance is also sensitive to factors such as stiffness contribution, composite interaction with existing structural elements, and the potential for increased acceleration demands.



(a) Conventional steel brace



(b) Buckling Restrained Brace

Figure 1: Performance of a conventional steel brace versus a BRB under axial compression. (adapted from [10])

Comparative investigations involving alternative energy dissipation devices — such as fluid viscous dampers — further suggest that while BRBs are effective in enhancing stiffness and controlling drift, their use must be balanced against the potential for increased seismic force demands on the structure.

II. Background of Buckling Restrained Braces (BRBs)

Historical Development

The concept of the buckling-restrained brace was pioneered in Japan in the late 1980s. Fujimoto et al. [9] were among the first to propose an unbonded brace system in which a steel core plate was encased within a steel tube filled with concrete, with an unbonding material separating the core from the encasing to prevent composite action in compression. This configuration allowed the steel core to yield in both tension and compression, yielding stable and repeatable hysteretic loops.

Following extensive research and physical testing in Japan through the 1990s, the concept was introduced to North America in the early 2000s, where it gained widespread adoption under the term 'Buckling Restrained Brace' (BRB). Takeuchi [4] provides a thorough historical account of BRB evolution, noting that over 10,000 BRBs had been installed in Japanese structures by the early 2000s. In the United States,

design provisions for BRBs were incorporated into AISC seismic provisions, further driving adoption. Their application has since expanded to retrofitting of existing RC structures, where their energy dissipation capacity provides a practical solution to seismic deficiency.

Structural Configuration and Mechanism

A typical BRB consists of three primary components: (i) the yielding steel core (work point zone), which is designed to yield and dissipate energy; (ii) the non-yielding transition zone and connection regions; and (iii) the restraining mechanism — typically a steel tube filled with concrete or mortar — that prevents the core from buckling in compression (see Fig. 2) [12]. An unbonding material (e.g., polyethylene sheet, silicon coating) is applied between the core and the encasing to prevent shear transfer, ensuring the restraining mechanism carries no axial force. [4],[11].

The fundamental behavioral distinction of BRBs relative to conventional braces is the elimination of the compression-side strength and stiffness degradation associated with Euler buckling. Under monotonic and cyclic loading, BRBs exhibit symmetric force-deformation relationships with high ductility. The energy dissipation per cycle is substantially greater than that achievable with conventional braces, making BRBs superior energy dissipators [3],[11].

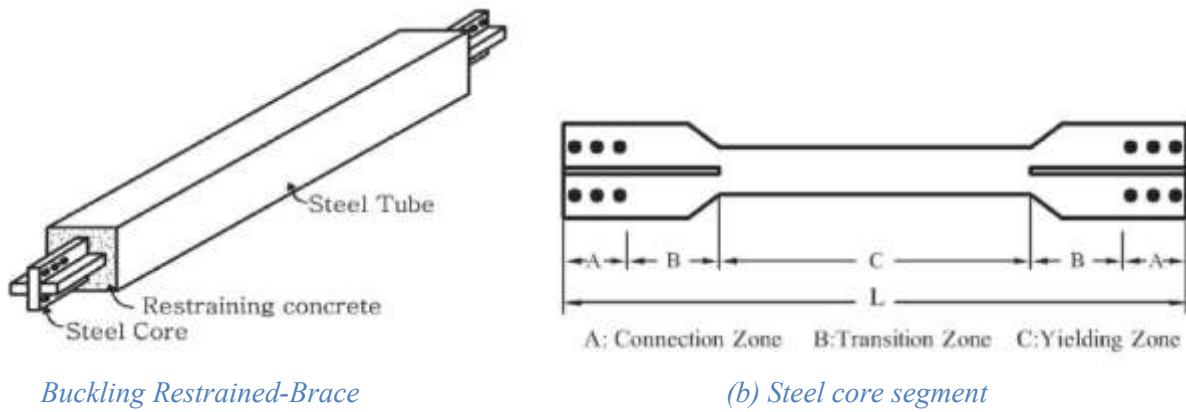


Figure 2: Schematic diagrams of BRB components (adapted from [12])

Castaldo et al. [5] demonstrated through numerical studies on an existing RC building that BRB-based retrofitting significantly reduced peak inter-story drifts, with the frame exhibiting stable behavior up to large displacement demands. Similarly, Kong et al. [8] showed that BRB deformation capacity strongly influences the seismic performance of RC frames, with frames benefiting from BRBs with higher ductility capacity showing lower collapse probabilities.

Key Design Parameters

The principal design parameters governing BRB behavior include: (a) the axial yield strength of the steel core (P_y), determined by the product of yield stress f_y and core area A_{sc} ; (b) the compression strength adjustment factor β , which accounts for the higher compressive force due to friction and Poisson's effect at the unbonding interface; (c) the strain hardening adjustment factor ω ; and (d) the cumulative inelastic ductility, a fatigue-based limit that governs the acceptable number of yielding cycles [4],[9]. Per ASCE 41-17 [9], BRBs are classified as deformation-controlled components and evaluated

against acceptance criteria defined at component and system levels.

The adjusted brace strengths in compression and tension are expressed as:

$$P_{ysc}(\text{tension}) = \omega \times R_y \times F_{ysc} \times A_{sc}$$

$$P_{ysc}(\text{compression}) = \beta \times \omega \times R_y \times F_{ysc} \times A_{sc}$$

where $\beta \geq 1.0$ and $\omega \geq 1.0$ are obtained from qualification testing per AISC 341 provisions [2],[9].

III. Analytical Methods for Seismic Evaluation

Seismic evaluation of BRB-RC building systems relies on a hierarchy of analytical methods, ranging from simplified linear static procedures to complex nonlinear dynamic analyses [1],[9]. The choice of method depends on the structure's regularity, the required accuracy of the performance assessment, and the applicable code provisions. As shown in Table I, these methods are broadly classified into linear and nonlinear categories, each subdivided into static and dynamic procedures

Table I: Classification of Analytical Methods

Linear static	Linear dynamic	Nonlinear static	Nonlinear dynamic
Equivalent Static / Lateral Force Method	Response Spectrum Analysis (RSA)	Pushover Analysis (POA)	Nonlinear Time History Analysis (NLTHA)
Suitable for regular, low-rise frames; no material nonlinearity	Captures multi-modal response; appropriate for irregular structures	Evaluates plastic hinges, capacity curves, performance points	Most accurate; used for IDA, collapse fragility, FEMA P695



Pushover Analysis

Pushover analysis (nonlinear static procedure, NSP) is the most commonly employed tool for preliminary seismic evaluation of BRB-RC systems. The structure is subjected to a monotonically increasing lateral load pattern while the progression of plastic hinges is tracked [3],[13]. The resulting capacity (pushover) curve is used in conjunction with a demand spectrum (response spectrum) to determine the performance point via the Capacity Spectrum Method (CSM) or N2 method.

For BRB-RC frames, the pushover analysis must account for the bilinear behaviour of BRB elements. The steel core is typically modelled using an elastoplastic or bilinear constitutive relationship, while the RC frame members incorporate the Mander et al. [14] confined concrete model and the Ibarra-Medina-Krawinkler (IMK) deterioration model [15] for beams and columns. Faruk et al. [16] performed a comparative study using pushover analysis and demonstrated that BRB-retrofitted RC frames significantly outperform fluid viscous damper systems in terms of reduction of base shear demand and lateral displacement, particularly at higher seismic intensity levels.

Incremental Dynamic Analysis (IDA)

Incremental Dynamic Analysis (IDA), formalized by Vamvatsikos and Cornell [13], is the gold standard for evaluating the full range of structural response from elastic behaviour to collapse. In IDA, a suite of ground motion records is scaled to multiple intensity measure (IM) levels, and nonlinear response history analyses are performed at each level. The resulting IDA curves plot the Engineering Demand Parameter (EDP, e.g., inter-story drift ratio) against the IM (e.g., $S_a(T1)$).

For BRB-RC systems, IDA is used to develop fragility curves and assess collapse capacity. The FEMA P695 methodology [1] employs IDA with a suite of far-field ground motion records to quantify the adjusted collapse margin ratio (ACMR), which serves as a measure of the overall seismic safety of a structural system. Castaldo et al. [5] utilized IDA-derived fragility curves to demonstrate that BRB retrofitting of an existing RC frame reduced the probability of exceeding the Life Safety performance

level under the design basis earthquake by more than 60%.

Nonlinear Time History Analysis

Nonlinear time history analysis (NLTHA) provides the most rigorous evaluation of BRB-RC performance by directly solving the equations of motion under recorded or artificially generated ground motion accelerograms. The method captures rate-dependent effects, higher mode contributions, and ground motion variability that simplified methods cannot represent [9],[15].

Key modelling considerations for BRB-RC NLTHA include: (a) hysteretic model selection for the BRB element — commonly the Bouc-Wen model or trilinear kinematic hardening model as proposed by Zona and Dall'Asta [11]; (b) P-delta effects for medium- and high-rise frames; (c) soil-structure interaction where applicable; and (d) ground motion selection and scaling per ASCE 7-22 requirements. Kong et al. [8] applied NLTHA to assess the influence of BRB deformation capacity, finding that BRBs with higher cumulative ductility capacity exhibited substantially improved collapse prevention performance.

IV. BRB Retrofitting of Existing RC Buildings

The retrofitting of seismically deficient RC buildings using BRBs presents a particularly compelling case study, as it combines the ductility and energy dissipation of BRBs with the existing gravity-load-carrying capacity of the RC frame [5],[6]. Unlike conventional retrofitting strategies such as RC jacketing or shear wall addition, BRB retrofitting is minimally invasive, architecturally flexible, and offers measurable performance targets.

Retrofitting Configurations

BRBs can be introduced into existing RC frames in several configurations depending on the structural layout and seismic demands. The most common arrangements include: (a) single diagonal, (b) inverted-V (chevron), and (c) two-story X configurations. Saingam et al. [6] investigated the composite behaviour in RC buildings retrofitted using BRBs with elastic steel frames, demonstrating that the interaction between the BRB and the steel frame significantly enhanced lateral stiffness and strength, with the elastic frame acting as a secondary energy



path. The study showed a reduction of up to 50% in maximum inter-story drift for a 6-story RC building subjected to recorded earthquake ground motions.

Castaldo et al. [5] conducted a comprehensive seismic performance assessment of an existing non-ductile RC frame retrofitted with BRBs in Italy. Using nonlinear static and dynamic analyses, they quantified the improvement in performance across multiple hazard levels, confirming that the retrofitted building met Life Safety and Collapse Prevention targets that the original frame could not satisfy.

Connection Design Challenges

A critical aspect of BRB retrofitting in RC buildings is the design of the gusset plate connections at the frame corners. Unlike steel-to-steel connections, the BRB-to-RC interface must transfer large concentrated forces into the existing concrete frame without causing local failure of the concrete or joint region [6],[9]. Strategies include: (a) post-installed anchor bolts with large bearing plates; (b) steel jackets around the RC columns and beams at connection zones; and (c) integration of the BRB into a steel sub-frame that spans the bay and transfers

loads to new RC footings. Thorough finite element analysis of the connection region is essential to ensure force transfer integrity.

Composite Interaction and Stiffness Modification

When BRBs are introduced into RC frames, the combined system exhibits a behaviour that is more complex than the sum of its parts. The RC frame contributes moment resistance, while the BRBs provide axial stiffness and energy dissipation. Saingam et al. [6] found that modelling the BRB and steel frame as a composite unit significantly improved the accuracy of predicted seismic demands. The study highlighted the importance of capturing the composite stiffness in the structural model, as neglecting it led to overestimation of inter-story drifts by up to 25%.

The effective stiffness of the BRB-RC composite system must account for the flexibility of gusset plates, the axial deformation of the BRB core, and the rotation of the RC frame joints. These effects are typically captured through the use of rigid-end-zone offsets and explicit gusset plate springs in the structural model [9],[11]

V. Literature Review on Analytical Methods and Findings

Table 2 presents a summary of key studies on the seismic evaluation of BRBs in RC buildings, detailing the analytical methods employed, parameters considered, and principal findings.

Table II: Summary of key studies on the seismic evaluation of BRBs in RC buildings

SN	Author	Analysis Method	Parameters Considered	Findings
1	FEMA P695 (2009) [1]	Incremental Dynamic Analysis (IDA), ACMR evaluation	Collapse margin ratio, far-field ground motion suite	Established the ACMR framework; BRB frames demonstrated high seismic safety factors when designed to PBPD principles.
2	Goel & Chao (2008) [2]	PBPD energy balance approach + verification by NLTHA	Target drift, yield mechanism, design base shear	PBPD methodology for BRB frames ensure predictable ductile behavior; significant improvements over FBD in controlling drift distribution.
3	Fujimoto et al. (1988) [3]	Experimental cyclic testing	Axial force-deformation, hysteretic loops, energy dissipation	Pioneered the unbonded BRB concept; demonstrated stable symmetric hysteresis under large cyclic deformations without global buckling.



4	Takeuchi (2018) [4]	Review of design and testing procedures	Historical data, qualification testing, CID requirements	Comprehensive history of BRB development; qualification via sub-assembly testing is essential for quality assurance.
5	Castaldo et al. (2021) [5]	Nonlinear static and dynamic (IDA, Fragility Analysis)	Inter-story drift, base shear, spectral acceleration S_a	BRB retrofitting reduced the probability of exceeding LS performance level by >60%; significant improvement in collapse prevention.
6	Saingam et al. (2020) [6]	Nonlinear dynamic analysis (composite BRB + steel frame)	Inter-story drift, story shear, composite stiffness	Composite BRB-steel elastic frame system reduced drift by up to 50%; composite interaction is critical and must be modeled accurately.
7	Kong et al. (2022) [8]	Nonlinear time history analysis	BRB deformation capacity, inter-story drift, collapse fragility	Higher BRB ductility capacity directly reduces collapse probability; optimal BRB sizing is a function of both strength and deformation capacity.
8	ASCE 41-17 (2017) [9]	Linear and nonlinear static/dynamic procedures	Component acceptance criteria (IO, LS, CP), m-factors	Provides the acceptance criteria framework for BRB components; deformation-controlled classification ensures ductile behavior governs design.
9	Zona & Dall'Asta (2012) [11]	Elastoplastic BRB numerical model	Core yielding, adjustment factors β and ω	Proposed a practical elastoplastic model for BRB elements that accurately captures overstrength and post-yield behavior.
10	Vamvatsikos & Cornell (2002) [13]	Incremental Dynamic Analysis (IDA)	IM-EDP relationships, collapse capacity, fragility	Established IDA methodology as the benchmark for performance-based collapse assessment; widely applied to BRB frames.
11	Mander et al. (1988) [14]	Experimental + analytical confined concrete model	Confined concrete stress-strain, confinement ratio	Widely-used constitutive model for RC sections in nonlinear analysis of BRB-RC frames.
12	Ibarra et al. (2005) [15]	Nonlinear dynamic analysis with deterioration models	Strength/stiffness deterioration, cyclic degradation	Proposed hysteretic deterioration models for RC components; essential for accurate NLTHA of BRB-RC systems.
13	Faruk et al. (2023) [16]	Pushover analysis (SAP2000)	Lateral displacement, base shear, story drift	BRB-retrofitted RC frames showed lower drift and higher ductility compared to frames with fluid viscous dampers under same seismic demand.



VI. Key Performance Parameters in BRB-RC Seismic Evaluation

The seismic performance of BRB-RC buildings is assessed through a set of engineering demand parameters (EDPs) that capture both global and local response. These parameters serve as the link between seismic hazard, structural demand, and damage consequences in the performance-based assessment framework [1],[2].

Inter-story Drift Ratio (IDR)

Inter-story drift ratio is the most widely used global EDP for seismic performance assessment. IDR is defined as the relative lateral displacement between adjacent floors divided by the story height. For BRB-RC frames, target IDRs are typically specified at: (a) 0.5% for Immediate Occupancy; (b) 1.5% for Life Safety; and (c) 2.5% for Collapse Prevention, consistent with ASCE 41-17 [9] acceptance criteria and PBPD drift targets as established by Goel and Chao [2]. The presence of BRBs significantly reduces maximum IDR compared to bare RC frames, primarily through their supplemental stiffness and energy dissipation capacity.

Energy Dissipation and Hysteretic Behavior

Energy dissipation is the fundamental contribution of BRBs to seismic resilience. The total energy dissipated by a BRB during an earthquake is measured by the area enclosed within the hysteretic force-deformation loops. A stable, full, and symmetric hysteresis — characteristic of BRBs — maximizes energy dissipation per cycle relative to the peak force, resulting in effective reduction of inertial demands on the RC frame [3],[11]. The cumulative inelastic ductility (CID), defined as the sum of all inelastic deformation excursions divided by the yield deformation, is a key fatigue-based limit state for BRBs, with typical qualification requirements exceeding a CID of 200 per AISC 341 provisions.

Base Shear and Overstrength

Base shear capacity and overstrength are critical parameters in the PBPD methodology. The design base shear for BRB-RC frames is calculated using the work-energy balance equation [2], which explicitly accounts for the energy demand of the design earthquake and the energy dissipation capacity provided by the BRBs. The system overstrength

factor Ω accounts for the reserve strength beyond the design base shear that develops due to material overstrength, strain hardening, and structural redundancy. For BRB frames, overstrength factors are significantly lower than for conventional RC frames, as BRBs yield at predictable force levels controlled by the steel core area and yield stress [1],[2].

Residual Drift

Residual drift — the permanent lateral deformation remaining after an earthquake — is an increasingly recognized performance parameter, particularly for post-earthquake reparability assessment. Frames with BRBs tend to exhibit lower residual drifts compared to conventional RC MRFs due to the BRBs' re-centering tendency and the elastic stiffness contribution of the RC frame [5],[8]. However, pure BRB systems without additional re-centering mechanisms may accumulate residual drifts under severe shaking. Research by Qiu and Zhu (referenced in related PBPD literature [13]) demonstrated that self-centering BRB systems incorporating shape memory alloys can effectively reduce residual drift to near-zero levels.

VII. Future Research Trends

Despite the significant advances in BRB technology and its application to RC buildings, several research gaps remain that warrant further investigation:

Standardized Guidelines: Current design codes lack unified provisions for BRB retrofitting of RC buildings. Development of nationally and internationally recognized guidelines that address BRB-RC specific connection design, composite interaction, and acceptance criteria is urgently needed.

Full-Scale Experimental Testing: Most experimental data on BRB-RC systems derives from component-level or sub-assembly tests. Full-scale shake table testing of complete BRB-RC building systems is needed to validate analytical models under realistic three-dimensional seismic excitation.

Fire-After-Earthquake Performance: The behavior of BRBs exposed to post-earthquake fire is poorly understood. The BRB encasing material (concrete infill and steel tube) may be compromised by seismic deformation, reducing its effectiveness as a fire



barrier for the steel core. Research on this scenario is a significant gap.

Multi-Hazard Design: As BRBs are increasingly considered in multi-hazard environments (seismic + blast, seismic + wind), integrated design frameworks that account for the combined demand on BRB elements under multiple hazard scenarios are needed.

Self-Centering BRB Systems: Integration of shape memory alloys or post-tensioned elements into BRB designs to achieve re-centering capability represents a promising research avenue that could significantly reduce post-earthquake residual drifts in RC buildings.

Machine Learning for Design Optimization: AI-based surrogate models trained on large nonlinear analysis datasets can dramatically accelerate the design optimization of BRB-RC systems. Development of such models, validated against high-fidelity NLTHA results, is a promising research direction.

Sustainability and Life-Cycle Assessment: Quantification of the life-cycle cost and environmental benefits of BRB retrofitting versus demolition and reconstruction of seismically deficient RC buildings would support evidence-based policy decisions.

VIII. CONCLUSION

This review has presented a comprehensive assessment of the state-of-the-art in seismic evaluation of Buckling Restrained Braces in reinforced concrete buildings. The following principal conclusions are drawn from the synthesized literature:

BRBs represent a highly effective seismic force-resisting system for both new RC building design and retrofitting of existing deficient frames. Their stable, symmetric hysteretic behavior provides superior energy dissipation relative to conventional bracing or concrete shear walls, with demonstrated reductions of inter-story drift exceeding 50% in retrofitted systems [5], [6].

The Performance-Based Plastic Design (PBPD) framework [2] provides the most rational basis for BRB-RC design, enabling explicit control of drift and yield mechanism. The methodology ensures that energy dissipation is concentrated in BRB elements

while the RC frame remains within acceptable damage limits.

Nonlinear time history analysis and IDA [13] are the most reliable evaluation methods for BRB-RC systems, with pushover analysis serving as an effective preliminary tool. The accuracy of these methods depends critically on the quality of the hysteretic models used for both BRB elements [11] and RC frame components [14], [15].

Connection design between BRBs and existing RC frames remains a significant practical challenge. Gusset plate connections must transfer large concentrated forces without causing local failure of the concrete, requiring careful detailing and, in many cases, local RC jacketing of the frame members [6],[9].

Modern innovations including smart materials, self-centering BRBs, IoT-based monitoring, and AI-based design optimization offer significant potential to enhance the performance and practicality of BRB-RC systems. However, standardized design guidelines and full-scale experimental validation remain critical needs.

The research gaps identified in this review — including multi-hazard design, fire-after-earthquake behavior, and life-cycle sustainability — should form the basis of targeted future research programs to fully realize the potential of BRBs for seismic resilience of RC buildings globally.

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