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Buckling-Restrained Braces for Seismic Retrofitting of RC Structures: State-of-the-Art and Critical Review

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Abstract **Review Article**

Many existing reinforced concrete (RC) buildings were constructed before modern seismic design codes were introduced, making them vulnerable to damage during strong earthquakes. Buckling-restrained braces (BRBs) have become an effective retrofitting option because they can dissipate seismic energy through stable yielding under both tension and compression. This paper reviews recent developments in BRB technology, with a focus on mechanical behavior, experimental performance, numerical modeling, and their use in the seismic retrofitting of existing RC structures. The review discusses different BRB systems, including conventional mortar-filled BRBs, all-steel assembled braces, self-centering systems, multi-stage energy dissipation devices, and externally attached precast sub-structures. It also examines important factors that affect cyclic performance, such as core yielding length, friction between the steel core and casing, strain hardening, and low-cycle fatigue. Previous experimental studies have shown that BRBs can improve the lateral strength, stiffness, and energy dissipation capacity of RC frames while reducing deformation demands on vulnerable structural members. However, conventional BRBs may still experience significant residual drifts after strong earthquakes, which has led researchers to develop hybrid and self-centering systems. This review also discusses numerical modeling methods, performance-based design approaches, seismic fragility assessment, and practical difficulties related to BRB installation in existing buildings. Although considerable progress has been made, several challenges remain, including gusset plate instability, connection behavior, fatigue under repeated seismic loading, and force transfer between external retrofitting systems and existing RC frames. Further research is needed to improve large-scale experimental validation, numerical modeling accuracy, and the long-term performance of sustainable and replaceable BRB systems. Overall, this paper summarizes the advantages and limitations of current BRB technologies and identifies areas for future research to improve the seismic safety and resilience of existing RC structures.

Keywords: Buckling-restrained braces (BRBs); Seismic retrofitting; Reinforced concrete structures; Energy dissipation; Hysteretic behavior; Self-centering systems; Seismic resilience.

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1. Introduction

1.1 Background and seismic vulnerability of RC structures

Many reinforced concrete (RC) buildings were constructed before modern seismic design codes and remain vulnerable to earthquakes due to inadequate transverse reinforcement, poor beam-column joint detailing, insufficient lap splices, and non-ductile shear-dominated failure modes. Vertical and plan irregularities can further increase seismic demands, particularly in buildings with soft-story or weak-

story mechanisms caused by sudden reductions in lateral stiffness or strength[1]. These conditions are common in buildings with open ground floors used for parking or shops, while masonry infill walls increase the stiffness of upper stories.

Post-earthquake investigations and numerical studies have shown that soft-story buildings are highly vulnerable to seismic damage[2]. Studies considering the Bangladesh National Building Code (BNBC 2020) and observations from the 2023 Kahramanmaraş earthquakes have highlighted excessive inter-story drifts concentrated at the ground level. Ground-story columns may experience high shear forces and bending moments due to the stiffness difference between stories. Conventional equivalent static methods may not adequately capture these concentrated demands, potentially increasing collapse risk if critical members are not properly designed. Therefore, effective seismic retrofitting is essential to improve structural safety, reduce collapse risk, and support post-earthquake building functionality.

1.2 Development and advantages of BRBs for seismic retrofitting

To improve the seismic performance of deficient reinforced concrete (RC) frames, several retrofitting methods have been developed. Traditional approaches, including concrete jacketing, steel encasing, and fiber-reinforced polymer (FRP) wrapping, improve member ductility and shear capacity but may not adequately address soft-story behavior and overall stiffness irregularities[3], [4]. Consequently, system-level retrofitting using supplemental energy dissipation devices has gained attention[5].

Among these methods, buckling-restrained braces (BRBs) act as structural fuses by yielding under both tension and compression without global or local buckling[6]. The steel core carries axial loads, while the surrounding casing provides lateral restraint, allowing stable, repeatable, and nearly symmetric hysteretic behavior. When installed in RC frames, BRBs form buckling-restrained braced frames (BRBFs) that dissipate seismic energy, reduce lateral drift demands, and limit damage to non-ductile members by concentrating inelastic deformation in potentially replaceable braces[7]. BRBs may also require smaller cross-sections than conventional braces and, depending on the design, reduce foundation uplift and compression demands. These benefits make BRBs a promising and potentially cost-effective solution for retrofitting existing RC structures.

1.3 Research gaps and objectives of the review

Buckling-restrained braces (BRBs) have demonstrated good experimental performance, their interaction with connections and existing reinforced concrete (RC) frames remains complex. Several challenges require further investigation, including out-of-plane instability of gusset plates under combined axial loads and frame deformations, low-cycle fatigue of new core materials under long-duration subduction earthquakes, and numerical modeling and practical implementation of interfacial shear transfer in externally attached precast sub-structures[8].

Despite their effectiveness in reducing peak displacements, conventional BRBs may experience significant residual drifts due to their low post-yield stiffness, increasing repair costs and delaying building recovery[9]. This limitation has encouraged research into self-centering mechanisms and hybrid brace configurations. This review examines recent developments in BRB technology for retrofitting existing RC structures, drawing on numerical simulations, large-scale shake-table experiments, and probabilistic seismic risk assessments. By comparing these findings and their limitations, the review identifies research gaps and provides insights for the performance-based design of BRB retrofitting systems to improve the seismic resilience of existing RC buildings.

2. BRB Fundamentals and Development

2.1 Working mechanism and key components

A buckling-restrained brace (BRB) is an energy-dissipation device used to improve the seismic

performance of structures by resisting axial forces under both tension and compression without buckling. A conventional BRB consists of three main components: a steel yielding core, an unbonding layer, and an external restraining mechanism[7]. The steel core carries the axial load and undergoes plastic deformation during earthquakes, which allows the brace to absorb and dissipate seismic energy[10]. The external restraining mechanism usually consists of a steel casing filled with mortar or concrete. Its main function is to provide lateral support to the steel core and prevent buckling under compressive loading[11]. The unbonding layer is placed between the steel core and the surrounding restraining material to reduce friction and allow the core to deform freely in the axial direction[7]. This layer also helps prevent significant axial forces from being transferred to the casing. With proper lateral restraint, the steel core can yield under both tension and compression, resulting in stable and nearly symmetric hysteretic behavior[12]. During repeated cyclic loading, the BRB dissipates seismic energy through plastic deformation of the steel core, helping to reduce the force and deformation demands on the surrounding reinforced concrete (RC) frame. The main components and working mechanism of a conventional BRB are shown in Figure 1.

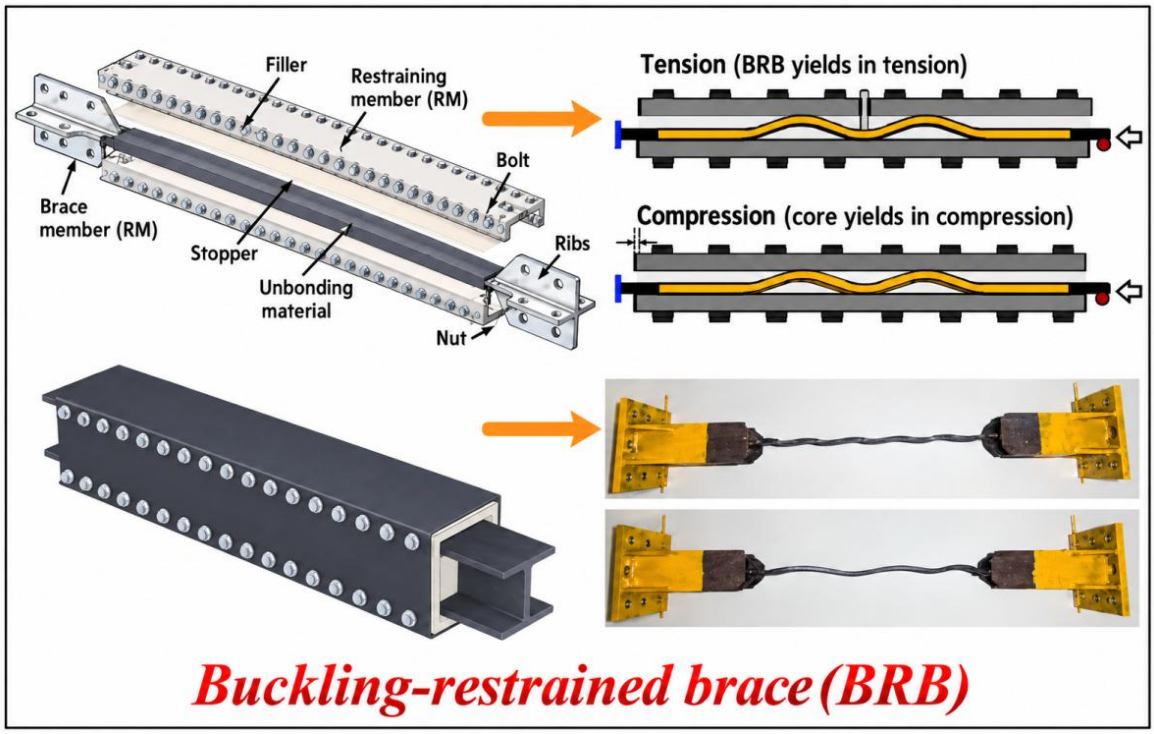


Figure 1-Schematic of BRB Components.

2.2 BRB configurations and material developments

Over the past two decades, buckling-restrained brace (BRB) technology has advanced to simplify construction, reduce weight, and improve post-earthquake inspection. The heavy weight and mortar curing requirements of conventional BRBs have encouraged the development of all-steel assembled

BRBs (AB-BRBs). These systems typically use two bolted steel restraining members, such as channels or hollow sections, surrounding a steel core plate. Gap clearances and shims allow core deformation while providing buckling restraint. Without mortar, AB-BRBs can reduce manufacturing and installation time, while removable bolted components allow direct inspection and replacement of damaged cores.

Material developments have also improved BRB cores and restraining systems. Ultra-high-performance concrete (UHPC) and engineered cementitious composites (ECC) have been explored as alternative restraining materials due to their improved crack resistance, mechanical properties, and durability. Sustainable alternatives, including timber and glued-laminated bamboo (glubam), have also been investigated for timber BRBs (T-BRBs) and bamboo BRBs (BBRBs)[11]. However, these casings require sufficient transverse stiffness and strength to restrain weak-axis core buckling and prevent premature splitting perpendicular to the grain under compression.

The unbonding layer is another important design factor. Materials such as silicone rubber, butyl rubber, chloroprene, and polytetrafluoroethylene (PTFE) films are used to reduce friction between the steel core and restraining casing[9]. The friction coefficient (μ) influences compressive overstrength and hysteretic behavior. PTFE typically exhibits dynamic friction coefficients of 0.04–0.13, while silicone rubber and polymer films may range from 0.065 to 0.16 under specified contact conditions. These values can increase due to surface damage or micro-plowing wear. Excessive friction increases unintended force transfer to the casing and may contribute to local instability and asymmetric hysteretic behavior, reducing BRB cyclic performance.

2.3 Hysteretic behavior and failure mechanisms

A properly designed buckling-restrained brace (BRB) exhibits stable, nearly symmetric bilinear or multilinear hysteretic behavior, dissipating seismic energy through repeated plastic deformation[9], [10]. However, inadequate core–casing interaction or boundary conditions can lead to several failure mechanisms that affect BRB performance.

First, high-mode buckling and casing bulging may occur during large compressive deformations[13]. Although the unbonding gap accommodates lateral expansion of the steel core, it also allows high-mode buckling within the restraining casing. Contact between the buckled core and casing generates outward forces and localized friction. If the casing lacks sufficient strength or stiffness, localized bulging, weld tearing, or rupture may occur.

Second, low-cycle fatigue (LCF) and ultra-low-cycle fatigue (ULCF) can develop due to repeated plastic deformation concentrated in the yielding core[12]. Large inelastic strain cycles gradually accumulate damage and may cause fracture. Fatigue life is commonly evaluated using the Coffin-Manson relationship, which relates plastic strain amplitude to the number of cycles to failure. Cumulative inelastic deformation (CID) is also used in BRB qualification tests to assess cyclic deformation capacity. These factors are particularly important under long-duration subduction zone earthquakes and sequential seismic events.

Third, global instability may occur despite effective restraint of the yielding core. Inadequate stiffness or stability of gusset plates and unbraced transition regions can lead to out-of-plane buckling under high compressive loads. Unlike local core or casing failure, this system-level instability may cause a sudden loss of lateral resistance and compromise the seismic performance of the retrofitted reinforced concrete (RC) frame.

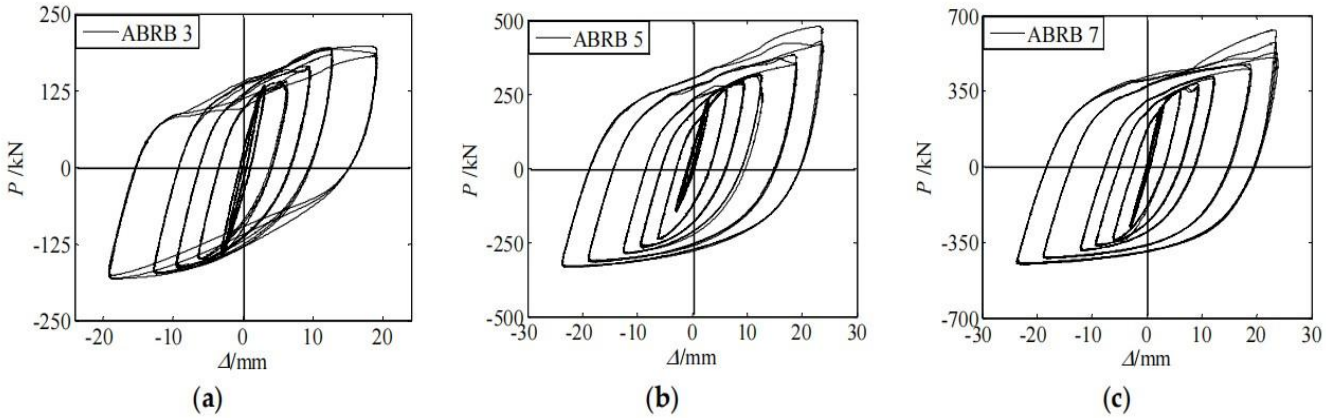


Figure 2- Load–displacement hysteresis curves of BRBs: (a) specimen ABRB 3; (b) specimen ABRB 5; (c) specimen ABRB 7[14].

2.4 Emerging BRB technologies

To reduce the large residual drifts commonly found in conventional metallic yielding systems, researchers have increasingly focused on developing self-centering buckling-restrained braces (SC-BRBs) and dual-stage energy dissipation devices over the past decade[15]. These systems combine traditional low-yield steel cores with shape memory alloy (SMA) rods or pre-tensioned basalt fiber-reinforced polymer (BFRP) tendons to achieve flag-shaped hysteretic behavior. In these configurations, the steel core dissipates seismic energy through plastic yielding, while the SMA rods or post-tensioned tendons provide a restoring force that helps the structure return toward its original position after an earthquake. This self-centering mechanism can significantly reduce permanent structural deformations and lower the repair costs associated with residual drifts, making it a useful approach for improving the seismic resilience of existing RC structures[16].

In addition, multi-stage capacity-adjustable buckling-restrained braces (MAS-CABRBs) have been developed for structures such as bridge bents and high-rise frames[17]. These devices use sacrificial steel plates arranged in parallel with the main yielding core to control their behavior under different levels of seismic loading. During low to moderate earthquakes, the sacrificial plates and the main core work together to provide sufficient initial stiffness and strength, helping to limit structural deformation and non-structural damage. However, under very large deformations, the sacrificial plates are designed to fracture in stages. This controlled fracture reduces the stiffness and strength of the brace at higher deformation levels, which helps limit the forces transferred to the surrounding RC frame. As a result, the system can reduce the risk of excessive force demands on existing structural members and foundations, providing an alternative approach to seismic retrofitting where controlling both displacement and force demands is important[18].

Table 1-Summary of emerging BRB technologies and their hysteretic properties.

BRB Technology	Configuration / Mechanism	Hysteretic Characteristics	Main Advantages	Limitations / Design Considerations
Double-Stage Yield BRB (DYB)	Two conventional BRBs with different yield strengths and cross-sections connected in series; a slotted-hole mechanism controls sequential activation.	Stable and repeatable double-stage hysteresis with good ductility and sequential yielding.	Graded energy dissipation; controllable deformation under different seismic intensities.	Relatively complex force-transfer mechanism; overall brace length may increase.
Steel Slit Damper–Double-Stage Yield BRB (SSD-DYB)	Steel slit damper acts as the first-stage dissipater and is connected in series with a double-stage BRB.	Fuller hysteretic loops and enhanced energy dissipation at small deformation levels.	Effective under minor earthquakes; lightweight and replaceable energy-dissipating component.	Requires accurate deformation coordination between the slit damper and BRB units.
Repairable Double-Stage Yield BRB (RDYB)	Short and long core plates of different widths are arranged in series with a displacement-limiting device; fully bolted construction.	Stable double-stage hysteretic response; hysteretic performance remains nearly unchanged after core replacement.	Replaceable cores; improved post-earthquake repairability and reduced maintenance effort.	Limited self-centering ability; residual deformation may remain after strong earthquakes.
Multi-Stage BRB with LYP–HYP Cores	Two low-yield-point (LYP) cores and one high-yield-point (HYP) core are arranged in parallel with different yield lengths.	Trilinear hysteretic response with sequential core activation and adjustable post-yield stiffness.	Improved staged energy dissipation; reduced residual drift; tunable yielding sequence.	Performance is sensitive to core strength and yielding-length ratios.
Parallel Double-Stage Yield BRB (PDY-BRB)	Multiple energy-dissipating cores with different strengths are arranged in parallel.	Fuller hysteretic loops, high initial stiffness, and favorable cyclic response.	More uniform force distribution; reduced stress concentration; improved low-cycle fatigue performance.	Requires careful selection of core strength ratios and yielding lengths.

BRB Technology	Configuration / Mechanism	Hysteretic Characteristics	Main Advantages	Limitations / Design Considerations
Synchronized Double-Stage Yield BRB (SDY-BRB)	Central LYP steel core combined with two parallel high-strength steel (HSS) tubes and an external restraining tube.	Plump and symmetric hysteretic loops with stable post-yield stiffness and partial self-centering behavior.	High bearing capacity; reduced residual drift; all-steel, mortar-free construction.	Proper synchronization and material proportioning between LYP and HSS components are required.
Parallel Double-Stage Yielding BRB (PDYBRB)	First-stage and second-stage cores are arranged in parallel; slotted holes and load-transfer bolts control asynchronous activation.	Stable and full hysteretic loops with a clear four-segment skeleton curve and negligible strength/stiffness degradation.	Clear staged yielding; stable energy dissipation; effective buckling restraint.	Relatively complex load-transfer and restraining system; precise detailing is required.

3. Experimental and Numerical Research on BRBs

3.1 Experimental investigations and major findings

The experimental qualification of buckling-restrained braces (BRBs) follows ANSI/AISC 341-22 seismic provisions, which require cyclic testing to verify stable hysteretic behavior, strength, and energy dissipation capacity. Full-scale brace specimens are subjected to increasing axial deformation cycles and must achieve a minimum cumulative inelastic deformation (CID) of 200 times the yield deformation without unacceptable strength degradation.

Two important parameters obtained from cyclic tests are the strain-hardening adjustment factor (ω) and compression strength adjustment factor (β)[7]. The factor ω represents the increase in tensile strength after yielding, while β describes the compression-to-tension strength ratio, calculated as $\beta = C_{max}/T_{max}$ at the specified deformation level. ANSI/AISC 341-22 limits this ratio to 1.5 during qualification cycles. Excessive friction between the steel core and restraining casing can increase β, particularly when high-mode buckling causes core–casing contact. Experimental studies have reported β values of approximately 1.14–1.36, while suitable air gaps and low-friction materials, such as polytetrafluoroethylene (PTFE), can reduce β below 1.25. Some BRB specimens have also achieved CID values of 800–1000 or higher before low-cycle fatigue failure. These findings highlight the importance of core design, unbonding materials, and casing restraint in improving cyclic performance and fatigue resistance.

3.2 Numerical modeling and simulation approaches

Accurate numerical modeling of BRB-retrofitted reinforced concrete (RC) structures requires material models that capture cyclic behavior, including the Bauschinger effect, strain hardening, and fatigue degradation. In OpenSees, BRB steel cores are commonly modeled using corotational truss or force-based beam-column elements with suitable uniaxial material models[10]. Steel02, based on the Giuffré-

Menegotto-Pinto formulation, and Steel4 can simulate cyclic steel behavior with isotropic and kinematic hardening, helping predict stress evolution and energy dissipation under repeated loading.

Fatigue prediction can be incorporated using OpenSees Fatigue Material, which tracks strain reversals through a modified rainflow cycle counting method. Damage accumulation is evaluated using Miner's Rule and a Coffin-Manson-based fatigue relationship. When the cumulative damage index reaches 1.0, the model simulates fatigue failure by reducing the material's load-carrying capacity. For detailed analysis of core–casing interaction, Abaqus models with nonlinear contact formulations can capture friction, contact pressure, and localized casing bulging associated with high-mode buckling[10]. While these detailed models help investigate local failure mechanisms, simplified OpenSees models are more practical for evaluating the global seismic response of BRB-retrofitted RC frames.

3.3 Experimental–numerical correlation and limitations

Although modern numerical models can accurately predict the uniaxial behavior of individual BRBs, often with only 2–5% differences in peak axial loads, larger discrepancies may occur when considering BRB–RC frame interactions[9]. These differences partly arise because simplified models underestimate frame action at corner gusset plate connections.

During earthquakes, beam-column joint deformations cause in-plane and out-of-plane (OOP) rotations, increasing demands on gusset plates. Idealized pinned connections may overlook localized plastic deformation, weld fracture, and secondary P-Delta moments transferred to the BRB transition region[8]. Accurate modeling therefore requires consideration of gusset plate rotational stiffness and interaction with surrounding RC members. The local stiffening effect of gusset plates may also shift RC beam plastic hinges away from the column face.

Including these effects can improve predictions of the seismic response of BRB-retrofitted RC frames.

3.4 Key parameters affecting BRB performance

Parametric studies using finite element analysis and experimental testing have identified key geometric and mechanical factors affecting buckling-restrained brace (BRB) performance and durability[19]. One important parameter is the core yield length ratio, defined as the yielding core length divided by the total work-point-to-work-point brace length. A smaller ratio increases elastic lateral stiffness but also raises plastic strain demands for a given story drift, increasing the risk of ultra-low-cycle fatigue and fracture. Conventional full-bay BRBs typically have ratios of 0.5–0.7, while specially designed braces using highly ductile core materials have been tested with ratios as low as 0.3.

Another critical parameter is the initial gap clearance between the steel core and restraining casing. Insufficient clearance restricts lateral expansion due to the Poisson effect, increasing core–casing friction, compression strength adjustment factor (β), and the risk of casing failure. Excessive clearance, however, may allow greater high-mode buckling, causing localized bending strains, premature core damage, and unstable cyclic behavior. Therefore, appropriate gap clearance is essential for maintaining stable hysteretic behavior and improving BRB durability.

4. BRB-Based Seismic Retrofitting of RC Structures

4.1 Applications and structural response

Buckling-restrained braces (BRBs) are widely used to improve the seismic performance of deficient reinforced concrete (RC) frames. Traditionally, BRBs are installed within existing frame bays in diagonal, chevron (V), or inverted-V configurations[20]. However, internal installation may disrupt building operations, reduce usable space, and require modifications to RC beam-column joints for gusset plate anchorage.

Externally attached sub-structures offer an alternative approach[21]. One example is the precast bolt-connected steel-plate reinforced concrete buckling-restrained-brace-frame (PBSPC BRBF), whose boundary columns, collector beams, and

BRBs are prefabricated off-site and assembled along the building exterior[22]. This dry-assembly method reduces on-site concrete work and construction time. However, its effectiveness depends on reliable interfacial shear transfer between the existing RC frame and external sub-structure. Post-installed chemical anchors, high-strength epoxy grout, and shear keys can provide this connection, transferring seismic forces while limiting interfacial slip[20].

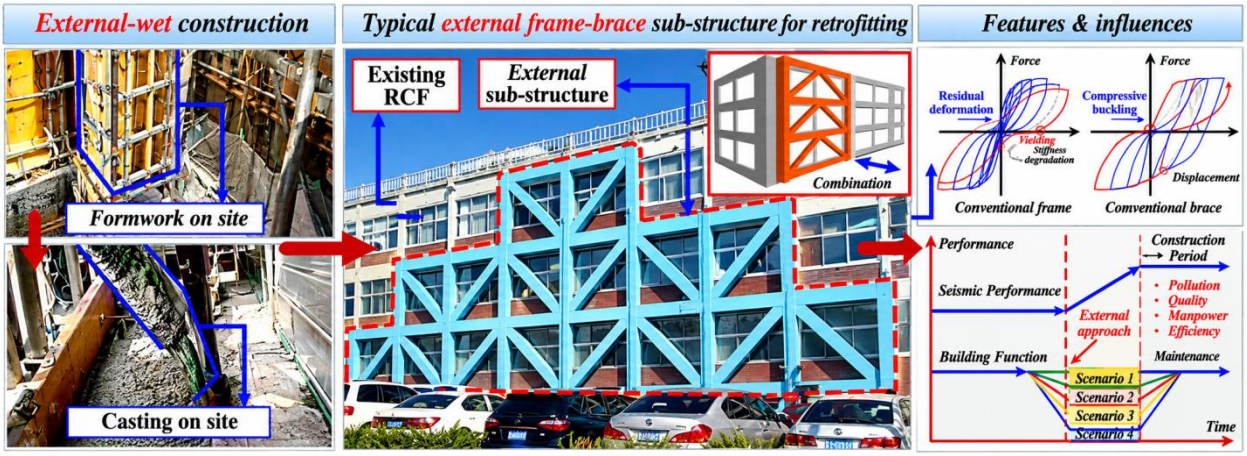


Figure 3-. Typical external retrofitting sub-structure[23].

Installing buckling-restrained braces (BRBs) internally or externally in existing reinforced concrete (RC) frames changes their seismic response by shifting part of the lateral load resistance from bending-dominated frame action toward truss action. BRBs carry a portion of the seismic forces and dissipate energy through ductile yielding, reducing force and deformation demands on vulnerable RC beams and columns. This helps limit flexure-shear damage and improves the overall seismic performance of retrofitted structures.

4.2 Seismic performance: strength, stiffness, ductility, and energy dissipation

Installing buckling-restrained braces (BRBs) in existing reinforced concrete (RC) frames improves seismic performance by increasing initial lateral stiffness, reducing the fundamental vibration period, and controlling inter-story drift during low-intensity earthquakes[24]. This also helps protect displacement-sensitive non-structural components. Under stronger earthquakes, including design basis earthquakes (DBE) and maximum considered earthquakes (MCE), BRBs dissipate seismic energy through stable hysteretic yielding.

Experimental cyclic tests on retrofitted RC frame sub-assemblages have reported increases in ultimate lateral bearing capacity of approximately 250–400% compared with unretrofitted frames, along with improved equivalent viscous damping[7]. By dissipating seismic energy, BRBs reduce force and deformation demands on vulnerable RC columns and beam-column joints, limiting nonlinear damage and helping preserve gravity load-bearing capacity. This can reduce the risk of soft-story failure and improve the overall seismic stability of existing RC buildings.

Table 2-Comparison of Performance Metrics (Stiffness, Ductility, Energy Dissipation) for Bare RC Frames vs. BRB-Retrofitted RC Frames.

Specimen	Retrofit Configuration	Maximum Stiffness, \(K_n\) (kN/mm)	Ductility / Deformation Behavior	Maximum Cumulative Energy Dissipation, \(E_c\) (kN·mm)	Maximum Equivalent Viscous Damping, \(\varphi\) (%)	Maximum Residual Displacement, \(D_r\) (mm)	Overall Performance
RCF	Bare RC frame; no external retrofit	**11.87**	Highest deformation capacity among the four specimens, but extensive cracking, concrete crushing and reinforcement exposure occurred at large drift	**43,275**	**10.81**	**20.50**	Low lateral stiffness and energy dissipation; severe damage and relatively large residual deformation
RCF-ED	RC frame retrofitted with external SC-PBSPC BRBF sub-structure and AB-BRBs; no prestressed tendons	**32.68**	Ductility reduced to some extent compared with the bare frame because of the much stiffer external sub-structure	**99,658**	**11.57**	**15.10**	Major increase in stiffness, strength and energy dissipation; damage transferred from the existing RC frame to the external sub-structure

RCF-SCED1	BRB-retrofitted RC frame with **one bundle of prestressed tendons**	**35.96**	Reduced deformation demand with flag-shaped hysteretic response; improved self-centering behavior	**176,159**	**12.18**	**5.86**	Very high energy dissipation and improved stiffness; substantially reduced residual deformation
RCF-SCED2	BRB-retrofitted RC frame with **two bundles of prestressed tendons**	**38.95**	Greater self-centering and smaller residual deformation; overall ductility lower than bare RCF, but deformation recovery significantly improved	**148,092**	**13.88**	**4.36**	Highest stiffness and damping coefficient; excellent residual-drift control and strong seismic resilience

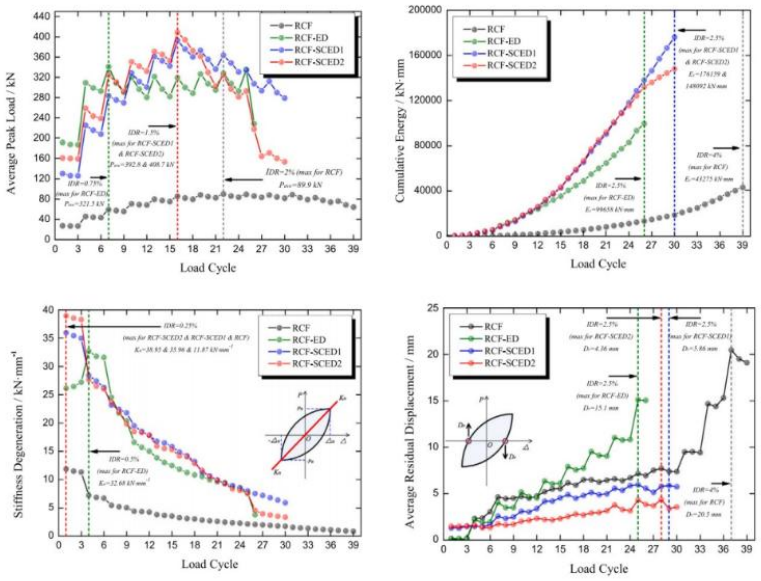


Figure 4-Hysteresis indicators to assess the seismic response tendency in experiments[22].

4.3 Design approaches and key design parameters

The design of buckling-restrained brace (BRB) retrofitting systems increasingly uses performance-based design (PBD) and direct displacement-based design (DDBD) rather than relying solely on conventional elastic force-based methods[8], [25]. In DDBD, a retrofitted multi-degree-of-freedom building is represented by an equivalent single-degree-of-freedom (SDOF) system. The effective period and damping ratio are determined iteratively to meet target displacement limits corresponding to performance levels such as immediate occupancy (IO) and life safety (LS).Loss-based displacement demand transition design also considers existing RC structural damage and potential economic losses[26] To evaluate buckling-restrained brace (BRB) retrofitting under uncertainty, researchers use Probabilistic Seismic Capacity Assessment (PSCA) and Incremental Dynamic Analysis (IDA)[27]. Acceptable expected annual losses (EAL) are used to establish target inter-story drift and displacement limits, which guide the required BRB axial yield forces at different stories[28]. Another important parameter is the lateral stiffness ratio between the BRB system and existing RC frame. Numerical studies suggest that ratios of 1.5–3.0 may provide a suitable balance for low-rise buildings by reducing drift without excessive base shear demands.

However, the optimal ratio depends on structural configuration, material propert- ies, and seismic design requirements. These approaches can improve seismic safety while helping limit repair costs and post-earthquake economic losses.

4.4 Fragility, resilience, reparability, and comparative assessment

To evaluate buckling-restrained brace (BRB) retrofitting under uncertainty, researchers use Probabilistic Seismic Capacity Assessment (PSCA) and Incremental Dynamic Analysis (IDA)[29]. Advanced OpenSees models are often combined with Monte Carlo simulation or Latin Hypercube Sampling (LHS) to account for uncertainties in material properties and structural parameters. These models are analyzed using scaled ground motion records to assess seismic performance at different intensity levels.

The results are used to develop seismic fragility curves that estimate the probability of exceeding damage states, including slight, moderate, extensive, and collapse, at different seismic intensities, commonly measured by peak ground acceleration (PGA) or spectral acceleration (Sa)[22], [30]. Comparing original and retrofitted RC frames helps quantify BRB effectiveness in reducing damage and collapse risk. Studies on older RC frames in near-fault regions have reported increases exceeding 120% in median collapse capacity after BRB retrofitting[24]. However, the improvement depends on structural characteristics, brace design, and ground motion conditions.

BRBs can also improve post-earthquake recovery by concentrating inelastic deformation in the braces and reducing damage to primary RC members. Damaged BRBs can often be replaced when surrounding members and connections remain structurally sound, avoiding extensive repairs to concrete components. This may reduce repair costs, building downtime, and business interruption, improving the overall seismic resilience of existing RC structures[31].

5. Critical Discussion, Research Gaps, and Conclusions

5.1 Critical comparison of existing BRB systems and retrofit strategies

The reviewed studies show that different buckling-restrained brace (BRB) systems offer distinct advantages depending on structural conditions, seismic performance requirements, and practical installation constraints. Conventional mortar-filled BRBs provide stable hysteretic behavior and reliable energy dissipation, but their relatively heavy restraining components and limited self-centering capability may increase installation difficulties and post-earthquake residual deformation[7]. In comparison, all-steel assembled BRBs (AB-BRBs) offer simpler fabrication, easier inspection, and improved replaceability because their restraining components can be disassembled[32]. However, their performance depends on appropriate core–casing clearance and connection detailing.

Self-centering buckling-restrained braces (SC-BRBs) provide an additional advantage by combining energy dissipation with restoring forces, which can reduce residual deformation and improve post-earthquake recovery[23], [33]. Nevertheless, these systems often require more complex mechanical arrangements and higher initial costs. Regarding installation strategies, internal BRB retrofitting provides a direct lateral load-resisting system but may interrupt building use and require strengthening of existing beam-column joints[20]. Externally attached BRB sub-structures can reduce these construction-related difficulties by allowing much of the retrofit system to be installed outside the building[34]. However, their effectiveness depends on reliable connections and force transfer between the existing RC structure and the external system[35].

Overall, no single BRB configuration is suitable for every retrofitting project. The selection should consider not only lateral strength, stiffness, and energy dissipation, but also residual drift, construction feasibility, connection performance, repairability, and lifecycle costs.

5.2 Major limitations and research gaps

Despite significant advances in buckling-restrained brace (BRB) technology, several technical challenges remain unresolved. One important issue is the stability of gusset plates and brace connections under large cyclic deformations[8]. Although the steel yielding core is restrained against buckling, inadequate connection stiffness and out-of-plane deformation may cause premature instability and reduce the effectiveness of the retrofitting system. In existing reinforced concrete (RC) frames, the interaction between BRB connections and beam-column joints also requires further investigation, particularly when the original structure has inadequate reinforcement detailing[6].

Another limitation concerns the fatigue performance of BRBs under repeated and long-duration earthquake loading. Large plastic strain demands may lead to low-cycle fatigue and premature fracture of the steel core, especially when the yielding length, unbonding gap, and core–casing interaction are not properly designed. Although numerical models can predict the overall hysteretic response of BRBs, accurately capturing localized buckling, friction, cumulative damage, and connection deterioration remains challenging[10], [26].

For externally attached BRB sub-structures, reliable interfacial shear transfer between the existing RC frame and external retrofitting system is another important research gap. Insufficient connection stiffness, anchor damage, and interface slip may reduce the expected seismic performance[35]. Furthermore, many existing studies rely mainly on numerical simulations or simplified experimental specimens, while full-scale three-dimensional tests considering bidirectional earthquake loading, torsional effects, and realistic construction conditions remain limited[36]. These challenges highlight the need for improved connection design, experimental validation, and more reliable numerical models for practical BRB retrofitting applications.

5.3 Future research directions

Future research on buckling-restrained braces (BRBs) should focus on structural resilience, component stability, and environmental sustainability. Physics-informed machine learning and AI-based surrogate models could reduce the computational cost of nonlinear dynamic analysis and support multi-objective retrofit optimization considering lifecycle costs. Environmental studies should also examine the embodied carbon of steel BRBs and alternative materials, such as mass timber and glued-laminated bamboo (glubam), using Life Cycle Assessment (LCA). Furthermore, large-scale three-dimensional (3D) shake-table tests under bidirectional ground motions are needed to evaluate torsional effects and BRB–RC frame interactions in externally retrofitted structures[36]. These studies could help validate numerical models and improve seismic design guidelines.

5.4 Conclusions

Buckling-restrained braces (BRBs) have become an effective and reliable method for improving the seismic performance of existing reinforced concrete (RC) structures, especially buildings constructed before modern seismic design codes were introduced. BRBs act as ductile structural fuses that can dissipate

a large amount of seismic energy without buckling under compression. By absorbing seismic energy through stable plastic deformation, they help reduce the force and deformation demands on vulnerable RC columns and beams. This can limit severe shear and flexural damage and reduce the risk of soft-story collapse during strong earthquakes. Over the years, BRB technology has developed from conventional designs to newer systems, including all-steel assembled BRBs, self-centering mechanisms, and externally attached precast sub-structures. These developments provide structural engineers with different retrofitting options depending on the structural conditions, construction requirements, available space, and project costs.

Advances in numerical modeling, including distributed plasticity models, probabilistic seismic assessment methods, and loss-based displacement design approaches, have also improved the understanding and practical application of BRBs in existing RC structures. These methods allow researchers and engineers to evaluate structural behavior more accurately and develop suitable retrofitting designs. However, several challenges still need further investigation, including out-of-plane gusset plate instability, ultra-low-cycle fatigue under long-duration subduction earthquakes, nonlinear soil-structure interaction, and the effects of material aging. More experimental studies and numerical analyses are needed to better understand these issues and improve the long-term performance of BRB systems. Addressing these research gaps will help improve the reliability, safety, and cost-effectiveness of BRB retrofitting and support the development of more sustainable and earthquake-resilient RC structures.

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