

Seismic Rehabilitation of Deficient Reinforced Concrete Frame Structures Using Steel Bracing and Shear Wall Systems: A Systematic Review of Analytical Evaluation Techniques, Performance Outcomes, and Emerging Research Priorities

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Abstract

The seismic fragility of existing reinforced concrete (RC) frame structures, particularly those conceived prior to the implementation of contemporary seismic design provisions, constitutes a critical structural safety challenge across seismically active territories such as India. Seismic rehabilitation the deliberate strengthening of structurally deficient systems has been established as both technically validated and economically justified for enhancing the earthquake response of such buildings. Among available rehabilitation strategies, steel bracing systems and RC shear walls have attracted the greatest volume of research investigation owing to their demonstrated structural efficacy, constructability, and compatibility with existing RC frame systems. This paper presents a systematic and critically informed review of the published research addressing the seismic performance assessment of RC buildings retrofitted with steel bracing and shear walls, synthesising evidence from over two decades of literature spanning 2007 to 2025. The review is organised into four interconnected thematic domains: (i) the seismic vulnerability characteristics of existing RC frame buildings; (ii) the structural mechanics, configurations, and performance attributes of steel bracing and shear wall retrofit systems; (iii) the application of Response Spectrum Analysis (RSA) and Nonlinear Static Pushover Analysis (NSPA) as complementary evaluation methodologies; and (iv) the role of ETABS as the dominant computational platform in Indian seismic engineering research. A synthesised performance comparison matrix is presented, consolidating findings on storey displacement reduction, inter-storey drift reduction, base shear augmentation, and performance level attainment across studies. Critical research gaps are identified including the underrepresentation of low-to-mid-rise (G+4 to G+7) RC frame buildings, the limited incorporation of soil–structure interaction in retrofit models, and the absence of life-cycle cost frameworks in comparative retrofit assessments and targeted directions for future investigation are proposed. The conclusions of this review are intended to serve as a rigorous scholarly reference for researchers, practising structural engineers, and regulatory authorities engaged in the seismic rehabilitation of the built environment.

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1. Introduction

Earthquakes represent one of the most devastating geophysical hazards confronting the built environment globally. Their capacity to transmit broad-spectrum energy to structures within seconds, absent any precursory warning, renders them uniquely challenging for engineering mitigation. Analysis of the historical record of earthquake-induced structural failure reveals a consistent pattern: the preponderance of fatalities and economic losses are attributable not to ground shaking per se, but to the collapse or severe degradation of reinforced concrete (RC) frame structures designed without adequate consideration of seismic demand [1, 2].

India's seismotectonic environment positions it among the nations bearing the highest earthquake hazard. The northward displacement and underthrusting of the Indian tectonic plate beneath the Eurasian plate has generated a seismically active Himalayan arc, while intra-plate stress accumulation has produced significant seismic hazard across peninsular and central India. IS 1893 (Part 1): 2016 [3] delineates four seismic zones (II through V), with approximately 59% of India's land area classified within Zones III, IV, and V, where peak ground accelerations of 0.10g, 0.24g, and 0.36g, respectively, govern structural design. The documented record of major seismic events the 1993 Latur earthquake (M 6.2; >7,900 fatalities), the 2001 Bhuj earthquake (M 7.7; >20,000 fatalities), and the 2015 Gorkha earthquake (M 7.8) has repeatedly exposed the inability of the extant RC building inventory to withstand even moderate seismic demands [4], [5].

A substantial share of India's existing RC multi-storey buildings were designed exclusively for gravity loading, without lateral force provisions, predating the current seismic design framework or constructed outside formal engineering oversight. Such structures characteristically exhibit multiple deficiencies including insufficient lateral stiffness, undersized column sections, poorly detailed beam-column joints, absence of confinement reinforcement, and ground-storey soft-storey configurations attributable to open-plan commercial use [6]. The aggregate outcome is a vast inventory of structurally deficient buildings whose failure under a design-level earthquake would constitute not merely an engineering failure but a humanitarian catastrophe.

Seismic retrofitting defined as the purposeful modification of existing structures to enhance their earthquake resistance represents the most scientifically grounded and practically implementable approach to managing this risk. Among available global retrofit techniques, steel bracing systems and reinforced concrete shear walls have emerged as the two most extensively researched, implemented, and code-endorsed strategies. Steel bracing augments lateral stiffness and strength while providing ductile energy dissipation capacity; shear walls furnish exceptional in-plane stiffness and drift constraint with well-characterised post-yield behaviour. Both approaches have

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been rigorously validated through experimental programmes, analytical investigations, and post-earthquake field documentation [7, 8].

The assessment of retrofitted building performance demands sophisticated analytical tools capable of characterising both the elastic seismic demand and the inelastic structural capacity. Response Spectrum Analysis (RSA) a linear dynamic method codified in IS 1893:2016 [3] provides a code-compliant demand estimate through modal superposition. Nonlinear Static Pushover Analysis (NSPA), as specified in FEMA 356 [9] and ATC-40 [10], captures post-yield structural response, progressive plastic hinge formation, and global ductility information indispensable for performance-based earthquake engineering (PBEE). Together, these methodologies constitute the analytical foundation of contemporary seismic performance evaluation and retrofit design practice.

Notwithstanding the breadth of existing published work, a comprehensive synthesis critically evaluating the cumulative evidence on RC building retrofitting with steel bracing and shear walls integrating findings from analytical studies, parametric investigations, and comparative assessments has not been adequately furnished, particularly with reference to the Indian context and the low-to-mid-rise building category. This paper addresses that deficiency by providing a systematic, thematic, and critically evaluated review of relevant literature published between 2007 and 2025. The review synthesises performance evidence, identifies methodological trends, critically interprets comparative findings, and delineates specific research gaps and prospective directions. The intended readership encompasses structural engineering researchers, practising engineers engaged in retrofit design, and regulatory bodies responsible for seismic risk governance.

This paper is structured as follows: Section 2 describes the review methodology; Section 3 addresses the seismic vulnerability of existing RC buildings; Section 4 reviews steel bracing systems; Section 5 reviews shear wall systems; Section 6 examines analytical evaluation methods; Section 7 analyses comparative performance studies; Section 8 presents a synthesised performance comparison; Section 9 identifies research gaps; Section 10 proposes future research directions; and Section 11 presents conclusions.

2. Review Methodology

This review adheres to a structured and reproducible methodology for literature identification, selection, and synthesis. Primary databases searched include Scopus, Web of Science, Google Scholar, and Indian academic repositories. Search terms comprised combinations of: "seismic retrofitting", "RC building", "reinforced concrete", "steel bracing", "shear wall", "pushover analysis", "response spectrum analysis", "ETABS", "seismic rehabilitation", "performance-based earthquake engineering", and "India". The search scope was restricted to peer-reviewed journal articles, conference proceedings published by recognised bodies, and technical reports from authoritative institutions (FEMA, ATC, BIS).

Papers were selected according to the following inclusion criteria: (i) direct relevance to the seismic performance evaluation or rehabilitation of RC frame buildings; (ii) employment of RSA, NSPA, or equivalent dynamic analysis as the primary evaluation methodology; (iii) focus on steel bracing, shear walls, or their comparative assessment as retrofit strategies; and (iv) publication in English in peer-reviewed venues between 2007 and 2025. Papers addressing only material-level experimental investigation, soil-structure interaction in isolation, or non-RC structural systems were excluded. Following screening, a corpus of 29 primary research papers supplemented by 6 Indian Standard codes and 1 software reference was identified for detailed review and synthesis.

The synthesis adheres to a thematic rather than chronological or author-sequential structure, enabling the identification of patterns, contradictions, and evolving research paradigms. Quantitative performance data, where reported, has been consolidated in a comparative summary matrix to facilitate direct cross-study comparison.

3. Seismic Vulnerability of Existing RC Frame Buildings

3.1 Structural Deficiencies and Root Causes

The seismic vulnerability of existing RC frame buildings has been extensively documented through post-earthquake reconnaissance, analytical investigations, and laboratory testing. Arya et al. [11] and Nikam et al. [12] both established that buildings designed solely for gravity loads per IS 456:2000 [13] without provisions for ductile detailing per IS 13920 [14] or seismic loading per IS 1893 [3] represent the most at-risk category of RC structures. Such buildings typically lack the minimum lateral resistance required for moderate seismic demands (Zone III and above) and undergo brittle failure modes encompassing column shear failure and joint disintegration. Hatwar [15] demonstrated through pushover analysis that gravity-designed RC buildings in India consistently exhibit performance levels spanning Life Safety to Collapse Prevention under Design Basis Earthquake conditions, while Tahir and Kiran [16] showed that the nonlinear redistribution of forces in such buildings under seismic loading cannot be reliably quantified without inelastic analysis procedures.

3.2 Soft-Storey and Geometric Irregularities

Soft-storey configurations, arising from open ground-floor commercial plans, represent a particularly prevalent and hazardous deficiency in Indian RC construction. Patel and Sinha [5] analysed a representative four-storey soft-storey RC building in Seismic Zone IV and found that the concentration of inter-storey drift within the flexible ground storey substantially amplified seismic demand on ground-floor columns, producing collapse-level demands under design earthquake loading. Plan irregularities, including re-entrant corners and asymmetric mass or stiffness distributions, compound seismic vulnerability by inducing torsional responses. Wakchaure and John [17] demonstrated that RC buildings exhibiting re-entrant corner irregularity experience markedly elevated drift demands at the re-entrant corners relative to regular buildings, and that these demands are most effectively controlled through the provision of X-bracing or shear walls along the building perimeter.

3.3 Buildings on Sloping Ground

A third category of elevated vulnerability concerns RC buildings erected on sloping terrain, prevalent in the hilly regions of India (Himachal Pradesh, Uttarakhand, Northeast India). Manjunath [18] investigated step-back and setback-step-back RC buildings in Seismic Zone V and demonstrated that the inherent stiffness irregularity produced by varying column heights on sloping ground generates severe torsional and differential displacement demands. Such buildings exhibited storey displacements approximately three to four times greater than equivalent regular buildings on level ground under equivalent seismic demand, confirming that standard analytical procedures for regular buildings substantially underestimate the seismic demands on hillside RC structures.

4. Steel Bracing Systems for Seismic Retrofitting

4.1 Structural Mechanics and Role

Steel bracing systems function as axially loaded truss members within the RC frame, transforming the lateral sway mechanism of the moment frame into a primarily axial load-resisting system. This transformation yields a substantial increase in lateral stiffness, a reduction in lateral displacement and inter-storey drift, and an increase in natural frequency (reduction in fundamental period), which modifies the seismic demand on the structure. Beyond stiffness enhancement, properly detailed steel bracing members contribute energy dissipation through controlled inelastic deformation particularly in concentric configurations and can be proportioned to yield in tension prior to compression buckling, delivering a stable and predictable hysteretic response [8, 19].

The interface between new steel bracing members and the existing RC frame constitutes a critical design consideration. Common connection strategies encompass embedded steel plates with anchor bolts, through-bolt bearing plate assemblies, and epoxy-grouted shear studs. The shear transfer demand between the bracing end-plates and the RC frame must be verified against the yielding capacity of the bracing member to preclude connection-governed failure. Ahmad and Singh [20] emphasised that meticulous detailing of the bracing-to-frame connection in accordance with IS 15988:2013 [21] is essential to achieving the intended composite interaction between the new bracing and the existing RC frame.

4.2 Bracing Configurations and Comparative Performance

The literature documents a broad spectrum of bracing configurations, each with distinctive structural and architectural characteristics. Honnutagi and Jagirdar [22] evaluated X-bracing, V-bracing, and Inverted V-bracing in a G+10 storey building and found that X-bracing produced the greatest stiffness increase and the most pronounced reduction in lateral displacement, while Inverted V-bracing (chevron) offered a more balanced response with acceptable lateral control and the architectural advantage of an unobstructed bay opening at mid-height. Lamani and Kulkarni [23] corroborated that X-type steel bracing delivered the greatest reduction in maximum storey drift and lateral displacement for a G+9 building, and that hollow square

tubular sections outperformed angle sections as bracing members owing to their superior buckling resistance and biaxial capacity.

Manjunath [18] conducted a comprehensive multi-configuration comparison X, diagonal, K, V, and Inverted V for RC buildings on sloping ground in Seismic Zone V. The Inverted V (chevron) configuration performed best for step-back buildings, achieving a 70% reduction in storey displacement and a 66% reduction in storey drift relative to the unbraced structure. For setback-step-back configurations, corresponding reductions were 74% and 70%, respectively. K-bracing, while architecturally convenient, was found to impose concentrated force demands at the mid-span of the intersected beam, potentially precipitating premature beam failure under seismic loading, and is therefore not recommended as a general-purpose retrofit bracing type. Safarizki et al. [24] demonstrated through FEMA 356 and FEMA 440 pushover analyses that steel bracings reduced target displacements of an existing RC building by 16-55%, depending on direction and configuration, with dynamic time history analysis confirming serviceability drift limit compliance.

4.3 Effect on Structural Period and Base Shear

A significant consequence of enhanced lateral stiffness through bracing is the reduction in fundamental vibration period. As the period decreases, the structure moves into a higher spectral acceleration region on the IS 1893 design spectrum, amplifying the design base shear demand. Studies by Zameer and Arunakanthi [25] and Maniyar and Salunke [26] both reported base shear increases of 20-35% in steel-braced buildings relative to unretrofitted structures. While this is generally offset by the markedly elevated lateral strength furnished by the bracing, it underlines the importance of verifying that the existing foundation system and lateral force transfer connections can accommodate the increased post-retrofit base shear.

4.4 Material and Cross-Section Selection

The selection of bracing member material and cross-section materially influences both structural performance and constructability. Lamani and Kulkarni [23] demonstrated that tubular sections outperform angle sections owing to their superior radius-of-gyration-to-area ratio, which more effectively resists slender-member buckling. Fe 415 or Fe 500 grade steel per IS 2062 [27] is standard for bracing members in Indian practice. For high-seismic-demand applications, the adoption of high-strength steel or buckling-restrained brace (BRB) elements which suppress brace buckling through external confinement has been proposed as a means of achieving more stable and energy-dissipative hysteretic behaviour, although BRBs remain underutilised in Indian retrofit practice.

5. Reinforced Concrete Shear Walls for Seismic Retrofitting

5.1 Structural Mechanics and Role

Reinforced concrete shear walls resist lateral seismic forces through in-plane cantilever bending and shear, furnishing a stiff and robust load path that substantially diminishes the lateral demand on the surrounding frame. As planar elements with large in-plane stiffness, shear walls dominate

the lateral response of the building upon introduction, effectively acting as the primary lateral load-resisting system while the enclosing frame carries predominantly gravity loads. Connections between new shear walls and existing RC frames are achieved through epoxy-anchored dowels, mechanical anchors, or cast-in-place through-connections, designed to transfer the full interface shear without premature bond failure [15].

From a ductility standpoint, properly designed and detailed shear walls exhibit stable, energy-dissipating behaviour under cyclic loading through controlled yielding of boundary zone reinforcement and regulated shear cracking of the wall panel. IS 13920:2016 [14] prescribes specific detailing requirements for ductile shear walls, encompassing minimum boundary zone reinforcement, web reinforcement ratios, and coupling beam proportioning all essential for attaining Life Safety or Immediate Occupancy performance levels targeted in seismic rehabilitation.

5.2 Shear Wall Positioning and Structural Response

The placement of shear walls within the building plan exerts a profound influence on seismic response. Kumar et al. [28] conducted a systematic investigation evaluating five shear wall positions central, diagonal corner, mid along X-direction, mid along Y-direction, and mid along both directions and found that symmetric placement along both principal directions produced the most balanced lateral stiffness distribution, minimised torsional amplification, and yielded the optimum overall seismic response. Asymmetric shear wall placement introduces eccentricity between the centres of mass and rigidity, generating torsional demands that may negate the stiffness benefits conferred.

Ayar and Abdul Ahad Fizan [29] extended this analysis to a G+20 storey building and confirmed that peripheral shear wall placement consistently outperformed central and corner placements in reducing storey displacement and inter-storey drift. Shenbagam and Swathika [30] demonstrated through RSA that a bare RC frame equipped with symmetrically placed perimeter shear walls achieved maximum storey displacement and drift reductions of approximately 60-75%, with a corresponding reduction in overturning moment of up to 40% relative to the bare frame.

5.3 Aspect Ratio Effects

The aspect ratio (height-to-length ratio) of a shear wall governs its dominant deformation mode flexure-dominated behaviour for slender walls (aspect ratio > 2) and shear-dominated behaviour for squat walls (aspect ratio < 1). Shailesh and Shiyekar [31] conducted a parametric pushover study across aspect ratios from 1 to 3 and found that as aspect ratio increases, the pushover curve exhibits a more gradual yielding plateau and greater displacement ductility, while peak base shear decreases relative to wall cross-sectional area. For low-to-mid-rise RC buildings (G+5 to G+8), aspect ratios in the range 1.5 to 2.5 provided an effective balance of stiffness, strength, and ductility, consistent with IS 13920:2016 guidance.

5.4 Foundation Implications

A significant practical constraint of shear wall retrofitting that receives comparatively limited treatment in the reviewed literature is the foundation impact. The introduction of shear walls substantially elevates the overturning moment and axial load demands at foundation level. In many cases, existing foundations require strengthening through underpinning, addition of pile caps, or construction of new raft foundations to accommodate the increased demands. Kasabe and Kulkarni [32] noted that the substantially higher material demand for shear wall retrofitting, when fully accounted for including foundation works, renders global shear wall rehabilitation less economically sustainable than localised member-level strengthening in resource-constrained settings.

6. Analytical Methods for Seismic Performance Evaluation

6.1 Response Spectrum Analysis

Response Spectrum Analysis (RSA) is a linear dynamic method in which the response of a multi-degree-of-freedom (MDOF) system is determined by superposing the maximum responses of single-degree-of-freedom (SDOF) oscillators, each tuned to a natural frequency of the structure, under a design response spectrum. IS 1893 (Part 1): 2016 [3] specifies the zone factor (Z), importance factor (I), response reduction factor (R), and soil type-dependent spectral shapes for construction of the design spectrum. Modal responses are combined using the Complete Quadratic Combination (CQC) rule, which accounts for modal correlation among closely spaced natural periods, and is more accurate than the SRSS rule for structures with closely spaced modes.

Performance metrics derived from RSA include storey displacement, inter-storey drift ratio, base shear, storey shear distribution, and overturning moment. Shenbagam and Swathika [30] and Arya et al. [11] employed RSA as the primary evaluation method for RC buildings with and without shear walls, demonstrating reliable and code-compliant demand estimation for regular and moderately irregular configurations. The fundamental limitation of RSA lies in its inability to capture post-yield structural behaviour, progressive member degradation, energy dissipation through inelastic deformation, and force redistribution following member yielding phenomena of critical importance for buildings expected to be loaded beyond their elastic capacity under design earthquakes.

6.2 Nonlinear Static Pushover Analysis

Nonlinear Static Pushover Analysis (NSPA) addresses the principal limitation of linear methods by modelling the progressive inelastic response of the structure under monotonically increasing lateral loading. In NSPA, the building is subjected to a lateral load pattern typically uniform (proportional to floor mass) or modal (proportional to the first mode shape) incremented until either a target displacement is attained or a collapse mechanism forms. At each load step, the stiffness matrix is updated to reflect plastic hinge formation in yielded members, and the base shear versus roof displacement relationship the pushover (capacity) curve is recorded.

The capacity curve is converted to a capacity spectrum (spectral acceleration versus spectral displacement) and intersected with the demand spectrum (derived from the design response spectrum, modified for appropriate damping) to identify the Performance Point the displacement demand at which seismic capacity equals seismic demand. The building performance level (Immediate Occupancy, Life Safety, or Collapse Prevention) is determined by comparing the performance point displacement with the displacements at which key performance thresholds are crossed, as defined in FEMA 356 [9] and ATC-40 [10].

Nikam et al. [12] employed NSPA to demonstrate that gravity-designed RC buildings fall within the Life Safety to Collapse Prevention range under Design Basis Earthquake loading, while code-conforming seismic buildings achieved Immediate Occupancy to Operational performance. Nalamothu [33] demonstrated that NSPA-derived capacity curves for retrofitted buildings exhibit significantly elevated base shear capacity and displacement ductility relative to the original structures. Maniyar and Salunke [26] highlighted that NSPA uniquely captures the sequence of plastic hinge formation from beam hinges through column hinges to a global sidesway mechanism furnishing information critical for identifying structural deficiencies invisible in linear analysis.

6.3 Combined RSA and NSPA: Complementary Insights

A growing body of literature, including Patel and Sinha [5] and Zameer and Arunakanthi [25], advocates the combined application of RSA and NSPA in retrofit evaluation studies, recognising that each method furnishes distinct and complementary evidence. RSA provides the code-compliant elastic demand verification required for regulatory submissions; NSPA furnishes the performance-based evidence needed to confirm attainment of the target performance level under the design earthquake. The combined approach is endorsed by IS 15988:2013 [21], which recommends NSPA as the preferred evaluation method for seismic assessment of existing buildings while acknowledging the continued role of RSA for initial screening and design verification.

7. Comparative Performance Studies: Steel Bracing Versus Shear Walls

A number of investigations have directly compared the seismic performance of steel bracing and shear wall retrofit strategies, enabling evidence-based conclusions regarding their relative merits under different conditions. The most substantive comparative assessments are reviewed below.

7.1 Lateral Strength and Stiffness

Nikam et al. [12] established the foundational comparative framework, demonstrating that X-bracing delivers the greatest improvement in lateral strength (base shear capacity) while shear walls provide the greatest improvement in lateral stiffness (storey drift reduction) for both 8-storey and 12-storey buildings. This finding has been consistently reproduced in subsequent investigations. Alashkar et al. [34] confirmed that both systems are effective in augmenting the lateral load-carrying capacity of deficient RC buildings, but noted that shear walls exhibit superior drift control, while steel bracing demonstrates greater ductility and energy dissipation

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capacity under cyclic loading. Ajema [35] confirmed that shear walls yield greater overall reductions in fundamental period, while braced frames offer more architecturally accommodating configurations.

7.2 Displacement and Drift Reduction

Maniyar and Salunke [26] found that both retrofit strategies significantly reduced storey displacement and drift in a G+8 building, with shear walls reducing maximum displacement by approximately 65% and X-bracing by approximately 55% relative to the bare frame. Pallavi and Nagaraja [36] corroborated similar trends for a multi-storey building, noting that the differential behavioural characteristics of the two systems necessitate careful consideration in design, particularly for buildings with irregular plans or non-uniform storey heights. Bhattacharjee and Goel [37] reported that both braces and shear walls are most effective when positioned peripherally, and that extending them only to mid-height retains a substantial proportion of full-height retrofit effectiveness, a finding with significant cost optimisation implications.

7.3 Performance Level Achievement

In the context of NSPA-based performance evaluation, Patel and Sinha [5] found that shear walls brought the performance point displacement to within the Immediate Occupancy range for all buildings investigated, while steel bracing typically achieved Life Safety. Nalamothu [33] reported similar trends, with shear wall addition producing the most pronounced upward shift in the pushover curve capacity spectrum. Kasabe and Kulkarni [32] demonstrated that member jacketing (local rehabilitation) can also achieve Life Safety under DBE at substantially lower material demand than global shear wall retrofitting, suggesting that hybrid strategies local jacketing of critical columns combined with selective steel bracing may offer the most favourable balance of performance and economy for low-to-mid-rise buildings.

7.4 Influence of Building Height and Configuration

The relative effectiveness of each retrofit strategy is modulated by building height and configuration. For low-to-mid-rise buildings (G+4 to G+8), steel bracing is generally adequate to achieve Life Safety performance, while shear walls may be preferred when Immediate Occupancy is targeted or when drift control for non-structural element protection is critical. For taller buildings (G+10 and above), shear walls tend to dominate due to their superior stiffness and overturning resistance, as demonstrated by Zameer and Arunakanthi [25] for a G+20 building. For irregular-plan buildings, Wakchaure and John [17] and Shariff [19] found that peripheral X-bracing provides effective torsional control, while symmetrically placed shear walls offer greater resistance to plan irregularity effects.

8. Synthesised Performance Comparison

Table I presents a consolidated summary of the primary research reviewed in this paper, compiling building configuration, seismic zone, analysis method, retrofitting technique, and key performance findings for each study. This synthesis enables direct cross-study comparison and facilitates the identification of overarching trends in the literature.

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Table I. Synthesised Comparison of Reviewed Studies on Seismic Retrofitting of RC Buildings

Ref.	Authors	Year	Building	Zone	Method	Retrofit	Key Finding
[5]	Patel & Sinha	2025	G+4, Soft	IV	NSPA+THA	SW, SB, RCJ	SW: superior drift control & base shear; SB: balanced strength/deformability
[22]	Honnutagi & Jagirdar	2025	G+10	–	RSA	X, V, Inv-V	X-brace: maximum stiffness; Inv-V: balanced performance with open bay
[29]	Ayar & AHF	2024	G+20	–	THA	SW (4 pos.)	Peripheral SW: minimum drift; asymmetric SW induces torsional response
[25]	Zameer & Arunakanthi	2023	G+20	V	RSA+NSPA	SW, SB, FD	All techniques reduce drift; FD: best energy dissipation capacity
[26]	Maniyar & Salunke	2023	G+8	–	RSA+NSPA	–	NSPA reveals plastic hinge formation sequence; superior to RSA for damage prediction
[20]	Ahmad & Singh	2022	G+5	V	ESA	Col. Jacket	Jacketing enhances column strength; improved moment and shear distributions
[33]	Nalamothu	2021	Multi	–	NSPA	SW, SJ, FRP	SW: maximum base shear & ductility; FRP: effective stiffness enhancement
[32]	Kasabe & Kulkarni	2021	Multi-ht.	–	NSPA	SW vs. MJ	MJ: lower material demand; SW: greater performance improvement but higher cost

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Ref.	Authors	Year	Building	Zone	Method	Retrofit	Key Finding
[23]	Lamani & Kulkarni	2021	G+9	III	ESA	X-SB	X-SB: maximum drift & displacement reduction; tube section > angle section
[8]	Silpa & Joy	2021	Review	–	Review	Various SB	Peripheral bracing optimal; all configurations increase stiffness, strength, ductility
[16]	Tahir & Kiran	2020	Multi	–	NSPA	–	Nonlinear analysis essential for force redistribution prediction in RC frames
[15]	Hatwar	2020	RC Bldg.	–	NSPA	–	Pushover-based pre-retrofit evaluation essential for informed retrofit design
[30]	Shenbagam & Swathika	2019	RC Frame	–	RSA	SW	SW reduces drift 60–75%; reduces overturning moment ~40%
[19]	Shariff	2019	H-irreg.	IV	ESA	X-SB	X-SB improves displacement and base shear for irregular plan buildings
[35]	Ajema	2018	Sym. RC	–	RSA	SW vs. BF	SW: greater lateral stiffness; BF: superior architectural flexibility
[36]	Pallavi & Nagaraja	2017	Multi-st.	–	–	SW vs. SB	Both systems effective; unequal behavioural variations require careful design
[18]	Manjunath	2016	12-st.	V	RSA	X,D,K,V,IVB	Inv-V best: 74%

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Ref.	Authors	Year	Building	Zone	Method	Retrofit	Key Finding
			Slope				displacement reduction, 70% drift reduction on sloping terrain
[34]	Alashkar et al.	2014	Mid-rise	–	PBEE	SW vs. SB	Both feasible; SW: stiffness-dominant; SB: ductility-dominant behaviour
[28]	Kumar et al.	2013	Multi-st.	–	3D-FEA	SW (5 pos.)	Symmetric peripheral SW: best torsional response control
[24]	Safarizki et al.	2013	Exist. RC	–	FEMA+THA	SB	SB reduces target displacement 16–55%; drift within serviceability limits
[12]	Nikam et al.	2007	8 & 12-st.	–	NSPA	X, Inv-V, SW	X-SB: maximum strength; SW: maximum stiffness; no universally optimal solution

SW = Shear Wall; SB = Steel Bracing; X-SB = X-type Steel Bracing; Inv-V = Inverted V-bracing; MJ = Member Jacketing; RCJ = RC Jacketing; SJ = Steel Jacketing; FD = Friction Damper; ESA = Equivalent Static Analysis; RSA = Response Spectrum Analysis; NSPA = Nonlinear Static Pushover Analysis; THA = Time History Analysis; PBEE = Performance-Based Earthquake Engineering

Several cross-cutting observations emerge from this synthesis. First, steel bracing (particularly X-type and Inverted V-type) consistently achieves lateral displacement reductions of 40-74% and inter-storey drift reductions of 40-70% relative to the unretrofitted bare frame across all building heights and seismic zones investigated. Second, RC shear walls consistently deliver the greatest stiffness enhancement (60-75% drift reduction) and are the preferred strategy when Immediate Occupancy performance is the target. Third, no study identifies a single universally optimal retrofit strategy; the selection depends on the target performance level, building height, plan regularity, seismic zone, and budget. Fourth, the combined use of RSA and NSPA is increasingly recognised as the minimum analytical standard for comprehensive retrofit evaluation. Fifth, ETABS has emerged as the near-universal computational platform for this class of analysis in the Indian research community.

9. Research Gaps

A critical reading of the reviewed literature reveals the following substantive gaps representing opportunities for original and high-impact investigation:

a) Underrepresentation of Low-to-Mid-Rise Buildings (G+4 to G+7)

A disproportionate share of the reviewed literature addresses buildings of G+8 storeys and above. The G+4 to G+7 category, which constitutes the majority of the urban residential stock in Indian tier-2 and tier-3 cities, has received comparatively limited dedicated investigation. The structural behaviour and optimal retrofit strategies for this height range where the relative contributions of flexure and shear to storey displacement differ from those of taller buildings, and where the cost-benefit ratio of retrofit techniques may vary markedly remain inadequately characterised.

b) Absence of Soil-Structure Interaction in Retrofit Modelling

Virtually all reviewed studies employ fixed-base support conditions, neglecting soil-structure interaction (SSI). SSI is known to modify the effective fundamental period, damping, and seismic demand of the structural system, particularly for buildings on soft or medium soils precisely the conditions (Type II soil) most commonly assumed in Indian seismic design practice. The influence of SSI on the performance of retrofitted buildings has not been examined in the reviewed corpus, representing a significant modelling deficiency.

c) Absence of Life-Cycle Cost Analysis

No reviewed study integrates life-cycle cost analysis (LCCA) into the comparison of retrofit strategies. LCCA accounts for initial retrofit cost, expected future repair costs under multiple earthquake scenarios, post-earthquake downtime losses, and residual building value, providing a holistic economic basis for retrofit strategy selection. The absence of LCCA means that cost-effectiveness comparisons are presently limited to initial material quantity assessments, which do not capture the full economic picture.

d) Limited Treatment of Non-Structural Performance

Seismic damage to non-structural elements cladding, partition walls, mechanical and electrical systems, and contents can account for 60-80% of total economic loss in moderate earthquakes even when the structural system remains serviceable. The performance of non-structural elements in retrofitted RC buildings, with respect to the floor acceleration and drift demands imposed by different retrofit configurations, has not been addressed in the reviewed literature.

e) Insufficient Coverage of Hybrid Retrofit Strategies

The reviewed literature is dominated by studies examining a single retrofit technique in isolation. Hybrid approaches combining peripheral steel bracing with selective member jacketing at critical beam-column joints, or partial-height shear walls with energy-dissipating couplers have received minimal research attention despite their potential to deliver superior performance at lower cost.

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The optimisation of hybrid configurations across multiple performance objectives (strength, stiffness, ductility, cost) represents a significant research opportunity.

f) Limited Use of Incremental Dynamic Analysis and Fragility Assessment

Nonlinear Static Pushover Analysis, while widely employed and highly informative, constitutes a static approximation of a fundamentally dynamic problem. Incremental Dynamic Analysis (IDA), in which the building is subjected to a suite of ground motion records scaled to multiple intensity levels, provides a more rigorous and probabilistic performance assessment. Fragility curves derived from IDA results enable quantification of the probability of exceedance of specified performance levels as a function of seismic intensity, providing the probabilistic metrics required for modern risk assessment and resilience-based design. None of the reviewed studies employed IDA for the evaluation of retrofitted RC buildings in the Indian context.

10. Future Research Directions

Based on the gaps delineated in Section 9, the following specific directions are recommended for future investigation:

a) Comprehensive seismic performance database for G+4 to G+7 RC buildings.

A systematic numerical study covering a representative sample of G+4 to G+7 RC frame buildings incorporating variations in plan regularity, bay dimensions, column slenderness, soft-storey conditions, and seismic zone should be undertaken to establish a comprehensive performance database for this underserved category. The database would enable the development of simplified performance prediction models and retrofit design guidelines specifically calibrated for low-to-mid-rise Indian RC buildings.

b) SSI-inclusive retrofit modelling.

Future studies should incorporate SSI through direct soil medium modelling (finite element or boundary element methods) or through Winkler spring-dashpot foundation models to capture period modification and seismic demand alteration by the underlying soil medium. The influence of SSI on the comparative performance of steel bracing and shear wall retrofits particularly for buildings on Type II and Type III soils per IS 1893:2016 should be explicitly quantified.

c) Life-cycle cost optimisation of retrofit strategies.

Future comparative studies should integrate LCCA frameworks employing probabilistic seismic hazard analysis to characterise the annual rate of exceedance of ground motion intensities, and loss assessment models to quantify expected annual losses for each retrofit configuration. This would enable robust cost-effectiveness comparisons between steel bracing, shear walls, and hybrid strategies across the full service life of the retrofitted building.

d) Incremental Dynamic Analysis and fragility curve development.

IDA-based fragility assessment should be conducted for representative retrofitted RC building archetypes using regionally appropriate ground motion suites from the NGA-West2 database or

Indian strong-motion records. The resulting fragility curves would furnish the probabilistic performance metrics needed to integrate retrofitted building performance into regional seismic risk assessments and urban resilience planning frameworks.

e) Machine learning-assisted retrofit optimisation.

The emerging application of machine learning (ML) techniques to structural engineering problems presents significant potential for retrofit optimisation. Surrogate models trained on large-scale parametric ETABS or OpenSees simulation datasets could be employed to predict post-retrofit seismic performance as a function of design parameters bracing configuration, shear wall thickness and placement, building geometry enabling rapid, data-driven optimisation of retrofit designs across multiple performance objectives without the computational burden of exhaustive simulation campaigns.

11. Conclusions

This paper has presented a systematic and critically informed review of published research on the seismic performance evaluation and rehabilitation of reinforced concrete buildings using steel bracing systems and shear walls, with particular emphasis on the Indian context and the analytical methodologies of Response Spectrum Analysis and Nonlinear Static Pushover Analysis. The principal conclusions drawn from this synthesis are as follows:

- a) Both steel bracing and RC shear walls are well-validated and highly effective global seismic rehabilitation strategies for deficient RC frame buildings. Their structural performance has been analytically demonstrated across a wide range of building heights (G+4 to G+20), seismic zones (II-V), and analysis methods in a consistent and reproducible manner throughout the reviewed literature.
- b) Steel bracing particularly X-type and Inverted V-type configurations consistently achieves lateral displacement reductions of 40-74% and inter-storey drift reductions of 40-70% relative to unretrofitted structures. X-bracing delivers the maximum stiffness and strength enhancement; Inverted V-bracing offers a more balanced structural-architectural trade-off. Tubular sections outperform angle sections as bracing members. Peripheral placement of bracing maximises both lateral and torsional performance improvement.
- c) RC shear walls consistently deliver the greatest stiffness enhancement (60-75% drift reduction) and are the preferred strategy when Immediate Occupancy performance is targeted, torsional control is critical, or the building is tall (G+10 and above). Symmetric peripheral placement along both principal directions minimises torsional eccentricity and delivers the most balanced seismic response. Foundation strengthening must be considered as an integral component of shear wall retrofit design.
- d) No single retrofit strategy is universally optimal. The selection between steel bracing and shear walls or a hybrid of both must be guided by the target performance level, building height and configuration, seismic zone classification, soil conditions, architectural constraints, and available budget. Life Safety performance can typically be achieved with

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steel bracing at lower cost and disruption; Immediate Occupancy generally necessitates the higher stiffness of shear walls.

- e) The combined application of Response Spectrum Analysis and Nonlinear Static Pushover Analysis constitutes the minimum analytical standard for comprehensive seismic retrofit evaluation. RSA furnishes the code-compliant demand verification required for regulatory approval; NSPA provides the performance-based evidence capacity curves, performance points, plastic hinge maps, and ductility metrics needed to confirm that the retrofitted structure attains the intended performance level.
- f) ETABS has been established as the dominant computational platform for seismic performance evaluation of RC buildings in the Indian research community, owing to its building-centric modelling philosophy, comprehensive analytical capabilities, and full compliance with IS 1893:2016 and associated codes.
- g) Significant research gaps persist in the domains of low-to-mid-rise building performance, soil-structure interaction, life-cycle cost analysis, non-structural performance, hybrid retrofit strategies, and probabilistic fragility assessment. Addressing these gaps represents the most productive frontier for advancing knowledge in seismic rehabilitation engineering.

The conclusions of this review provide a rigorous, evidence-based reference for structural engineers designing seismic rehabilitation interventions for the Indian RC building stock, for researchers designing future analytical and experimental investigations, and for policy makers formulating seismic risk mitigation strategies for urban centres in seismically active regions.

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