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Seismic Retrofitting of Existing RC Buildings: A Comprehensive Review of Methods, Analysis Techniques, and Future Directions

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Abstract- India is one of the most seismically active countries of the world with about 50-60% of its land area being seismically prone. The majority of RC buildings built prior to the seismic code of practice are highly vulnerable to seismic events due to lacking lateral load resistance. Over the last ten years, seismic retrofitting has become an effective and feasible approach to improve building performance without demolition. This review paper summarizes the most recent approaches, computational analysis frameworks, non-destructive evaluation (NDE) techniques, and performance-based engineering design aspects employed in seismic rehabilitation of existing reinforced concrete (RC) structures. It combines the results of the best international studies conducted between 1999 and 2024 with a focus on comparing retrofit technologies from the past with the new ones. The literature always shows that a retrofit implementing a combination of shear wall additions, steel bracing, fibre-reinforced polymer (FRP) jacketing and optimisation of infill walls performs better than any single retrofit technique in terms of reducing storey drifts, bending moments, shear, and axial load. It is possible to reliably characterize in-situ concrete strength by non-destructive testing (NDT) including the rebound hammer method for pre-retrofit. Advanced software platforms such as STAAD. Accurate linear and non-linear seismic simulations are achieved using Pro, SAP2000 and ETABS. This provides opportunities to incorporate damage prediction using machine-learning, real-time structural health monitoring (SHM) sensors, and to continue the analyses with shape-memory alloy (SMA) dampers in tall structures subjected to combined wind and dynamic loading scenarios.

Keywords: Seismic retrofitting, RC frames, masonry infill walls, non-destructive testing, rebound hammer, STAAD.Pro, performance-based design, IS 1893, fibre-reinforced polymer, structural health monitoring.

I. INTRODUCTION

1.1 Overview of the Topic

Among the most destructive natural hazards on Earth are earthquakes, which kill thousands of people and inflict damage to the economy annually. India being a part of three tectonic plates, namely the Indian, Eurasian and Arabian plates, is especially vulnerable to seismic activity. The Indian plate is moving north ward with a velocity of around 47 mm per year which gives rise to major and minor seismicity in the subcontinent.

Many of the buildings in existence - especially those built prior to the 1980s and based on RC frame structures - were not built with sufficient seismic provisions. The existing earthquake-resistant design code in India, IS 1893, has been revised multiple times (most recently in 2016), and many existing pre-2010 buildings fail to meet its standards. Research shows that as much as 60% of India's land mass is earthquake prone (Zones II-V) and a significant number of the buildings in urban areas are structurally unsound (RC buildings in Zones II-V). [1][2]

Seismic retrofitting is the process of making modifications to a building to enhance its seismic characteristics. Retrofitting offers several benefits over demolition and reconstruction – it retains embodied carbon, lowers construction waste volumes and is cost-effective, typically 35-65% less expensive than new construction. The need for systematic retrofit programmes for vulnerable building inventories has been clearly illustrated by several earthquake disasters that have happened globally, such as the 1994 Northridge (USA), 1995 Kobe (Japan), 2001 Bhuj

(India) and 2023 Kahramanmaraş (Turkey) earthquakes.

1.2 Importance and Motivation

There are four reasons for this review. First of all, there is an urgent need to bring together the disjointed information from numerical, experimental and field study areas in one cohesive reference. Second, the fast development of computational tools, such as non-linear dynamic analysis, BIM integration, and AI-based design, require updated synthesis. Third, third-generation materials (such as ultra-high-performance concrete (UHPC), SMA rebars, and carbon-fibre composites) present potential retrofit opportunities that are not yet included in the existing codes. Fourthly, in developing countries such as India, Bangladesh and Nepal, informal RC structures are rapidly being constructed with low to medium height, hence, there is a critical need for practical and economical retrofit design guidelines. Forth, there is a significant need in developing countries like India, Bangladesh and Nepal for practical and economical retrofit design guidelines for low to medium RC structure. .[3][4]

1.3 Objectives of the Review

The purpose of this review is as follows:

1. Look over and categorize current seismic retrofitting techniques for RC frame structures.
2. Compare traditional and advanced techniques for assessing structures using nondestructive testing methods, focusing on the rebound hammer test.
3. Analyse computational platforms (STAAD.There is an understanding of the types of structural simulation software (such as Pro, SAP2000, ETABS) and how they are used in pre and post retrofit structural analysis.
4. Combine performance information pertaining to the response parameters: bending moment, shear force, axial load, and storey displacement.
5. Determine gaps in current research and possible future research directions.

II. LITERATURE REVIEW

2.1 Existing Studies

Experimental studies, numerical simulations and field case studies document the body of knowledge on seismic retrofitting of RC frames. For example, Šipoš et al. [1] developed a simplified seismic design methodology for the masonry-infilled RC frame structures, concluding that rational placement of infill masonry can reduce inter-storey drift up to 40% without enlargement of sections. They studied models of interaction between infill and frame to demonstrate the significance of this interaction under lateral loading for global structural behaviour.

Pujol et al. [3] proposed masonry infill wall as a low cost retrofitting solution for low-rise RC frames in developing countries. Their cyclic load tests showed that strategically placed solid infill panels have an increase in lateral stiffness of 200-350% over bare frames with a corresponding reduction in storey drift during their World Conference on Earthquake Engineering tests in 2008.

In-plane lateral load behaviour of RC frames with masonry infill openings and modelling of them were given by Surendran and Kaushik [4]. The study compared the strength of the infill models used: macro-models (equivalent diagonal strut) and micro-models (FEM-based), and found that the equivalent strut approach is sufficiently accurate for engineering design without being too computationally complex.

Ozkaynak et al. [5] studied masonry infill walls as energy dissipation devices, and determined that the equivalent viscous damping of infilled RC frames can be 15–30% greater than the equivalent viscous damping of bare frames when subjected to cyclic loading. This has significant implications for seismic retrofitting in which an increase in damping can significantly reduce peak floor accelerations.

Kauffman and Memari [6] investigated masonry infill wall systems with fuse panels, which is a new idea in which fuse panels are designed to offer the first resistance to load, while the surrounding frame is protected. Cyclic in-plane load tests showed that fuse equipped infill systems had a controllable and reparable failure mechanism, with the residual drift being reduced by 25-30% compared with conventional infilled frames.

Infills were found to be effective in reducing the maximum base shear demand by 18–22% and lateral displacement by 30–38% over bare frames under maximum lateral load for five-storey RC frame as assessed by Paudel [7] using ETABS software.

In the above study, Tamboli and Karadi [9] carried out linear static and response-spectrum analysis of RC frames with and without masonry infill for the seismic loading corresponding to Zone III as per IS 1893, and found that maximum lateral displacement at roof level reduced by 42% for the infilled frame as compared to the bare frame.

Tsige and Zekaria [11] used non-linear pushover analysis to compare the performance of RC buildings with masonry infills, and found that having masonry infills uniformly distributed significantly enhances the ductility and diminishes the potential for soft-storey failures, which is a major source of collapse in pre-code RC buildings.

Pawar et al. [14] studied the performance of multi-storey RC frames with concentric steel bracing under the combined seismic and gravity loads through STAAD.Pro discovered that storey drift could be up to 55% less, and inter-storey shear could be up to 35% less than that of conventional moment-resisting structures.

Patel et al [15] assessed the seismic performance of various bracing systems (V, inverted-V, X and diagonal) for high-rise RC buildings with respect to storey displacement, distribution of base shear and member utilisation ratios and found that X-bracings have the best overall performance.

2.2 Methods and Technologies Used

The literature survey reveals that the following four major approaches to retrofit are presented: (i) Member-level strengthening (e.g., column/beam jacketing, FRP wrapping); (ii) system-level modification (e.g., shear wall addition, steel bracing, base isolation); (iii) infill-based strategies (e.g., masonry infill panels, polypropylene-band overlays); and (iv) energy-dissipation devices (e.g., viscous dampers, buckling-restrained braces, SMA devices). Almost all contemporary retrofit studies rely on a numerical simulation, which is performed with STAAD.Linear static analysis, response-spectrum analysis and non-linear pushover analysis are the main areas of the literature that are dominated by Pro, SAP2000 and ETABS, respectively.

2.3 Comparative Summary

Table 1: Comparative Summary of Selected Seismic Retrofitting Studies

Ref.	Author(s)	Retrofit Method	Analysis Tool	Key Outcome	Limitation
[1]	Šipoš et al., 2018	Masonry infill RC frame	ELSEVIER numerical model	40% drift reduction	Limited to low-rise frames
[3]	Pujol et al., 2008	Solid masonry infill panels	Experimental cyclic tests	200–350% stiffness gain	No software validation
[4]	Surendran & Kaushik, 2012	Infill with openings (macro-model)	Analytical (strut model)	Design guidelines	No experimental validation
[5]	Ozkaynak et al., 2013	Masonry infill for damping	ABAQUS / experimental	15–30% added damping	High-rise not considered
[6]	Kauffman & Memari, 2014	Structural fuse infill system	In-plane cyclic test	25–30% residual drift drop	Complex installation cost
[9]	Tamboli & Karadi, 2012	Masonry infill—RC frame	SAP2000	42% lateral disp. reduction	Static analysis only
[13]	Patil et al., 2018	Eccentric bracing—steel frame	STAAD.Pro	Effective lateral load control	Tall buildings only

[14]	Pawar et al., 2015	Concentric bracing	STAAD.Pro	55% storey drift reduction	Gravity-dominant design
[15]	Patel et al., 2017	Various bracing systems	CSI ETABS	X-bracing most efficient	RCC not steel hybrid
[19]	Rahul Krishna et al., 2017	Concentric bracing—irregular RC	ETABS	Wind-load performance data	Seismic zone not varied

III. CURRENT TRENDS AND DEVELOPMENTS

3.1 Recent Advancements in Retrofit Practice

Driven by the paradigm shifts that occurred in recent decades from prescriptive to performance-based earthquake engineering (PBEE). The PBEE framework was developed by the Pacific Earthquake Engineering Research Center (PEER) to create a probability relationship between ground motion intensity, structural response, damage state, and economic/societal loss. Under this framework, retrofit decisions are based on explicit performance objectives (e.g., Immediate Occupancy, Life Safety, Collapse Prevention) and not only on prescriptive force demands.This approach takes into consideration explicit performance goals in addition to prescriptive force demands in making retrofit decisions (e.g., Immediate Occupancy, Life Safety, Collapse Prevention).

The use of Fibre-Reinforced Polymer (FRP) composites has become common in the jacketing of columns and beams. CFRP and GFRP wraps can provide column confinement pressure, axial capacity, and ductility increases of 40-120% depending on the thickness of the wraps and direction of fibres. One of the major benefits is that FRP jacketing does not add any extra weight, thus not adding to the seismic demand, and can be applied with minimal disruption of the architectural structure. [6] [7]

Buckling-Restrained Braces (BRBs) are an important new development in retrofit technology. BRBs differ from traditional steel bracing in that they dissipate energy symmetrically in tension and compression via the steel core, which is filled with concrete.Unlike conventional steel bracing, BRBs provide stable hysteretic energy dissipation with no strength degradation, over many cycles of loading. Many retrofit projects around Japan, USA and more recently in South and Southeast Asia, have used BRBs.[11][12]

Retrofitting of critical facilities such as hospitals, governmental buildings, heritage structures, and others have been done using seismic isolation, mainly by the use of lead-rubber bearing (LRB) and friction pendulum system (FPS) seismic isolators. Well-designed systems can yield 60–80% reductions in spectral accelerations via isolation. [13][14]

3.2 Non-Destructive Testing (NDT) for Pre-Retrofit Assessment

In order to determine the in-situ strength and condition of the existing structure, prior to the finalisation of any retrofitting scheme, the information needs have to be well defined. The main NDT methods used in the literature surveyed are summarised in Table 2.

Table 2: Comparison of NDT Techniques for Concrete Strength Assessment

NDT Method	Principle	Accuracy (±%)	Advantages	Limitations
Rebound Hammer (Schmidt)	Surface hardness correlation	±15–25%	Fast, portable, low cost	Affected by carbonation, moisture
Ultrasonic Pulse Velocity (UPV)	Elastic wave propagation	±10–20%	Detects internal flaws	Operator skill dependent
Core Extraction	Direct compressive test	±5–8%	Most accurate	Destructive, sampling limited

Ground Penetrating Radar (GPR)	EM wave reflection	Qualitative	Detects rebar, voids	Costly, requires interpretation
Pull-out / Pull-off Test	Bonding force measurement	±10–15%	Semi-destructive, reliable	Local surface damage

Table 2 lists the non-destructive testing methods used for pre-retrofit structural assessments.

In-situ concrete assessment is almost always done using the rebound hammer test, which was standardised in IS 13311 (Part 2): 1992 and ASTM C805, due to its portability and low cost. Rebound number R is correlated by the empirical calibration curves with compressive strength fc. One of the most popular approximate relations is::

$$fck \approx a \bullet R^n \quad \left(\frac{N}{mm^2}\right) \quad \ldots (1)$$

where a and n are empirical constants depending on the type of cement, the characteristics of the aggregate and the surface conditions. For ordinary Portland cement concrete, a ≈ 0.50–0.75 and n ≈ 1.5–2.0. Only acceptable accuracy can be obtained with the interpretation of the results in conjunction with carbonation depth corrections and reference-core calibrations.

3.3 Computational Tools and Structural Modelling

Pre-retrofit vulnerability assessment and post retrofit performance verification have become indispensable software platforms. STAAD.Pro from Bentley Systems is used to carry out finite-element modelling, linear static, dynamic (response-spectrum) and non-linear analysis to comply with over 90 international building codes such as IS 1893, IS 456 and IS 800. It integrates with the BIM workflows, with Revit and AECOsim, providing seamless data exchange and multi-discipline collaboration.

Non-linear pushover and time-history analyses are available on robust platforms of SAP2000 and ETABS (Computers and Structures Inc.). They can be used for modelling isolators, dampers and BRBs and hinge assignments per ASCE 41/IS 1893 can be used to assess performance level directly. Tarque et al. [17] have given results that showed that the micro-FEM models provided by ABAQUS can give accurate results for the masonry infill crack pattern and failure mode, albeit with a considerably higher computational cost.

Table 3: Comparison of Structural Analysis Software for Seismic Retrofit Studies

Software	Developer	Analysis Types	Non-linear Capability	Code Support (India)	Primary Limitation
STAAD.Pro	Bentley Systems	Linear/Response Spectrum/Non-linear	Moderate (P-Δ, P-ε)	IS 456, IS 1893, IS 800	Complex non-linear hinging requires STAAD Advanced
SAP2000	CSI	Static/Dynamic/Pushover/THA	High (fibre hinges, links)	ASCE 41; IS via custom	Steep learning curve
ETABS	CSI	Building-specific static & dynamic	High (shear walls, isolators)	ASCE 41; IS 1893 (manual)	Limited to building typologies

ABAQUS	Dassault Systèmes	Full non-linear FEM	Very high (material/geometric)	None (custom UMATs)	High CPU cost; specialist user
OpenSees	UC Berkeley (open-source)	Non-linear THA	Very high (fibre sections)	Custom scripting	No GUI; code knowledge needed

IV. CHALLENGES AND LIMITATIONS

4.1 Technical Challenges

4.1.1 Structural Irregularity and Torsional Effects

Plan and vertical irregularity are the two major challenges faced when retrofitting existing buildings. Unsymmetrical structural layouts create torsional coupling when loaded laterally, increasing lateral drift demands at peripheral columns. Yadollahi et al. [12] showed that short-column effects due to the presence of partial-height masonry infills in RC frames resulted in significant stress concentrations during the 1999 Düzce earthquake, and initiated brittle shear failures, which were not well addressed by the common retrofit methods.

4.1.2 Soft-Storey and Weak-Storey Mechanisms

Many pre-code RC buildings have a soft-storey condition at the ground level, where an open garage or commercial space is present, which has significantly less lateral stiffness than the storeys above. In seismic loading, inter-storey drift is concentrated at the soft storey, often causing collapse. Infilling selected bays, installation of steel moment frames and/or shear walls generally are required for retrofit of soft storeys, which substantially changes the structural system and use.

4.1.3 Foundation and Soil–Structure Interaction

Bigger increases in lateral resistance of the superstructure (such as from the addition of shear walls) will result in greater base shear demands placed on the foundation. These are increased requirements for many existing foundations. Underpinning, micropile installation or soil grouting are all expensive and complex methods for strengthening shallow foundations and can be impractical in urban areas.

4.1.4 Concrete Carbonation and Rebar Corrosion

In pre-code RC buildings, the bonding and the effective cross-section may be diminished due to corrosion of reinforcing steels caused by carbonation. In carbonated zones, concrete strength values determined by NDT may be optimistic (rebound hammer over estimates in surface carbonated layer). Combined NDT and limited coring is needed to be able to make an accurate assessment, especially near the concrete cover.

4.2 Research Gaps

There is still a lot to be done, but there are some gaps in research. First, the majority of experimental works are conducted on single-bay, single-storey and/or low-rise subassemblies, and multi-storey retrofitted buildings rarely are tested in full scale. Secondly, the durability of FRP composites in tropical climates (high humidity, UV exposure, thermal cycling), in the context of South Asia, is not well investigated. Thirdly, retrofits and non-structural elements (furniture, partitions, MEP services etc.) are rarely modeled together. Fourth, there is no single guideline for India similar to ASCE 41-23 to guide practitioners, and instead there are a number of separate CPWD guidelines, IS standards, and foreign codes.

Table 4: Key Research Gaps Identified in the Reviewed Literature

Research Gap	Impact on Practice
Lack of full-scale experimental data for multi-storey retrofitted buildings	Over-reliance on sub-assembly test data may not capture 3D response

Insufficient long-term durability data for FRP under Indian climatic conditions	Design life predictions are uncertain; conservatism increases cost
No unified Indian performance-based seismic retrofit standard (PBSR)	Practitioners use outdated prescriptive approaches or foreign codes
Limited modelling of soil–structure interaction in retrofit analyses	Foundation demands may be under-estimated in design
Absence of AI/ML-assisted rapid visual screening for large building inventories	Manual vulnerability surveys are slow and inconsistent
Underexplored combined loading (earthquake + wind + temperature) for retrofitted structures	Design conservatism cannot be quantified without combined analyses

V. FUTURE RESEARCH DIRECTIONS

5.1 Machine Learning and AI-Assisted Vulnerability Assessment

There is still a lot to be done, but there are some gaps in research. First, the majority of experimental works are conducted on single-bay, single-storey and/or low-rise subassemblies, and multi-storey retrofitted buildings rarely are tested in full scale. Secondly, the durability of FRP composites in tropical climates (high humidity, UV exposure, thermal cycling), in the context of South Asia, is not well investigated. Thirdly, retrofits and non-structural elements (furniture, partitions, MEP services etc.) are rarely modeled together. Fourth, there is no single guideline for India similar to ASCE 41-23 to guide practitioners, and instead there are a number of separate CPWD guidelines, IS standards, and foreign codes.[1][7]

5.2 Structural Health Monitoring Integration

MEMS accelerometers, strain gauges and fibre-optic sensors can be placed in retrofitted members for real-time structural health monitoring (SHM) to continuously monitor the state of the structure. These systems can be used to identify early damage after a moderate earthquake, guiding decisions on building maintenance and minimizing the potential for post-earthquake occupancy of damaged buildings. A new frontier in smart infrastructure management is the combination of IoT-enabled SHM and digital twins, virtual representations updated in real time using data streams from sensors.

5.3 Novel Materials for Retrofitting

Self-centering retrofit devices in beam-column joints and bracing systems may be made of Shape-Memory Alloys (SMAs), especially superelastic Nitinol. When a SMA yields, it will regain its original shape when it is unloaded, dramatically reducing residual drifts. In thin cross-sections, Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) jackets offer an extremely high tensile strength, impact resistance and an extremely high compressive strength (>120 MPa) and thus are attractive to be used for confinement-enhancement without significant geometric changes.

5.4 Extension to Tall Buildings and Complex Loading

Most published retrofit studies have focused on the low to medium rise (G+3 to G+7) building category. Wind–earthquake interaction, wind-induced fatigue and thermal loading are all multi-hazard sources that need to be accounted for in extending robust performance-based retrofit frameworks to tall structures (>15 storeys) as the urban densification trends grow the high-rise building stock in seismically active zones.

5.5 Standardisation of Indian Retrofit Guidelines

There is no such a comprehensive national performance-based seismic retrofit code for India as available in other countries like ASCE 41 (USA), Eurocode 8 Part 3 (Europe), or JSCE (Japan). The development of an IS standard for assessment and improvement of existing buildings under seismic loading (with incorporation of PBEE concepts) would help in establishing a uniform consistent and reliable retrofit design practice throughout the country.

Performance Equation for Storey Drift Verification:

$$\frac{\Delta\_s}{h\_s} \leq \theta_{limit} \qquad \ldots (2)$$

Where Δs is the design storey drift (mm), hs is the storey height (mm), and θlimit is the drift limit for the desired performance level (Immediate Occupancy is 0.004, Life Safety is 0.010, and Collapse Prevention is 0.020, according to ASCE 41-23).

Design Base Shear (IS 1893:2016, Cl. 7.6):

$$V_B = (Z / 2) \bullet (I / R) \bullet (S\_a / g) \bullet W \qquad (3)$$

where Z = zone factor; I = importance factor; R = response reduction factor; Sa/g = spectral acceleration coefficient; W = seismic weight of the building. This equation is key to proving an increase in the base shear capacity of a retrofitted structure is equal to or greater than the base shear demand for the desired performance level.

VI. CONCLUSION

6.1 Summary of Findings

Based on the results of nineteen key studies that were published between 1999 and 2024, the state-of-the-art in seismic retrofit of existing RC structures was systematically reviewed. The main findings are:

1. Seismic retrofitting is technically practicable and could be cost-effective. Construction cost savings have been reported consistently as 35-65% less for demolition/reconstruction.Seismic performance is reported as equivalent or better and construction cost savings range from 35-65% when compared to demolition/reconstruction.
2. Retrofitting two techniques is more effective than a single technique intervention. It is found that the maximum reductions achieved via integration of infill walls, steel bracing, FRP jacketing, and columns are 20-30% in bending moment, 30-40% in shear force, 8-10% in axial force and 15-45% in storey drift, respectively, depending upon the building configuration.
3. It is vital to have NDT based pre retrofitting assessment. Although the error of the rebound hammer test is ±15–25%, it is a very valuable means of obtaining concrete strength data in-situ in a quick and economical manner. The accuracy is significantly increased when combined with UPV and selective core testing.
4. Tools of computation are essential. STAAD.Pro, SAP2000 and ETABS are used to accurately simulate structures throughout linear and non-linear analysis ranges, facilitating the rigorous performance-based design and comparison of retrofit options.
5. Vulnerability driver #5 is still structural irregularity. Any scheme must account for damage potential, especially with unsymmetrical layouts, soft storeys and short-column effects which increase potential damage.
6. There are many identified areas of research need. The most urgent unmet research needs are the full-scale experimental data, long-term durability studies of FRP, harmonisation of Indian PBSR standards, artificial intelligence-based screening tools, and multi-hazard analyses.

6.2 Key Recommendations

(1) Performance-based assessment frameworks (as per IS 15988:2013 and ASCE 41 principles) should be used instead of prescriptive, force-based approaches for reliable and quantifiable retrofit outcomes.

(2) At identified critical locations (2), the use of at least two independent methods (e.g. rebound hammer + UPV) and minimal core extraction should be combined to ensure a reliable characterisation of in-situ material strength for NDT campaigns.

(3) For buildings that are highly irregular or located in Zones III–V, (3) non-linear pushover or incremental dynamic analysis should be used to represent realistic demands beyond elastic response in the structural analysis.

(4) Research funding agencies should focus on full-scale experimental programs, durability testing of FRP systems in terms of exposure to climatic conditions, and an overall Indian seismic retrofit code for FRP.

(5) SHM provisions and digital-twin frameworks should be integrated into future retrofit research to aid in rapid assessment after the event and long-term structural integrity assurance.

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