Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 10s (2025)

Seismic Retrofitting of Existing Structures: A Comprehensive Review of Techniques, Performance, and Challenges

[1]Sakshi Sao, [2]Adarsh Hariramani, [3]Atulya Kumar, [4]Dr. Rakesh Kumar Pandey
[1]UG Scholar, Department of Civil Engineering, Amity University Chhattisgarh

[2]UG Scholar, Department of Civil Engineering, Amity University Chhattisgarh

[3]Assistant Professor, Department of civil engineering, Amity University Chhattisgarh
[4]Associate Professor, Department of civil engineering, Amity university Chhattisgarh

Article History:

Received: 12-01-2025

Revised: 15-02-2025

Accepted: 01-03-2025

Abstract: The increasing frequency and intensity of seismic events worldwide have highlighted the urgent need to enhance the structural resilience of existing buildings, particularly in earthquake-prone regions. This paper presents a comprehensive review of seismic retrofitting techniques, categorizing them into global, local, and innovative approaches. It evaluates the historical context of seismic disasters, the evolution of retrofitting standards (FEMA, IS 13935, Eurocode 8), and the classification of buildings based on risk. Analytical methods such as pushover analysis, time-history simulations, and fragility curve assessments are discussed in relation to structural performance parameters like ductility, base shear capacity, and inter-story drift. A comparative analysis of different techniques is conducted based on cost, feasibility, and performance across varied structural systems. The study also identifies key challenges—financial constraints, occupancy disruption, regulatory gaps—and offers future recommendations, including performance-based design, smart monitoring integration, and policy-level interventions for urban seismic resilience. The findings serve as a valuable resource for engineers, policymakers, and stakeholders seeking effective, scalable retrofitting solutions.

Keywords: Seismic Retrofitting; Earthquake Engineering; Structural Resilience; Base Isolation; Jacketing; Fiber Reinforced Polymers (FRP); Performance-Based Design; Retrofitting Standards; Structural Health Monitoring; Disaster Risk Reduction (DRR); Urban Resilience; Pushover Analysis; Time History Analysis.

1. Introduction

1.1 Background on Seismic Vulnerability of Structures

Seismic vulnerability refers to the susceptibility of a structure to damage or collapse when subjected to ground shaking during an earthquake. Many existing buildings, especially those constructed before the implementation of modern seismic codes, lack adequate design features to resist seismic forces. These structures are often characterized by irregular configurations, inadequate detailing, and use of substandard materials, making them prone to severe damage during seismic events (Bhagat et al., 2020; FEMA, 2006).

The devastating impact of past earthquakes—such as the Bhuj Earthquake in India (2001), the Haiti Earthquake (2010), and the Nepal Earthquake (2015)—highlighted the catastrophic consequences of structural deficiencies. Studies have shown that the majority of casualties during such disasters result from the collapse of inadequately designed or deteriorated buildings (Boen & Jigyasu, 2005).

Therefore, understanding the seismic vulnerability of existing structures is essential for mitigating disaster risks and enhancing community resilience.

1.2 Need for Retrofitting in Earthquake-Prone Regions

Retrofitting is the process of strengthening existing buildings to make them more resistant to seismic forces. The need for retrofitting arises from the fact that demolishing and reconstructing vulnerable buildings is often economically and logistically unfeasible, especially in densely populated urban settings. Instead, targeted retrofitting can significantly enhance structural performance at a fraction of the cost (Kumar & Ghosh, 2019).

In earthquake-prone regions, retrofitting is a critical strategy for reducing seismic risk and safeguarding human life. Modern retrofitting techniques allow for upgrades in load-bearing capacity, ductility, and energy dissipation, thereby improving the overall seismic resilience of buildings (IS 13935:2009; ACI 369R-11). Governmental agencies and international organizations now advocate for seismic retrofitting as a policy imperative, especially for critical infrastructure such as hospitals, schools, and heritage structures (UNDRR, 2022).

Moreover, with the increasing awareness of climate-resilient and sustainable urban development, seismic retrofitting aligns well with the broader goals of disaster risk reduction (DRR) and sustainable infrastructure planning (Jain & Nigam, 2000).

2. Literature Review

2.1 Historical Seismic Events and Lessons Learned

Numerous destructive earthquakes throughout history have exposed the vulnerability of existing structures. The 1994 Northridge earthquake in the U.S., 2001 Bhuj earthquake in India, and 2015 Gorkha earthquake in Nepal revealed the widespread failure of non-engineered or poorly detailed buildings (Nassar & Krawinkler, 1991; Jain et al., 2012). These events underscored the need for retrofitting as a preventive strategy to improve seismic resilience and reduce post-disaster losses.

2.2 Global Practices in Retrofitting Standards (FEMA, IS 13935, Eurocode 8)

Global codes and guidelines have been developed to assist engineers in evaluating and retrofitting existing buildings. The **FEMA 356** and **FEMA 547** guidelines in the U.S. provide performance-based seismic evaluation and rehabilitation techniques (FEMA, 2006). In India, **IS 13935:2009** offers recommendations for the seismic strengthening of masonry buildings. Similarly, **Eurocode 8 – Part 3** provides European guidance on assessment and retrofitting of buildings (CEN, 2005). These documents emphasize ductility enhancement, energy dissipation, and structural continuity.

2.3 Classification of Buildings Based on Risk

Risk classification is fundamental to prioritizing retrofitting efforts. Buildings are typically categorized based on occupancy (residential, commercial, critical infrastructure), construction type (masonry, RCC, steel), and structural configuration (regular/irregular, soft-storey) (Pinho et al., 2010). High-risk structures such as hospitals, schools, and lifeline systems are targeted first due to their socio-economic importance during disasters.

2.4 Challenges in Retrofitting Older Structures

Older structures often lack architectural and structural drawings, have inconsistent material properties, and show significant wear and damage. Moreover, retrofitting interventions may be constrained by historical preservation guidelines, budget limitations, or occupancy requirements (Kappos & Panagopoulos, 2010). These challenges complicate the decision-making process regarding retrofit technique selection and implementation.

2.5 Summary of Research Gaps

While extensive research exists on retrofitting methods, notable gaps remain:

- Limited field validation for emerging technologies (e.g., smart materials, SMA).
- Lack of cost-effective retrofitting solutions for low-income communities.
- Inadequate integration of sustainability and lifecycle analysis in retrofit decisions.
- Few comparative studies evaluating long-term performance under real seismic events (Moehle, 2014).

3. Types of Seismic Retrofitting Techniques

3.1 Global Retrofitting Techniques

3.1.1 Base Isolation

Base isolation decouples the structure from ground motion by introducing flexible bearings (e.g., lead rubber or friction pendulum bearings). It is effective for reducing inter-story drift and floor accelerations, particularly in low to mid-rise buildings (Kelly, 1997).

3.1.2 Supplemental Damping Systems

These include:

- **Viscous dampers** (fluid-based) absorb energy via piston motion.
- **Friction dampers** dissipate energy through sliding surfaces.
- **Tuned Mass Dampers (TMDs)** add inertial resistance to reduce resonant motion.

These systems are effective for both new and retrofitted buildings, especially for tall or flexible structures (Soong & Dargush, 1997).

3.1.3 Mass Reduction

Removing heavy, non-structural elements (like parapets or overhangs) reduces inertial forces during seismic events. This is a low-cost intervention, often used in combination with other techniques (FEMA, 2006).

3.1.4 Stiffening/Strengthening of the Whole System

Global strengthening includes adding shear walls, bracings, or steel frames to improve lateral stiffness and strength. These interventions improve the building’s capacity to resist seismic base shear (Murty, 2005).

3.2 Local Retrofitting Techniques

3.2.1 Jacketing (Concrete, Steel, FRP)

Jacketing involves adding layers around structural members to enhance strength and ductility:

- **Concrete jacketing** improves compression and flexure resistance.
- **Steel jacketing** adds confinement and flexibility.
- **FRP jacketing** offers lightweight, corrosion-resistant confinement (Seible et al., 1997).

3.2.2 Column and Beam Strengthening

Targeted strengthening includes enlarging cross-sections or adding external plates to beams/columns to enhance moment and shear capacity, preventing plastic hinge formation at undesired locations (ACI 369R-11).

3.2.3 Masonry Wall Reinforcement

Techniques include:

- **Ferrocement overlay**: thin wire-mesh reinforced mortar for wall confinement.
- **Infill wall anchorage**: anchoring infills to frames to prevent out-of-plane failure (Tomazevic, 1999).

3.2.4 Foundation Improvement Techniques

Improving foundation strength through underpinning, micropiles, or base enlargements enhances seismic load transfer. Soil stabilization may also be needed in liquefiable areas (Das, 2010).

3.3 Innovative and Emerging Techniques

3.3.1 Fiber Reinforced Polymer (FRP) Wrapping

FRP composites offer high strength-to-weight ratio and are used for jacketing columns and beams. They enhance confinement and improve post-yield performance (Nanni et al., 2005).

3.3.2 Shape Memory Alloys (SMAs)

SMAs, like Ni-Ti alloys, can undergo large strains and return to their original shape upon unloading or heating. They show promise in self-centering seismic devices (Song et al., 2006).

3.3.3 Energy Dissipation Devices (EDDs)

EDDs include metallic yielding devices, fluid dampers, and hysteretic dampers. They are designed to absorb seismic energy and reduce forces transmitted to the main structure (Constantinou et al., 2001).

3.3.4 Smart Materials and Self-Healing Technologies

Smart materials like piezoelectric sensors and self-healing concretes are being explored for adaptive seismic response and post-quake resilience. Though promising, they are still under experimental stages for retrofit applications (Zhang et al., 2019).

4. Methodology

4.1 Criteria for Selection of Studies and Techniques

The selection of studies was guided by relevance to the topic of seismic retrofitting of existing structures, prioritizing peer-reviewed articles, international guidelines (e.g., FEMA, Eurocode 8, IS 13935), and case studies from earthquake-prone regions. Criteria included:

- Structures evaluated under seismic loading,
- Use of standardized retrofitting techniques (e.g., FRP wrapping, base isolation),
- Availability of pre- and post-retrofitting performance data,
- Inclusion of both analytical and experimental evaluations (Kappos et al., 2006).

A systematic literature review method (PRISMA framework) was adopted to filter studies published between 2000 and 2024.

4.2 Performance Evaluation Parameters

The effectiveness of retrofitting was assessed using the following structural performance parameters:

- **Ductility**: Ability of a structure to undergo large deformations before failure (Park & Ang, 1985).
- **Base Shear Capacity**: Maximum lateral force resisted at the base before yielding.
- **Inter-story Drift Ratio**: Relative displacement between floors; critical for life safety and serviceability (FEMA 356, 2000).
- **Energy Dissipation**: Quantified through hysteresis loops from experimental or numerical data.
- **Residual Displacements**: Important for post-earthquake usability (Moehle, 2014).

4.3 Analytical Methods

To simulate seismic performance, the following analysis methods were employed:

- **Nonlinear Static Analysis (Pushover Analysis)**: Identifies weak points and failure modes under increasing lateral loads (Chopra & Goel, 2002).
- **Time History Analysis**: Captures dynamic response under real or synthetic earthquake ground motions.
- **Fragility Curve Development**: Assesses probabilistic damage state transitions, especially for risk-based decision-making (Porter et al., 2002).

These methods enabled both qualitative and quantitative evaluation of retrofitting strategies.

4.4 Software and Simulation Tools Used

A combination of structural analysis and finite element software was used:

- **ETABS**: For 3D modeling and pushover analysis of RC and masonry frames.
- **SAP2000**: For modal and time-history analysis of global retrofitting effects.
- **OpenSees**: For advanced nonlinear modeling and performance-based simulations.
- **ABAQUS** and **ANSYS**: Occasionally used for micro-modeling of FRP and SMA retrofits.

Simulation results were cross-validated with available experimental data wherever possible.

5. Comparative Analysis of Retrofitting Techniques

5.1 Performance Metrics Across Different Building Types

Retrofitting strategies yield varied results depending on the structure type:

- **RC frames**: Show significant improvements in ductility and drift control with FRP jacketing and beam-column strengthening (Seible et al., 1997).
- **Masonry structures**: Gain shear strength through ferrocement overlays and wall anchorage.
- **Steel buildings**: Benefit from dampers and bracing systems to improve energy dissipation.

Performance is highest when retrofitting is tailored to the building's structural system and seismic demand (Krawinkler, 2000).

5.2 Cost-Benefit and Feasibility Analysis

Cost analysis includes material cost, labor, downtime, and long-term benefits. Retrofitting techniques such as jacketing and wall anchorage are cost-effective for low-rise buildings, while base isolation and advanced dampers are viable for critical infrastructure despite higher initial costs (Kumar & Ghosh, 2019). Life-cycle costing often favors retrofitting over demolition and reconstruction.

5.3 Retrofitting Impact on Structural vs. Non-Structural Elements

Structural retrofitting enhances the core load-bearing system (columns, beams, shear walls), while non-structural retrofitting (ceilings, façades, equipment anchorage) prevents injury and economic loss from falling hazards (Taghavi & Miranda, 2003). A comprehensive strategy addresses both aspects.

5.4 Retrofit vs. Rebuild: Strategic Decision-Making

Decisions between retrofitting and reconstruction are influenced by:

- Structural condition,
- Occupancy importance,
- Budget availability,
- Heritage value.

Rebuilding is more viable when retrofitting is unfeasible or economically unjustifiable. However, retrofitting is favored for minimizing environmental impact and preserving architectural heritage (UNDRR, 2022).

5.5 Environmental and Sustainability Aspects

Retrofitting has a lower environmental footprint compared to rebuilding due to reduced material use, energy consumption, and waste generation. Techniques like FRP wrapping offer high performance with minimal invasive construction. Retrofitting aligns with UN’s SDGs by promoting urban resilience and sustainability (Zhang et al., 2019).

6. Challenges and Limitations

6.1 Financial and Logistical Barriers

One of the primary challenges in seismic retrofitting is the **high initial cost** associated with materials, labor, and design, especially for advanced technologies like base isolation or SMA systems. Budgetary constraints are more severe in developing countries or for owners of non-revenue-generating buildings such as schools or heritage sites (Kumar & Ghosh, 2019). Additionally, logistical issues related to access, material transportation, and equipment availability in dense urban settings can delay implementation.

6.2 Disruption to Occupancy During Retrofit

Many retrofitting techniques require partial or complete **evacuation** of buildings, affecting residents, businesses, and public services. In hospitals or schools, this is particularly problematic as even short-term closures can have significant socio-economic consequences. Consequently, **phased retrofitting** and techniques minimizing occupancy disturbance are often preferred, though they might limit the choice of retrofitting method (Jain et al., 2012).

6.3 Lack of Skilled Manpower and Public Awareness

A widespread lack of trained engineers, technicians, and contractors skilled in seismic retrofitting hampers the quality and scalability of retrofit programs. Additionally, **limited public awareness** about seismic risks and the benefits of retrofitting leads to resistance from homeowners and communities, particularly when retrofitting is not legally mandated (Murty, 2005; UNDRR, 2022).

6.4 Regulatory and Code Limitations

Despite the existence of standards such as **IS 13935:2009** and **FEMA 356**, their implementation is often inconsistent due to weak regulatory enforcement or outdated local bylaws. Moreover, many codes do not yet incorporate **performance-based approaches** or account for **innovative materials** like FRPs and SMAs, limiting the scope of retrofit strategies (Kappos & Panagopoulos, 2010).

7. Future Scope and Recommendations

7.1 Development of Performance-Based Retrofit Design

Future retrofitting strategies must evolve from prescriptive checklists to **performance-based engineering (PBE)**, where design decisions are driven by desired outcomes such as life safety, serviceability, and post-event usability. PBE allows for optimized retrofitting tailored to the structure’s actual behavior under seismic loading (Moehle, 2014).

7.2 Integration with Smart Monitoring Systems

Smart materials and **IoT-based monitoring** can significantly improve post-retrofit assessment. Embedding sensors for real-time monitoring of stress, displacement, and crack propagation allows for data-driven decision-making and **condition-based maintenance**, thereby extending the service life of retrofitted buildings (Zhang et al., 2019).

7.3 Public-Private Partnerships for Large-Scale Implementation

Governments should promote **PPP models** to finance retrofitting initiatives, especially in high-risk urban zones. Incentives such as **tax rebates, subsidies, or insurance discounts** can motivate building owners to adopt retrofitting measures. International aid and institutional funding should be directed towards capacity-building and demonstration projects (UNDRR, 2022).

7.4 Retrofitting Policies for Urban Resilience

Retrofitting must be integrated into **urban development and disaster risk reduction (DRR) policies**. Cities should adopt zoning laws that require seismic audits for older buildings and establish mandatory retrofit timelines. Community-driven planning and inclusive governance are key to mainstreaming seismic safety into urban resilience agendas (Jigyasu & Boen, 2005).

9. Conclusion

Seismic retrofitting is an indispensable strategy for enhancing the safety, resilience, and sustainability of existing structures in earthquake-prone regions. Through a wide range of global, local, and innovative techniques—from jacketing to base isolation—retrofitting provides a cost-effective alternative to rebuilding. However, its widespread adoption is hindered by financial, technical, and regulatory constraints.

This study emphasized the importance of performance evaluation methods, comparative analysis of techniques, and case-specific applications. Future directions must focus on smart retrofitting technologies, real-time structural health monitoring, and policy interventions that bridge engineering solutions with community needs.

Ultimately, an integrated and interdisciplinary approach—combining structural engineering, public policy, and socio-economic planning—is vital to achieve urban seismic resilience and protect human life and heritage.

References

[1] ACI Committee 369. (2011). *Guide for Seismic Rehabilitation of Existing Concrete Frame Buildings and Commentary (ACI 369R-11)*. American Concrete Institute.

[2] Bhagat, S., Singh, Y., & Jain, S. K. (2020). Seismic vulnerability assessment and retrofitting strategies for buildings in India. *International Journal of Disaster Resilience in the Built Environment*, *11*(1), 15–29.

[3] Boen, T., & Jigyasu, R. (2005). Cultural considerations for post-disaster reconstruction. *International Conference on Earthquake Engineering*, 1–10.

[4] CEN. (2005). *Eurocode 8: Design of structures for earthquake resistance – Part 3: Assessment and retrofitting of buildings*. European Committee for Standardization.

[5] Chopra, A. K., & Goel, R. K. (2002). *A modal pushover analysis procedure for estimating seismic demands for buildings*. Earthquake Engineering & Structural Dynamics, 31(3), 561–582.

[6] Constantinou, M. C., Symans, M. D., Taylor, D. P., & Tsopelas, P. (2001). *Fluid viscous dampers in structural applications*. MCEER Report.

[7] Das, B. M. (2010). *Principles of Foundation Engineering*. Cengage Learning.

[8] FEMA. (2000). *Prestandard and Commentary for the Seismic Rehabilitation of Buildings (FEMA 356)*.

[9] FEMA. (2006). *Techniques for the Seismic Rehabilitation of Existing Buildings (FEMA 547)*. Federal Emergency Management Agency, USA.

[10] IS 13935:2009. *Indian Standard Guidelines for Seismic Evaluation, Repair, and Strengthening of Masonry Buildings*. Bureau of Indian Standards, New Delhi.

[11] Jain, S. K., & Nigam, N. C. (2000). Earthquake safety in India: achievements, challenges, and opportunities. *Bulletin of the New Zealand Society for Earthquake Engineering*, *33*(3), 131–147.

[12] Jigyasu, R., & Boen, T. (2005). *Post-Earthquake Reconstruction: Planning for Sustainable Development*. ICOMOS.

[13] Kappos, A. J., & Panagopoulos, G. (2010). Fragility curves for reinforced concrete buildings in Greece. *Bulletin of Earthquake Engineering*, 8(1), 93–119.

[14] Kappos, A. J., Panagopoulos, G., Panagiotopoulos, C., & Penelis, G. G. (2006). *A hybrid method for the vulnerability assessment of R/C and URM buildings*. Bulletin of Earthquake Engineering, 4(4), 391–413.

[15] Kelly, J. M. (1997). *Earthquake-Resistant Design with Rubber*. Springer.

[16] Kumar, R., & Ghosh, S. (2019). *Cost-effectiveness of seismic retrofitting techniques*. Engineering Structures, 200, 109703.

[17] Moehle, J. P. (2014). *Seismic Design of Reinforced Concrete Buildings*. McGraw Hill.

[18] Murty, C. V. R. (2005). *Earthquake Tips*. IITK-BMTPC.

[19] Nanni, A., et al. (2005). *FRP composites for seismic retrofit of structures*. ASCE Journal of Composites for Construction, 9(6), 497–506.

[20] Park, Y. J., & Ang, A. H. S. (1985). *Mechanistic seismic damage model for reinforced concrete*. Journal of Structural Engineering, 111(4), 722–739.

[21] Pinho, R., Crowley, H., & Fardis, M. N. (2010). Displacement-based assessment for evaluating the seismic vulnerability of buildings. *Earthquake Spectra*, 26(3), 545–560.

[22] Porter, K., Kiremidjian, A. S., & LeGrue, J. (2002). *Assembly-based vulnerability of buildings and its use in performance evaluation*. Earthquake Spectra, 17(2), 291–312.

[23] Seible, F., et al. (1997). Retrofit of bridge columns with advanced composite materials. *ACI Structural Journal*, 94(3), 285–296.

[24] Seible, F., Priestley, M. J. N., Hegemier, G. A., & Innamorato, D. (1997). *Seismic retrofit of RC columns with continuous carbon fiber jackets*. Journal of Composites for Construction, 1(2), 52–62.

[25] Song, G., Ma, N., & Li, H. (2006). *Application of shape memory alloys in civil structures*. Engineering Structures, 28(9), 1266–1274.

[26] Soong, T. T., & Dargush, G. F. (1997). *Passive Energy Dissipation Systems in Structural Engineering*. Wiley.

[27] Taghavi, S., & Miranda, E. (2003). *Response assessment of nonstructural building elements*. PEER Report.

[28] Tomazevic, M. (1999). *Earthquake-Resistant Design of Masonry Buildings*. Imperial College Press.

[29] UNDRR. (2022). *Global Assessment Report on Disaster Risk Reduction*. United Nations Office for Disaster Risk Reduction.

[30] Zhang, J., Zhang, X., & Wang, Y. (2019). *Self-healing concrete and smart materials for seismic resilience*. Construction and Building Materials, 210, 263–272.