COMPREHENSIVE REVIEW OF SEISMIC RETROFITTING APPROACHES FOR EXISTING REINFORCED CONCRETE BUILDINGS

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Abstract

Earthquakes pose significant effects on reinforced concrete (RC) buildings, particularly on older buildings that are not designed according to appropriate seismic guidelines. Structural weaknesses, like improper reinforcement detailing, soft story irregularities, and insufficient ductility, can result in more severe destructions when an earthquake occurs. This paper provides an extensive analysis of important seismic weaknesses, earthquake damages, and traditional and innovative retrofitting technologies that are employed in enhancing the seismic performance of existing RC buildings. Traditional technologies such as concrete jacketing, steel jacketing, shear walls, and steel bracing systems have been reviewed alongside contemporary strategies, such as FRP retrofitting, base isolation systems, energy dissipation mechanisms, intelligent materials, and hybrid retrofitting solutions. The paper further contrasts the different retrofitting technologies in terms of their efficiency, cost effectiveness, and practicality. Moreover, the research also presents current difficulties associated with seismic retrofits and possible future directions in terms of sustainability, AI-based monitoring technologies, and performance-based seismic design.

Keywords: Seismic Retrofitting, Reinforced Concrete Buildings, Earthquake Resistance, FRP Retrofitting, Base Isolation, Seismic Performance, Earthquake Engineering.

1. INTRODUCTION

Earthquakes are amongst the most damaging natural calamities, posing a threat to human lives, structures, and economic systems all over the world. Urbanization along with high-density human habitation in earthquake-prone regions has led to an increased level of vulnerability of the structures in these regions. Nations situated in the vicinity of tectonic plates are often affected by earthquake activities on varying scales, leading to structural damage and destruction. Moreover, in developing countries, especially in urban areas, the structures made of reinforced concrete do not follow any seismic requirements for construction [1].

As mentioned above, structures made of reinforced concrete represent the majority of housing and other facilities due to their sturdiness, cost-effectiveness, and ease of construction. Nonetheless, the previous earthquakes proved that insufficient reinforcement and detailing of structures can lead to severe issues, including cracking, shear failure, columns' failure, and deterioration of structure in general. The need to strengthen existing structures against earthquakes was illustrated by the occurrence of events like the Bhuj Earthquake, the Nepal Earthquake, and the Tohoku Earthquake and Tsunami.

1.1. Need for Seismic Retrofitting

Seismic retrofits have emerged as a crucial approach in enhancing the seismic performance of existing reinforced concrete structures. Several old reinforced concrete buildings were built using obsolete building regulations or inadequate seismic detailing practices. With advancing seismic engineering science and design principles, several old buildings have failed to meet new safety standards. This has made the buildings susceptible to seismic attacks.

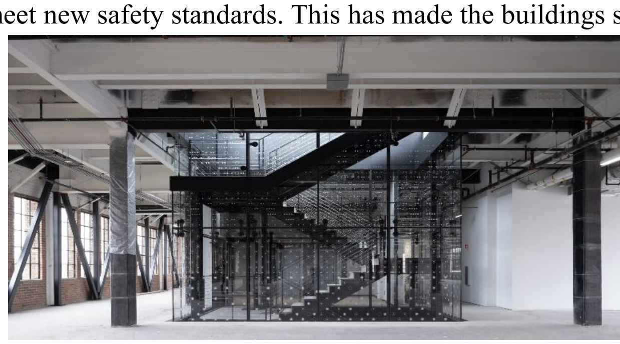

Figure 1: Seismic Retrofitting

The other important issue to consider is the aging of infrastructures. With time, due to the effects of environmental elements, deterioration, corrosion, and improper maintenance practices, the strength and durability of RC structures tend to diminish. Issues such as weak lateral resistance, low structural flexibility, poor beam-to-column connections, and soft stories make these structures more susceptible to failure during earthquakes.

1.2. Objectives of the Review

The specific objectives of the review are as follows:

- To review the existing seismic retrofitting approaches adopted for RC buildings.
- To compare conventional and modern retrofitting methods based on structural efficiency, cost-effectiveness, and practical applicability.
- To analyse the advantages, limitations, and performance characteristics of different retrofitting techniques.
- To identify the major challenges associated with seismic retrofitting implementation.
- To highlight future research directions and emerging technologies in the field of earthquake-resistant structural rehabilitation.

2. SEISMIC DEFICIENCIES AND FAILURE MECHANISMS IN EXISTING RC BUILDINGS

The reason behind the extensive application of RC buildings for constructing various types of structures, such as residential buildings, commercial buildings, and industrial buildings, is because of their strength and cost-effectiveness. Nonetheless, several RC buildings were built without taking into account the seismic aspects, especially in areas where the construction of earthquake-resistant buildings was not considered mandatory in the past. These structures tend to suffer from substantial structural weaknesses during earthquakes, making them vulnerable to collapse.

2.1. Structural Deficiencies in RC Buildings

The performance of RC buildings under seismic loads is mainly dependent on the quality of their structural design and reinforcement detailing. Several problems associated with RC buildings include weak story irregularity, weak column/strong beam effect, and poor reinforcement detailing. These shortcomings make the structure unable to withstand the effects of the seismic load.

Soft-story irregularities arise where the ground floor is less stiff and strong compared to other floors. Thus, the structure experiences excessive lateral displacement when subjected to the earthquake loads. Other structural defects associated with RC buildings include weak column and inadequate reinforcement detailing [2]. This makes the structure less ductile and more susceptible to structural failures.

Table 1: Common Structural Deficiencies in RC Buildings

Structural Deficiency	Description	Effect During Earthquake
Soft Story Irregularity	Lower stiffness at one floor level	Excessive lateral displacement and collapse
Weak Column–Strong Beam Effect	Columns weaker than beams	Progressive structural failure
Poor Reinforcement Detailing	Inadequate anchorage and confinement	Brittle failure and reduced ductility
Inadequate Lateral Load Resistance	Insufficient seismic resistance system	Increased seismic vulnerability
Material Deterioration	Corrosion and aging of materials	Reduction in structural strength

2.2. Common Earthquake-Induced Failures

Earthquakes produce lateral loads that exert considerable stress on RC structures. If these loads surpass the structural capacity, there could be flexural, shear, joint, and foundation failure, based on the pre-existing structural inadequacies. Flexural failure is normally associated with beams and columns, characterized by cracking due to excessive bending stresses, whereas shear failure is instantaneous in nature because of the sudden development of diagonal stresses surpassing the shear capacity of the structural elements.

Joint failure is common in the beam-to-column joints due to poor reinforcement detailing, leading to cracking and instability of the structure under seismic loads. Moreover, foundation failure may happen owing to weak soils, soil liquefaction, slippage, and excessive settlement, significantly compromising the stability of the structure.

2.3. Factors Affecting Seismic Performance

Performance of RC structures during earthquakes depends on parameters like the type of materials used in the construction process, the level of construction quality, and the age of the structure. Degradation of materials due to corrosion, water leakage, carbonation, and other environmental elements leads to the weakening of concrete and reinforcing materials used in the building process.

The quality of construction works is equally important for earthquake resistance. The poor quality of construction work, lack of proper mixing of concrete, inadequate curing, and improper placing of reinforcing materials are some of the reasons that lower the integrity of the structure. Furthermore, aging of structures and obsolete construction techniques render old RC structures susceptible to seismic damage.

3. CONVENTIONAL SEISMIC RETROFITTING TECHNIQUES

The traditional method of seismic retrofits is utilized to increase the strength, stiffness, ductility, and seismic resistance of the building made out of reinforced concrete. The technique involves making the structural members like beams, columns, joints, and foundations strong in order to increase energy absorption by the structure. These techniques have been found to be efficient and reliable due to which they are widely utilized.

3.1. Concrete Jacketing

The jacketing of concrete is one of the most commonly used traditional techniques for retro-fitting to strengthen RC structural elements. In this case, an additional coating of concrete will be applied to the beams, columns, and joint areas to strengthen their ability to carry loads and increase their stiffness and ductility. It usually includes surface preparation, providing additional reinforcing and applying new concrete on the existing structure.

By using the concrete jacketing technique, one can effectively increase the flexural and shear capacity of RC structures and increase the column confinement to enhance their seismic performance. This technique works best for buildings that have poor design regarding the detail of reinforcement and the sizes of the structural elements.

3.2. Steel Jacketing

Another effective form of retrofitting is steel jacketing that helps in improving the seismic behavior of RC buildings. In this process, steel plates, steel angles, and steel sections are added to existing structural members especially the columns and the joints between beams and columns. The addition of steel jackets to the members improves the confinement effect and thus improves the behavior of the members under seismic loads [3].

The application of steel jackets is very useful in cases where there is need for strengthening of deficient columns since it improves both the axial and shear strength of columns. In comparison to the use of concrete jackets, the process of adding steel jackets requires less time and the added weights of the structures are considerably lower.

3.3. Addition of Shear Walls

One of the best ways to increase the resistance of an existing RC structure to lateral loads is by the installation of shear walls. Shear walls are basically vertical structures whose role is to resist horizontal forces due to earthquakes and minimize horizontal displacements as much as possible. They are normally made up of reinforced concrete and installed in strategic parts of the building.

Installation of shear walls improves the stiffness of the building since it helps in increasing the lateral resistance capacity of the building. The building will therefore experience less inter-story drift and minimal damages to both non-structural and structural parts of the building.

3.4. Steel Bracing Systems

Steel bracing systems have been extensively employed as a retrofitting technique in the form of seismic upgrading of RC structures due to their ability to enhance the lateral stiffness and energy absorption capacity of RC buildings.

Bracing systems incorporate steel elements which are installed in the diagonal direction of the structural frame to withstand earthquake-induced lateral loads.

Figure 2: Steel Bracing Systems

The biggest strength associated with the use of steel bracing is that it helps in increasing the rigidity of the structure without adding extra weight. Braces are able to limit movement in buildings and absorb seismic energy as well. Besides, steel bracing can be used to strengthen an already built building without disturbing any of the activities taking place inside.

3.5. Section Enlargement Methods

This is a traditional method of reinforcement that can be used to enlarge the dimensions of structural elements like beams, columns, and slabs. This is achieved by placing reinforced concrete (RC) jackets with extra reinforcement to enhance the capacity of the structural element.

This method is very effective when the structural elements are insufficient in size, have deteriorated due to corrosion, or have been subjected to excessive loads. Section enlargement improves the flexural and shear capacity of the structure while also increasing its ductility in seismic loadings.

4. ADVANCED AND MODERN RETROFITTING APPROACHES

The evolution of earthquake engineering and material science, various modern methods of seismic retrofits for improving the seismic response of existing structures have been introduced. Contrary to traditional techniques that concentrate on strengthening of structures through the addition of more load and time-consuming procedures, modern techniques seek improvement in structural efficiency without increasing the load, construction period, and changes in architectural appearance [4]. In general, modern retrofitting schemes aim to improve the efficiency of structures in terms of energy dissipation, ductility, durability, and seismic stability. Contemporary retrofitting techniques are becoming more popular in rehabilitation programs because of their efficiency, feasibility, and flexibility.

4.1. Fiber Reinforced Polymer (FRP) Retrofitting

The Fiber Reinforced Polymer (FRP) retrofitting technique is among the most popular advanced strengthening methods that can be used to upgrade RC structures. The FRP materials consist of strong fibers made of carbon, glass, or aramid, which are embedded into a polymer matrix. The FRP materials are applied to structural elements via epoxy adhesives to strengthen them.

The FRP retrofitting technique is quite efficient at improving the flexural, shear, ductility, and confinement capacity of RC beams, columns, slabs, and beam-column connections. The lightness and high strength-to-weight ratio of the FRP composites make them very efficient in strengthening concrete structures. Moreover, FRP materials are corrosion resistant, which ensures good durability [5].

Figure 3: Fiber Reinforced Polymer

The second advantage of the FRP technology is that it is easy to install; hence, it can be used in the retrofitted building without causing any significant disturbance. The efficiency of the FRP system relies on adequate surface treatment and bonding. The high price of materials and sensitivity to heat and fire are some of the constraints of FRP technology. Nonetheless, the use of FRP technology in structural seismic retrofitting has increased because of its performance and adaptability.

4.2. Base Isolation Systems

Base isolation refers to the use of sophisticated seismic design to minimize the amount of force transmitted from the earth to the structure. This approach involves installing flexible base isolation mechanisms in the gap between the superstructure and the building foundation. With this method, it becomes possible to minimize the effect of seismic events to a great extent [6].

Examples of commonly used base isolators include laminated rubber, lead rubber, and friction pendulum systems. Base isolators effectively work by dissipating seismic forces and minimizing acceleration and lateral movements within buildings. Base isolation systems have proven useful when dealing with essential structures like hospitals and emergency centers.

4.3. Energy Dissipation Devices and Dampers

Energy dissipation devices are referred to as dampers and are employed to dissipate and consume seismic energy during earthquakes, hence minimizing vibration and damage to structures. They are incorporated in the structure itself to regulate lateral movement and mitigate the effects of dynamic loads on the structure.

Several kinds of dampers have been utilized in seismic retrofits; these include viscous dampers, friction dampers, metallic dampers, and tuned mass dampers. Viscous dampers are energy dissipating devices whose working principle is based on fluid flow, while friction dampers rely on friction between two surfaces to dissipate energy. On the other hand, metallic dampers dissipate energy by yielding, whereas tuned mass dampers combat vibrations in structures by adding extra masses to them [7].

The inclusion of dampers in structural designs improves stability, decreases inter-story drift, and increases occupant comfort during earthquakes. Furthermore, energy dissipation systems can often be retrofitted into structures without undergoing extensive modifications since their installation does not affect the structural integrity of the structure. Nevertheless, their incorporation requires thorough dynamic analysis and technical skills.

4.4. Smart Materials and Shape Memory Alloys

The advancement of smart materials has provided new prospects regarding the development of seismic retrofitting technology. Smart materials have the capability to respond to external stimuli such as stress, heat, and deformation, thereby making structures more adaptable and allowing them to recover themselves in the case of an earthquake. Shape Memory Alloys are a type of smart material which has gained immense popularity among engineers dealing with earthquake applications [8].

Shape Memory Alloys are types of metallic materials that have the unique characteristic of being able to return to their initial configuration despite undergoing a large degree of deformation. This property makes SMA materials ideal for providing self-centering characteristics in structures where there will be less residual displacement after the occurrence of an earthquake. Such materials are typically used in braces, dampers, and beam column connections.

Some of the many benefits of using smart materials include increased durability, structural safety, and post-earthquake performance of buildings [9]. Unfortunately, there are few instances of using such materials in seismic retrofitting due to their cost factor.

4.5. Hybrid Retrofitting Techniques

Hybrid retrofitting techniques include the incorporation of two or more of the conventional and advanced strengthening methods with the aim of enhancing structural performance during an earthquake. Through the application of several retrofitting strategies, engineers get the opportunity to solve structural weaknesses concurrently to optimize structural performance.

For instance, FRP wrapping technology and steel bracing systems could be applied together in order to enhance both structural ductility and lateral rigidity. Also, base isolation technology and dampers could be used together to increase the ability of the structure to dissipate energy during an earthquake. Such techniques are very useful when dealing with complicated structures that require more than one technique to provide adequate protection against seismic damage [10].

The main advantage of hybrid retrofitting systems is their flexibility and customization capabilities, which offer users tailor-made protection from earthquake damage. Additionally, these systems significantly enhance structural properties such as strength, rigidity, stability, and durability. On the other hand, hybrid retrofitting systems demand careful planning, extensive analysis, and increased financial input. In spite of these problems, hybrid retrofitting systems are becoming increasingly popular techniques of seismic protection.

Table 2: Summary of Literature on Seismic Retrofitting Approaches for RC Buildings

Author Name	Topic Covered	Research Study Title
Almeida et al. (2025) [11]	Financial incentives and integrated approaches for energy and seismic retrofitting of RC buildings	*Financial Incentives for Energy and Seismic Retrofitting of* RC *Buildings: A Review of an Integrated Approach*
Antoniou (2023) [12]	Conventional and advanced seismic retrofitting techniques for existing RC buildings	*Seismic Retrofit of Existing* RC *Buildings*
Li et al. (2025) [13]	Contemporary seismic enhancement techniques and performance-based retrofitting approaches for RC frame buildings	*Seismic Enhancement Techniques for* RC *Frame Buildings: A Contemporary Review*
Saeed and Hejazi (2025) [14]	Use of ultra-high-performance fiber- RC (UHPFRC) in retrofitting RC structural members	*A Comprehensive Review of Retrofitted* RC *Members Utilizing Ultra-High-Performance Fiber-* RC
Asadimanesh and Jalilifard (2025) [15]	Modern seismic retrofitting methods including FRP systems, smart materials, dampers, and hybrid techniques	*Review of Modern Methods for Seismic Retrofitting of* RC *Structures*

5. CHALLENGES IN SEISMIC RETROFITTING

Although seismic retrofitting significantly improves the earthquake resistance of RC buildings, its implementation is associated with several challenges that affect efficiency, cost, and practical applicability.

- **Economic Constraints:** One of the key problems faced by structural seismic retrofits is their expensive nature, which includes costs involved in the process of assessment, procurement of building materials, labor, and construction work. New retrofit technologies, such as the use of FRP technology, dampers, and base isolation, demand higher expenses due to specialized equipment and experts. Developing nations face limitations in terms of financial means that hinder comprehensive retrofits of old structures.

- **Technical Difficulties:** Another major problem related to retrofits is that of technical difficulty. Many old buildings have no design documents, which makes the job of assessing their structure difficult. Structural irregularities, presence of structural damage, low-quality materials, and improper details for reinforcements make the process even more difficult. Compatibility of these systems with the structure already present must be carefully considered. Otherwise, it will result in bad behavior of the building during earthquakes.
- **Code Compliance Issues:** Retrofitting structures has to adhere to the new building code and earthquake-resistant designs. But, due to the disparity between the codes in old versus new construction, it makes it hard to determine whether the building needs reinforcement and which measures need to be employed. For some areas, a lack of guidelines on retrofits as well as enforcement of earthquake design codes presents problems for retrofitting practices.

Table 3: Challenges in Seismic Retrofitting

Challenge	Description
Economic Constraints	High retrofitting and material costs
Technical Difficulties	Complex assessment and implementation
Code Compliance Issues	Difficulty in meeting updated seismic standards
Construction Limitations	Space and occupancy restrictions
Skilled Labor Requirement	Need for specialized professionals

6. CONCLUSION

Retrofitting is necessary for improving the seismic performance and safety of existing RC structures. The present literature review identified key issues with structural weaknesses, frequent failure modes under earthquakes, and different types of conventional and innovative retrofitting methods, including concrete jacketing, steel bracing, FRP retrofitting, base isolation, and energy dissipation devices. It was concluded from the findings that there are unique merits and drawbacks of each retrofitting approach concerning their capacity, ductility, economy, and applicability. Conventional approaches are cost-effective and practical, while advanced methods can provide better seismic resistance and durability. Future directions of retrofitting were also outlined with an emphasis on sustainable construction materials, artificial intelligence, information technology, and PBSD techniques.

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