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Retrofitting and Strengthening Techniques in Structural Engineering Applications: A Review

Musharaf Farooq[1], Ajay Vikram[2]

[1,2]Rayat Bahra University, Punjab, India

Abstract
Retrofitting techniques gain popularity in construction industry as the concrete and masonry structures face deterioration with aging and severe damage due to cyclones, excessive building loading, Tsunami, earthquakes etc. The retrofitting techniques strengthen the existing structures, minimise their premature collapse and enhance their performance as well as life span. Several retrofitting and its strengthening techniques were discussed by various researchers which helps structural engineers to improve the strength of the structures while designing the mutli-storey buildings and repairing the existing infrastructure. In this work, various retrofitting (global and local) and its strengthening methods such as Jacketing, reinforced polymer, concrete replacement, metal shear Panels (Steel and Aluminum), steel bracing, shape modification of structural elements etc. were reviewed to provide insights to new researchers by presenting limitation of existing techniques and suitable recommendations to improve the reinforced concrete(RC) elements using different retrofitting methods to provide sustainable approach in construction industry with improved cost and energy efficiency. Study concluded that Jacketing and FRP is highly efficient method for strengthen the RC columns.

Keywords: Retrofitting, Reinforced concrete, Rehabilitation, Strengthening, Structural engineering, Structural elements

1. Introduction

The damage of un-reinforced and reinforced concrete structure is one of the global problems faced by structural engineers which cause massive economic losses to nation. However, the construction industry faced several challenges such as appropriate finding, investments which effect the growth of the construction sector. Even, developed nations like US and Uk faced decline of construction sector after the world war-II due to lack of reproduces, labour shortage, skilled labour, low technology, funding, local disputes and other factors like performance, over dependency on neighbouring nations and productivity [1]. Over a time, with the advancement in the technology, construction industry shifted towards more economical and sustainable strategies to repair the existing infrastructure. Rehabilitation is one of the significant strategies which includes concepts of structure retrofitting, strengthening, repair which effected over-loading, aging, natural calamity like Tsunami, cyclone and earthquake [2]. However, structure repair refers to revive the original quality of deteriorated portion to improve the longevity of the existing structure while strengthening refers to interventions in the properties of the RC structure to further enhance the structure against natural aging and disasters like earthquake by improving their machinal and physical characteristics such as compressive strength, distress factors, stiffness, tensile strength and ductility. However, retrofitting techniques include modification in prior structures to improve their capabilities and strength against the damage while offering a cost-effective, environmental friendly and sustainable solutions to construction engineers [3]. In contrast, retrofitting techniques provide potential opportunities for minimising the energy consumption and GHG emissions. It provides potential solutions to achieve sustainability by considering economic and environmental aspects [4]. However, retrofitting methods considers various aspects related to building such as energy sources, geographic location, services systems, age, type, size of the building, etc. as shown in Figure 1.

Figure 1. various aspects of building retrofits

However, Masonry is one of the oldest building techniques. Numerous un-reinforced masonry (URM) structures are historic and incredible works of architecture. They represent a substantial segment of the global building inventory. Numerous buildings have suffered damage due to the cumulative impacts of material deterioration, ageing, overloading, and foundational settlement, rendering them structurally defective or marginally suitable for contemporary usage. In addition to these considerations, changes in use and more rigorous retrofitting and strengthening requirements to upgrade structure properties and design for longer life span [5]. Although structures endure geophysical and anthropogenic pressures throughout their operational lifespan. When the severity of these stresses surpasses the capacity or durability of the structures which cause serious damage to the existing structural elements. The integrity of a structure may diminish owing to the use of inferior materials, the imposition of extra loads from altered functions, or earthquakes for which the building was not initially built. These circumstances need the reinforcement or enhancement of the structure to accommodate the increased load. The traditional methods replace the damaged ones with new which economic loss from operational disruptions and several environmental effect, it is imperative to choose for the restoration of the existing structure with effective technique and retrofitting provides a range of structural enhancement and used throughout the years for various structures. [6]. Nevertheless, various factors contributing to structural degradation includes incidence of natural disasters such as earthquakes, insufficient understanding of critical design requirements in construction, and inadequate supervision quality. These causes result in structurally insufficient strength. Specifically, structural overloading results in significant deformations and corrosion that need substantial care. In many instances, even recently constructed structures need repair and reinforcement to rectify flaws arising from design or construction errors. The restoration of concrete structures or their components has always posed significant challenges, sometimes requiring lengthy interventions for effective solutions. Specialised solutions for fortification, reinforcement, and restoration are required for bridges, industrial buildings, urban transportation infrastructures, maritime constructions, and earth-retention structures need maintenance or enhancement [7]. Throughout their service life, RC buildings must undergo various changes and enhancements for several reasons. To mitigate these consequences on RC buildings retrofitting, or strengthening are often necessary actions in the building industry today.

In this scenario, there are two potential solutions: replacement or retrofitting. The replacement of whole buildings incurs drawbacks such as elevated labour and material prices. Therefore, it is desired, the structure may be repaired or upgraded by retrofitting, provided it is attainable and practical. The main objectives of this review papers are: (1) To study the different retrofitting techniques used in RC structural applications, (2) To study the various strengthen methods used to improve the strength of the structural elements (beam, column, slap etc.). Present study adds significant contribution in the knowledge of structural engineers by proving insights of existing retrofitting and its strengthening methods. This work reviewed the existing research retrofitting and strengthening used in structural applications to provide in-depth understanding related to the existing retrofitting techniques which helps to implement sustainable strategies in building repair and designing. The review examines the methods, findings and limitations of existing methods and highlight the merits of using retrofitting methods in RC structures. This review also highlights key areas requiring further academic attention to advance and enrich the present knowledge in the field of structural engineering applications.

Further, this work is organised as follows: Section 2 provides related work. In section 3 includes discussion and main findings, Section 4 challenges and limitations and Section 5 conclusion.

2. Related work

Retrofitting involves the reinforcement of existing structures or structural parts to improve its performance by the incorporation of new technologies, features, and elements. Retrofitting may often be categorized into two classifications such as local and global [4], [7], [8]. [9]. Several studies have been analysed to understand the role of retrofitting technique in structural engineering applications.

Pohoryles et al. (2024) [9] assessed the efficacy of an innovative capacity-design retrofit aimed at enhancing the local and global performance of existing RC structures by the use of FRP. The methodology was evaluated on beam-column connections and is now used at the structural level. The suggested approach showed high cost-benefit and seismicity advanctages.

Almeida et al. (2024) [10] analysed the integrated retrofitting of existing RC structures. The retrofitting approach is essential for improving efficiency and resistance to severe events. A survey of contemporary worldwide policies and incentive programs concerning independently analysed. Finding showed high sustainable effect of building interventions and minimise energy consumption.

Rodrigues et al. (2024) [11] experimentally analysed the Beam-to-column linkages of existing RC buildings. Nonetheless, they also provide a source of considerable destruction, as shown in recent seismic events. Various designs are prevalent, including the use of a dowel, neoprene, or simply supposing a concrete-to-concrete contact. Both have limited deformation and strength capability, demonstrating considerable susceptibility to seismic forces. In light of this motive, a new low-cost and easily implementable retrofit connection is presented to mitigate this risk. The experimental testing demonstrated the efficacy of the suggested retrofit solution, highlighting its significance in frictional connections for the regulation of horizontal displacements.

Shahedan et al. (2024) [12] investigated the prospective use of fly ash geopolymer concrete in the repair of maritime infrastructure. The chemical composition and physical properties of fly ash provide resilience and sustainability in the restoration of maritime infrastructure, assuring long-term durability against corrosion. Further, research examines the main types of damage and causes of concrete deterioration in coastal environments. Furthermore, it examines contemporary methods for the repair and retrofitting of concrete in maritime settings, providing a robust solution for the development of durable marine constructions.

Avulapalle et al. (2023) [13] investigated the seismic performance of a five-storey RC framed structure using static non-linear pushover analysis. The pushover study of a RC frame is performed to assess its effects, outcomes indicated that shear walls enhance initial stiffness and base shears by 2.6% and 19% respectively, in comparison to a bare frame. Retrofitting using diagonal bracings increases base shear by a factor of 7.7.

Attia et al. (2023) [14] tested a series of RC beams in three-point bending to assess the efficacy of different strengthening strategies in enhancing the beams' flexural capacity. The suggest approaches used GFRP laminates, NSM systems, and U-jacket applications. The experimental investigation evaluated several strengthening techniques to understand the flexural behaviour of RC beams. Findings showed that the B3-St. Plate-NSM sample exhibits enhanced stiffness, resulting in a 21.12% reduction in deflection at peak load compared to the control sample. The results derived from computational finite element models demonstrate strong concordance with the experimental findings.

Al-Zu'bi et al. (2023) [15] Investigated the effects of flexural retrofitting using NSM-FRP technology. It contrasted NE-only retrofitting with FRP and GFRP reinforcing bars. The findings indicated that NE-only retrofitting enhanced capacity by 38%, while FRP reinforcement augmented both capacity and ductility twofold. Placing GFRP bars near the groove's edge had a little effect on capacity but reduced ductility by 24%.

Gorji Azandariani et al. (2023) [16] aimed to improve seismic vulnerability and retrofitting of RC frames using steel strongback bracing system. The research designs RCMFs for 5-, 10-, and 15-story structures. Results found robust bracing system significantly enhances structural performance and reduces drift ratio between floors.

Blasi et al. (2023) [17] investigated the impact of in-plane shear retrofitting of infills on the seismic performance of reinforced concrete structures. The suggested outcomes significantly improved the vulnerability and structural designs based on seismic standards.

Gusella et al. (2023) [18] introduced novel to assess the maximum load. Throughout the structure's lifespan, the design loads may alter due to a change in use purpose. In standard practice, every design alteration of existing structures that alters the number of loads necessitates an assessment of the load-bearing capability of the structure. A nonlinear analysis that accounts for the rotation capacity of key sections until structural breakdown may be more beneficial than a basic elastic analysis. A retrofitting design technique is provided to determine appropriate structural reinforcement for important locations, using derived equations. The method's correctness is verified by comparing it with numerical results. The approach serves as a valuable instrument for engineers to locally enhance existing reinforced concrete structures.

Haruna et al. (2023) [19] developed NC-PUG composite and beam specimens to find the performance of retrofitting strategy. The composite specimens underwent dynamic and flexural loading tests, with various PUG overlay thicknesses and designs used to enhance impact and flexural performance. The results showed that the composite U-shaped specimens had significantly enhanced.

Ro et al. (2023) [20] analysed seismic performance by mitigating early brace buckling. It incorporates a sliding groove, facilitating steel link movement. Experimental findings show reduced sliding slot lengths postpone shear fractures and concrete spalling, with retrofitted specimens showing a load capacity 1.5 times higher. The system's feasibility for forecasting hysteretic behavior has been validated.

Lee et al. (2022) [21] developed stiff-type polyurethane (STPU) by altering FTPU's prepolymer/hardener ratio. Testing revealed superior tensile strength and reduced elongation compared to FTPU. STPU also showed exceptional mechanical and durability characteristics. Concrete specimens reinforced with STPU showed higher load ratios than unreinforced ones, making it suitable for retrofitting and strengthening concrete elements to withstand seismic and high loads.

Joseph et al. (2022) [22] explored the use of natural fibres and epoxy binders to improve ductility in composites. It found that MWCNT, when added to epoxy nano and multiscale composites, increases tensile and fracture capabilities up to 1 wt.%. The study also found that MWCNT-incorporated FRP improved concrete's load-carrying ability, energy absorption, and ductility. The study also found that epoxy modification can improve natural FRP confinement strength.

3. Discussion

The structural engineers are responsible for the building maintenance and often do repairs without sufficient comprehension of the underlying issues causing the faults. The selected repair technique involves replacing damaged materials without addressing the underlying issues. Numerous structural engineers inadvertently focus on alleviating signs rather than addressing the underlying cause-and-effect relationships. This strategy may provide a prompt solution with little disruption to the residents [23]. However, there exists a significant likelihood that the underlying source and cause of the discomfort remain unaddressed, prolonging issues even after surface remedies have been implemented. As structural problems are addressed in this manner, they stay concealed behind finishes, creating a deceptive feeling of security for the residents and allowing the issue to go unaddressed. A logical method for any repair and rehabilitation task is to evaluate both the root of the issue and its symptoms concurrently. However, strengthening the existing structure are very important to avoid the mishappening due to any structural collapse. As the masonry constructions were constructed in the past when adequate theories and understanding were lacking. Individuals often constructed their homes based on the prevailing knowledge and expertise. Numerous existing structures do not comply with standard regulation, therefore, retrofitting and its strengthening techniques gained popularity [4], [6].

The process of retrofitting follows some steps as mentioned in flowchart (Figure 2).

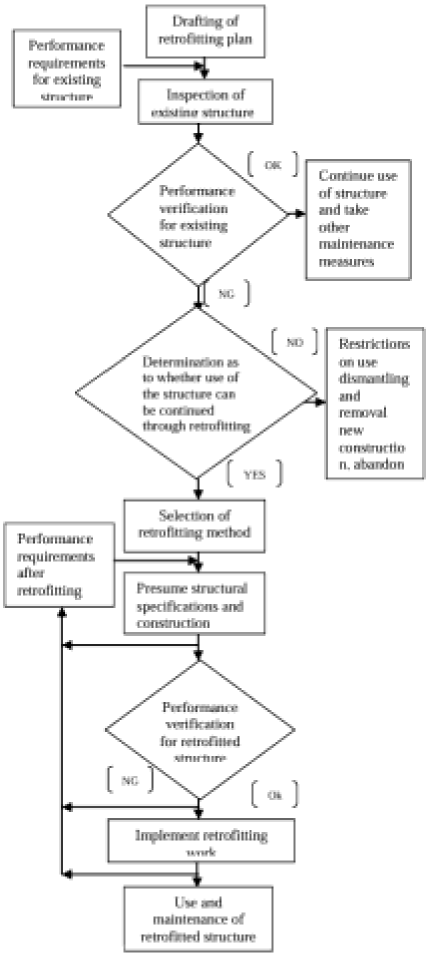

Figure 2. Process of retrofitting analysis

(1) Determine the performance criteria for the current structure designated for retrofitting and formulate a comprehensive plan including inspection, selection of retrofitting techniques, design of the retrofitting structure, and execution of retrofitting activities, (2) Examine the current structure designated for retrofitting. Additionally, (3) assess the structural performance based on the inspection findings and confirm compliance with performance criteria. (4) If the structure fails to meet performance criteria and retrofitting is preferred for continuing use, begin with the construction of the retrofitting design. The Select a suitable retrofitting technique and determine the materials, structural requirements, and construction methodology to be used, (6) Assess the structural performance post-retrofitting and confirm compliance with performance criteria, (7) If it is ascertained that the retrofitting structure can meet performance criteria with the chosen retrofitting and strengthening techniques, proceed with the retrofitting activity.

Some important retrofitting and strengthening methods are discussed as follows:

A. Concrete replacement

Concrete replacement is a cost-effective method to remove loose debris as shown in Figure 3. If minor buckling occurs, reinforcing steel bars must be rectified. The new concrete is blended and injected, and the upper section may be completed with high-strength epoxy grout. However, the repair of the shear structure disrupts the building's functionality and makes it unsuitable for use if accessibility is required. [7], [23].

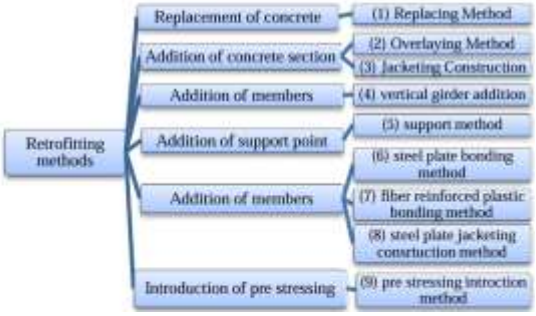

Figure 3. Retrofitting methods

B. Concrete jacketing

The approach involves adding more concrete to the existing web to improve structural dimensions and enhance the structure's strength and ductility as shown in Figure 4. This can be done using vertical and horizontal bars or diagonal bars, and the reinforcement must be secured to the structural basis. Anchoring involves inserting reinforcement into holes drilled in the foundation, grouted with epoxy, and cast with revised dimensions. Two reinforced concrete buildings were tested, showing enhanced strength and deformation capacity despite initial stiffness being over 50% of the original constructions. Reinforcing the foundation may be necessary to accommodate the building's weight and anticipated increase in lateral load [7], [24].

Figure 4. RC jacketing

C. Steel material based retrofitting and strengthening

Steel is the predominant material used for the retrofitting of reinforced concrete buildings. Steel sections were used to upgrade reinforced concrete shear structures using various techniques to improve distinct response metrics as shown in Figure 5. The reduced additional weight on the structure, in contrast to concrete jacketing, together with little interruption to building occupants, are benefits of using steel retrofitting techniques. Conversely, the susceptibility of steel to corrosion, the need for scaffolding, and the challenges associated with manoeuvring large steel plates on-site are issues that emerge while retrofitting with steel [2], [7], [25].

Figure 5. Steel plate bonding

D. Steel plates based retrofitting and strengthening

Steel plates are used to augment the strength, stiffness, ductility, or a mixture of these attributes in constructions as shown in Figure 6. The impact of rehabilitation strategies for retrofitting shear structures with steel plates showed that external steel plates may augment structural stiffness without modifying strength by adhering them throughout the length of the structure at the margins. The plates or bars may be affixed to slabs at varying structural elevations and encased in ductile material for enhanced corrosion and fire resistance. The IDM permits the plates to function alone after surpassing a specified displacement threshold [7], [24], [26].

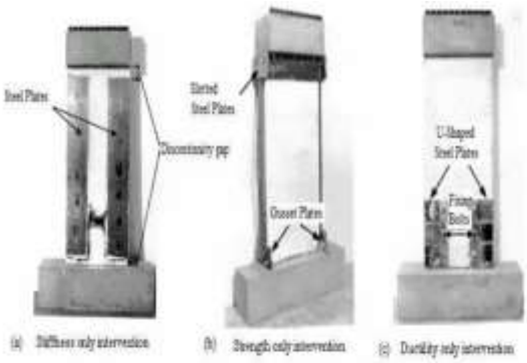

Figure 6. Retrofitting by steel plates

The retrofitting technique involves using U-shaped external confining steel plates to enhance structural ductility and stiffness without compaction. These plates are adhered to the structure with epoxy and secured using pre-stressed bolts. This enhances the structure's energy dissipation capacity, improving its seismic performance.

E. Steel bracing based retrofitting and strengthening

Steel bracings employed for rehabilitation of supposedly ductile moment-resisting frame constructions as shown in Figure 7. It may provide the requisite strength, stiffness, and ductility for the construction, contingent upon careful consideration of their connections to the existing framework.

Figure 7. Steel bracing

Steel bracings can enhance seismic performance in reinforced concrete shear constructions by reducing buckling length and increasing the capacity of the bracing member. This is compared to retrofitting moment-resisting frames, which are influenced by compressed bracing member buckling. Vertical steel strips are recommended for diagonal bracings, as diagonal forces increase overall forces on the structure. Vertical strips at the ends counteract some of these forces with concrete [7], [24], [26], [27].

F. composite materials based retrofitting and strengthening

FRP composite materials are popular for retrofitting existing buildings due to their strength, lightweight nature, and ease of application. They can be used in laminates, sheets, or rods, and can be pre-stressed for enhanced efficiency. This solution is particularly useful when complete evacuation is unfeasible, providing necessary strength without disrupting occupancy [1], [6], [15].

4. Challenges and limitation

It is observed from the various existing studies, the existing structure have various challenges and limitations as shown in Figure 8. Buckling and bulging are prevalent phenomena associated with the collapse of RC columns [20]. In a flexural member such as a beam bending and deflection are prevalent phenomena associated with the collapse of RC columns [17], [18]. The joint has always been regarded as the weakest component of the construction. Inadequate attention to the beam-column or slab-column connection during both the design and construction phases may result in early deterioration of the structure [10], [11]. Factors contributing to the deterioration of the RC element include inadequate longitudinal reinforcement and insufficient cover, low ductility, inadequately designed for earthquake loads, unforeseen overloading, horizontal ties or stirrups are absent at the mandated intervals, inferior grade of materials used and quality of craftsmanship is substandard [14], [15]. Neglect of vertical or diagonal fissures, concrete spalling, reinforcing corrosion, surface moisture, unforeseen impact loads, and vibration, among others [8], [9]. Inadequate ductile detailing, substandard concreting at the junction, and poor maintenance, among other factors [14], [18], [21], [22]. Therefore, advance retrofitting and its strengthening techniques highly suitable to mitigates these challenges and limitation of the existing building and provide sustainable solutions which are cost & environment friendly.

Figure 8. Reasons of early deterioration of structures

5. Conclusion

The study reviewed several retrofitting and its strengthening techniques. The study found that retrofitting procedures improve structural performance, particularly in areas susceptible to seismic activity. These results help the construction experts while decision-making and designing new engineering projects to alleviate the effects of earthquakes on RC structures and infrastructure. Further, study found that the selection of most appropriate strengthening technique is significantly important for distressed RC beams to improve the overall performance. However, the requirements of the construction sector for various strengthening techniques depend on factors such as the availability of local materials, total cost, skilled labour, sufficient load-bearing capacity and serviceability post-strengthening, as well as the failure characteristics of the strengthening methods. It is acknowledged that to modify the practical usefulness of a certain building, an alternative method would be employing retrofitting for its renovation. The retrofitting technique is time, energy and cost effective and highly crucial for construction sector to prioritises sustainable development for future projects. In addition, FRP and concrete jacketing has several benefits in retrofitting material compared to traditional materials and future researchers should focus on the new composite materials to enhance the properties of the RC structural elements and made the retrofitting technique more useful and cost-effective, sustainable, eco-friendly and customer-friendly.

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