A COMPREHENSIVE REVIEW OF RETROFITTING TECHNIQUES FOR EXISTING REINFORCED CONCRETE STRUCTURES

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Abstract

Modern reinforced concrete (RC) structures tend to undergo aging, deterioration, higher service load, exposure, and seismic demands exceeding their original design capabilities. Retrofitting is one of the most effective ways to increase the capacity of a structure and improve its durability, seismicity, and lifespan. The present paper considers existing technologies of strengthening including concrete/steel jacketing, FRP systems, steel plates, and bracing, external/near surface bonding of reinforcing bars, and modern material technologies including ultra-high-performance concrete, textile-reinforced mortar, shape memory alloys, and nanomaterials. These technologies are compared in terms of strength, stiffness, ductility, seismic response, durability, cost-effectiveness, ease of construction, and environmental impact. Conventional technologies offer a high degree of reinforcement while FRP technology is lighter and faster. Modern materials enhance durability and seismic response. In general, retrofit choice depends on the existing structural weaknesses, load conditions, environmental effects, construction aspects, costs, and service life of a building.

Keywords: *Reinforced concrete, structural retrofitting, structural strengthening, concrete jacketing, steel jacketing, FRP, CFRP, GFRP, TRM, UHPC, seismic strengthening, durability.*

1. INTRODUCTION

Reinforced concrete (RC) is extensively used in structures due to high strength, flexibility in use, and easy construction process. Nevertheless, ageing, corrosion, cracking, exposure to the environment, fatigue, seismic actions, changes in loadings may decrease the strength, durability, and serviceability of existing structures [1]. Structures that initially had sufficient capacity now might not comply with contemporary criteria of safety and efficiency.

Retrofitting is an effective solution that allows to restore the structural capacity of a building, extend the service life, and enhance its ability to resist further loadings [2]. Retrofitting can save money and reduce environmental pollution. Retrofitting is needed because of poor design, improper construction, deterioration of a structure, additional loads, outdated seismic regulations, etc [3]. Depending on what deficiency the structure has, the strengthening can relate to flexural capacity, shear capacity, confinement, ductility, crack resistance, or seismic performance.

The selection of appropriate retrofitting method is determined by the state of a structure, necessary performance of a structure, environmental exposure, and other practical considerations. Traditional retrofitting methods like concrete and steel jacketing are still extensively used, while FRP systems allow using more efficient light-weight solutions. The advanced methods based on TRM, UHPC, and shape memory alloys provide even more possibilities for improvement of the performance of existing RC structures [4].

1.1 Causes of Deterioration and Structural Deficiencies

Degradation of current reinforced concrete buildings is due to multiple reasons such as environmental, mechanical, materials related, construction, and operational causes [5]. Corrosion of reinforcement due to carbonation and chlorides can result in cracks, delaminations, spalling, loss of reinforcement area and bonding between steel and concrete [6]. Exposure of the building to the environment like moisture, chemicals, thermal changes, and marine environment can cause further deterioration of concrete and loss of durability [7].

Mechanical factors including overloading, fatigue, impacts, change in structural usage, and increased traffic or occupancy loads can impose additional loads on the structure which exceed the design criteria [8]. Also, lack of appropriate reinforcement detailing, poor quality concrete, construction deficiencies, lack of confinement, and old design criteria can be causes of the structural deficiencies [9]. Seismic actions can lead to concrete crushing, reinforcement buckling, large drift, shear failures, and beam column joints failures.

Thus, an assessment of the current structure needs to be done before the retrofitting method is selected to ensure that the selected retrofit is appropriate for the structural deficiency [10].

1.2 Objectives of the Study

The specific objectives are:

1. To review the major conventional, composite, and advanced techniques used for retrofitting existing reinforced concrete structures.
2. To evaluate the effectiveness of different retrofitting techniques in improving load-carrying capacity, strength, stiffness, ductility, seismic performance, and durability.
3. To compare the reviewed retrofitting techniques based on cost, constructability, material compatibility, and environmental considerations.
4. To examine the major challenges and limitations associated with the practical application of existing and emerging retrofitting techniques.

2. RETROFITTING TECHNIQUES FOR REINFORCED CONCRETE STRUCTURES

The retrofitting of RC structures involves traditional reinforcement techniques, FRP-based techniques, reinforcement using steel, externally applied reinforcement, and advanced material techniques [11]. The choice of a particular method depends upon the nature of the problem of structural deficiency, desired capacity, environmental effects, space availability, economy, and construction considerations [12].

2.1 Conventional Retrofitting Techniques

- **Concrete jacketing:** Increases the cross-sectional area and reinforcement of existing members, improving axial and flexural capacity, stiffness, ductility, and confinement. Its main limitations are increased member dimensions, additional dead load, labour requirements, and the need for effective bonding between old and new concrete.

- **Steel jacketing:** Uses steel plates, angles, or channels to provide additional strength, confinement, and ductility with relatively little increase in member dimensions. However, proper load transfer, grouting, corrosion protection, and fire protection are essential.

- **Section enlargement:** Increases the dimensions of beams, columns, walls, or foundations using additional concrete and reinforcement. It can improve flexural, shear, axial, or bearing capacity but increases member size and requires consideration of bonding, shrinkage, creep, and stiffness differences.

2.2 Fibre-Reinforced Polymer (FRP) Techniques

Advantages of FRP Strengthening Systems include light weight and quick application, high strength to weight ratio, and corrosion resistance as well as small change in dimensions of the structural elements [13]. CFRP has high strength and stiffness and is often used for strengthening purposes due to its high strength and stiffness. GFRP is characterized by high corrosion resistance and represents an economical material in the cases where extremely high stiffness is not necessary. AFRP is characterized by high tensile strength, light weight, and good impact resistance [14].

2.3 Steel Plate and Steel Bracing Techniques

The steel plates give significant tensile and reinforcing properties to beams, slabs, columns, and walls, but steel bracing helps in providing lateral reinforcement especially in seismic retrofitting. But the main disadvantage of these techniques is that they are heavy compared to FRP, and special installation techniques have to be used along with rust proofing.

2.4 Externally Bonded and Near-Surface Mounted Reinforcement

Extrinsically bonded techniques involve direct bonding of FRP or steel strengthening material to the concrete substrate, while near-surface mounted technique involves placing the reinforcement in grooves in the concrete cover layer. These techniques offer good strengthening capability while making little changes to the structure. They rely heavily on the condition of the substrate, surface preparation, and quality of adhesion.

2.5 Advanced Materials and Emerging Retrofitting Techniques

There are several advanced materials that can be used to enhance the performance of the existing RC structures further. FRCs and UHPC/UHPFRCs are high-strength, low-permeable, and crack-resistant materials despite being expensive and difficult to install in addition to having bonding issues with other materials [15]. TRMs are inorganic alternatives to FRPs that are made of polymers [16]. These materials can increase strength and stiffness, reduce cracking, and improve the seismic performance of the RC structures depending on the interaction between the textiles and matrix and proper bonding of the materials. SMAs have good potential for self-centering and residual-deformation reduction during earthquakes, but they are too expensive and lack standardization [17].

Table 1. Summary of Selected Literature on Retrofitting Techniques for Existing Reinforced Concrete Structures

Author(s) and Year	Topic Covered	Title of the Study
Valente & Milani (2018) [18]	Alternative retrofitting strategies for preventing failure of under-designed RC frames	*Alternative retrofitting strategies to prevent the failure of an under-designed reinforced concrete frame*
Almeida et al. (2017) [19]	Seismic retrofitting of RC buildings using Buckling Restrained Braces (BRBs)	*Seismic retrofit of RC building structures with Buckling Restrained Braces*
Di Cesare & Ponzo (2017) [20]	Seismic retrofit using hysteretic bracing systems, including design procedures and behaviour factors	*Seismic retrofit of reinforced concrete frame buildings with hysteretic bracing systems: design procedure and behaviour factor*
Eldin et al. (2020) [21]	Seismic retrofit using self-centering precast concrete frames and friction dampers	*Seismic retrofit of RC buildings using self-centering PC frames with friction-dampers*
Pohoryles & Bournas (2020) [22]	Seismic retrofitting of infilled RC frames using Textile-Reinforced Mortar (TRM) and analytical modelling	*Seismic retrofit of infilled RC frames with textile reinforced mortars: State-of-the-art review and analytical modelling*

3. PERFORMANCE EVALUATION AND COMPARATIVE ASSESSMENT OF RETROFITTING TECHNIQUES

The efficiency of a retrofitting system needs to be measured not only in terms of the increment in the strength of the structure but also in terms of how it affects its stiffness, ductility, behavior in earthquakes, durability, economy, constructability, and performance regarding the environment [23]. Because each system brings different combinations of advantages to the table, its choice should be made according to the deficiency and requirements of the existing structure.

3.1 Enhancement of Load-Carrying Capacity

The primary goal of retrofitting is usually to increase the capacity of the structure. In terms of increasing the load-bearing capacity, concrete and steel jacketing can be used effectively to achieve this objective. FRP systems have the capacity to increase tensile strength while providing confinement with very little weight added to the structure. In addition, UHPC overlay and TRM system can help in increasing the flexural and shear capacity of beams and slabs. Thus, in choosing an appropriate system, one needs to take into account the nature of the structural problem that exists in the building.

3.2 Improvement in Strength, Stiffness and Ductility

Retrofitting systems affect strength, stiffness, and ductility differently. The system of concrete jacketing may greatly enhance strength and stiffness due to its effect on increasing the cross-sectional area of the structure [24,25]. Strengthening and stiffness of the structure are achieved with steel plates and bracing. The FRP system enhances the strength of flexure and shear with no added mass but greater strength is not necessarily associated with greater ductility. Deformation capability may be improved by confinement technique, while TRM improves stiffness and cracking behavior. Shape memory alloys have some added advantages because of their properties of superelasticity and self-centering.

3.3 Seismic Performance of Retrofitted RC Structures

Seismic evaluation of the structure must include the assessment of strength, stiffness, ductility, energy dissipation, drifts, failure modes, and residual deformations. Jacketing with concrete and steel will enhance the column confinement and lateral stiffness; jacketing with FRP may reduce the chance of shear and compressive failures. The use of steel bracing in RC structures may greatly enhance the lateral stiffness of such structures; however, it may affect the seismic load distribution in the building as well. TRM gives an option for strengthening RC members and infilled frames. SMA materials may provide self-centering ability and reduced residual deformations [26]. Thus, the seismic retrofitting must be carried out considering the whole structural system as there is no need to strengthen one component to overload others.

3.4 Durability and Long-Term Performance

Durability is important in the sense that the main reason for carrying out retrofits is to increase the service life of the existing structures. The FRP system is relatively durable and has good corrosion resistance, but the material of which the FRP system is made can be influenced by temperature changes, moisture, ultraviolet rays, among other environmental factors [27,28]. In case of steel, there is need for adequate corrosion protection, while in the case of concrete jacketing, it can be influenced by cracking, carbonation, and corrosion of the reinforcing bars. TRM has the possibility of offering long-term durability due to its inorganic matrix, while UHPC has low permeability and high durability [29].

3.5 Cost, Constructability and Environmental Considerations

Economic evaluation of retrofitting should cover material and labor cost, equipment, preparation of surface, installation time, maintenance, inspection, disruption, and anticipated lifespan of the system [30]. Concrete Jacketing can be cost-effective when standard construction services exist, provided that there is enough space and labor for its construction. Steel Jacketing involves fastening of the structure but involves prefabrication, installation, connections, and corrosion resistance measures [31,32]. FRP systems are light weight and easy to install, but TRM and UHPC provide excellent performance. In terms of environmental impact, retrofitting helps in minimizing the necessity of demolition and reconstruction of the structure and saves materials and other resources [33]. Therefore, life-cycle analysis can give a much more thorough approach for comparison of retrofitting technologies from the perspectives of economics and environment.

4. CHALLENGES AND LIMITATIONS

There are certain problems associated with the use of retrofitting technology for reinforcement of already built reinforced concrete structures [34,35]. The ability of the strengthening technique depends not only on the strength characteristics but also on the state of the structure, compatibility of the material of the structure with the newly introduced one, durability and constructability [36]. Moreover, there is a set of disadvantages associated with each method, and their presence makes the use of the retrofitting technique undesirable in some structural and environmental conditions.

Challenges

- **Technical and design challenges:** Existing structures often have uncertain material properties, reinforcement details, hidden deterioration, or incomplete drawings. Strengthening one member may also alter the load path and increase demands on adjacent members, joints, and foundations, particularly under seismic loading [37].
- **Material compatibility and bonding:** Differences between existing concrete and retrofit materials in terms of shrinkage, creep, thermal behaviour, and stiffness can affect composite action. Proper surface preparation, bonding, anchorage, curing, and quality control are therefore essential for effective stress transfer.
- **Durability and maintenance:** FRP, steel, cementitious, and advanced strengthening systems may experience different forms of environmental degradation. Corrosion, cracking, moisture exposure, high temperatures, and interface deterioration can affect long-term performance, while advanced materials such as SMA and nanomaterial-based systems still require more long-term field evidence [38].
- **Cost and constructability:** Advanced retrofit techniques may require specialized materials, equipment, and skilled labour, increasing implementation costs. Limited access, operational constraints, and the need to minimize structural dimensions can also influence technique selection; therefore, the most suitable method should balance structural effectiveness, durability, cost, and ease of installation.

Limitations of Existing Retrofitting Techniques

- **Concrete jacketing:** Provides substantial capacity enhancement but increases member dimensions, dead load, and construction requirements [39.
- **Steel jacketing:** Offers high strength and confinement with relatively limited dimensional increase, but requires corrosion protection and careful load transfer.
- **FRP systems:** Provide lightweight and efficient strengthening but are sensitive to bond quality, substrate condition, fire, and environmental exposure.

- **Steel plates and bracing:** Provide high strengthening capacity but add weight and may require complex installation, connections, and corrosion protection.
- **Externally bonded and NSM systems:** Offer effective strengthening with limited structural modification, but their performance depends strongly on surface preparation, anchorage, and bonding quality.
- **TRM and UHPC:** Provide improved durability and high-performance strengthening, but may involve higher material costs and specialized application procedures.
- **Shape memory alloys (SMA):** Offer promising self-centering and seismic performance, but their high cost, limited standardization, and specialized installation restrict wider application [40].
- **Nanomaterial-based systems:** Show potential for improving mechanical and durability properties, but large-scale application and long-term performance remain limited.

5. CONCLUSIONS

The strengthening of existing RC structures is important from the point of view of ensuring safety, extending the service life of the structure, and making the structure more resilient and sustainable. The conventional methods like concrete jacketing and steel jacketing continue being efficient for gaining significant increases in strength and confinement of the structure, while the FRP, externally bonded, and near-surface mounted systems are efficient, lightweight, and cause minimal changes in the structure. The advanced materials like UHPC, UHPFRC, and TRM increase the efficiency of the structure due to their increased durability, strength, and compatibility, while shape memory alloys have good prospects due to their ability to make the structure self-centering and increase seismic performance. At the same time, there are different limitations in all types of methods because of the issues of bonding, durability, cost, constructability, fire resistance, and long-term performance. Thus, there is no universally applicable method of reinforcing the existing RC structure, and the selection should be based on the structural condition, necessary strength and ductility, seismic demands, environmental conditions, cost, and service life.

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