



REVIEW

Jacketing Techniques for Repair and Rehabilitation of RC Column Structures: A Review

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ABSTRACT: This review presents a comprehensive evaluation of jacketing techniques used in reinforced concrete (RC) columns repair and rehabilitation. It critically examines reinforced concrete jacketing, steel jacketing, fiber-reinforced polymer (FRP) jacketing, fiber-reinforced cementitious matrix (FRCM) jacketing, and ferrocement jacketing based on recent experimental, analytical, and numerical studies. The paper discusses material characteristics, application methods, and performance under different loading and environmental conditions. Special focus is placed on advancements such as hybrid FRP systems and high-performance composites, which aim to overcome limitations of traditional jacketing techniques. The review also explores non-destructive testing methods for assessing retrofitted structures. Comparative analysis of different techniques is presented with respect to load-carrying capacity, ductility, constructability, durability, and cost. Findings indicate that while all jacketing methods can improve structural performance, hybrid systems and FRCM offer promising balance between strength enhancement and constructability. This work provides practical recommendations for selecting jacketing systems in various contexts and identifies key research gaps.

KEYWORDS: FRP; FRCM; jacketing; retrofitting of RC column; cementitious composite; seismic strengthening

1 Introduction

1.1 Background and Significance of Repair and Rehabilitation of RC Column Structures

The repair and rehabilitation of existing deteriorated concrete structures have become paramount in modern civil infrastructure management, particularly in earthquake-prone regions. Expenditure allocated to repairing damaged structures now surpasses that designated for constructing new ones [1]. The concrete structure integrity and stability are jeopardized since it sustains damage, whether from seismic activity, impact, or excessive loads. Based on recent studies, most of structural failures have been recording on the account of seismic activities as it increases the shear force beyond the capacity of the RC columns with inadequate ductility, which make retrofitting techniques critical for maintaining building integrity and safety [2]. Several reports globally have shown that higher repair costs are associated with aging structures than that of new construction projects. Especially, as developing countries intensify rapid urbanization, so also there is the drive for structural retrofitting. It is unfeasible to demolish existing structures and reconstruct new ones. This highlights the necessity of using advanced jacketing techniques, which are

not only cost-effective but also practical for on-site implementation, thus minimizing disruptions to the building's operation [3].

Urgent action is needed to repair the damage and avert the potential collapse of the existing structure. Numerous approaches exist to tackle the damage, including downgrading the structural function, demolition, partial or complete reconstruction of the structure, or employing rapid repair techniques to halt further deterioration [4]. Considering time and economic constraints, immediate repair of the damaged section can be the most preferred option. Previous research has demonstrated the effectiveness of externally confining damaged concrete in reinstating its original load-bearing capacity. Furthermore, it has been noted that such confinement can also enhance the ductility of impaired concrete elements [1,4–6].

1.2 Overview of Jacketing Techniques and Their Importance in Structural Restoration

Retrofitting of RC columns usually follow one of the three following techniques include reinforced concrete jacketing, FRP wrapping, and external steel jacketing, as shown in Fig. 1. Reinforced concrete jacketing method can increase the overall structural capacities (axial load, shear strength, flexural strength, and deformation capacity); however, it typically requires a jacket thickness of more than 70–100 mm [7]. This results in a reduction of architectural space and an increase in the overall mass of the structure. In contrast, the other techniques (FRP wrapping and steel jacketing) offer several advantages over reinforced concrete jacketing, including reduction on thickness, lower weight, and improved constructability. However, their strengthening effects are limited to enhance shear strength and deformation capacity. While axial load capacity can be improved through confinement, the enhancement is relatively limited. Additionally, considerations such as fire resistance and corrosion protection are critical when selecting these methods. A technique known as shape modification—where a square column is transformed into a circular one before applying FRP wrapping—has been shown to enhance confinement effectiveness. This approach was explored initially by Priestley and Seible [8]. Consequently, there are two main methods to strengthen a square RC column using FRP wrapping. The first, more conventional approach involves rounding the corners of the column before applying the FRP wrap. The second, newly proposed technique strengthens the existing square column by enclosing it with four precast segmental circular concrete covers, which are then wrapped with FRP. Since the FRP wrapping technique is most suitable for circular columns, it eliminates the need for on-site corner rounding. This reduction in on-site labor makes the process more efficient in real-world applications. However, casting the segmental covers is constructed in a factory which may reduce the labor cost and increase the quality control.

External steel jacketing is a structural reinforcement technique in which steel plates or prefabricated steel jackets are installed around existing structural elements such as columns, beams, or piers to enhance their strength, stiffness, and ductility. This method is widely used in the retrofitting and rehabilitation of structures, particularly in seismic regions or for elements suffering from concrete deterioration or reinforcement corrosion. Steel jacketing also helps in corrosion mitigation by acting as a physical barrier by limiting the ingress the corrosion agents such as moisture, chlorides, and oxygen into the concrete, which will result in slowing the corrosion of the embedded reinforcement. In addition, the steel jacketing provides a confinement that reduces crack widths and crack propagation in the concrete, which will restrict the pathways for corrosive agent. When combining the steel jacketing with proper surface treatment, protective coatings, or corrosion-resistant steel (e.g., stainless steel), steel jacketing can significantly enhance the service life and durability of corrosion-damaged structural elements [9].

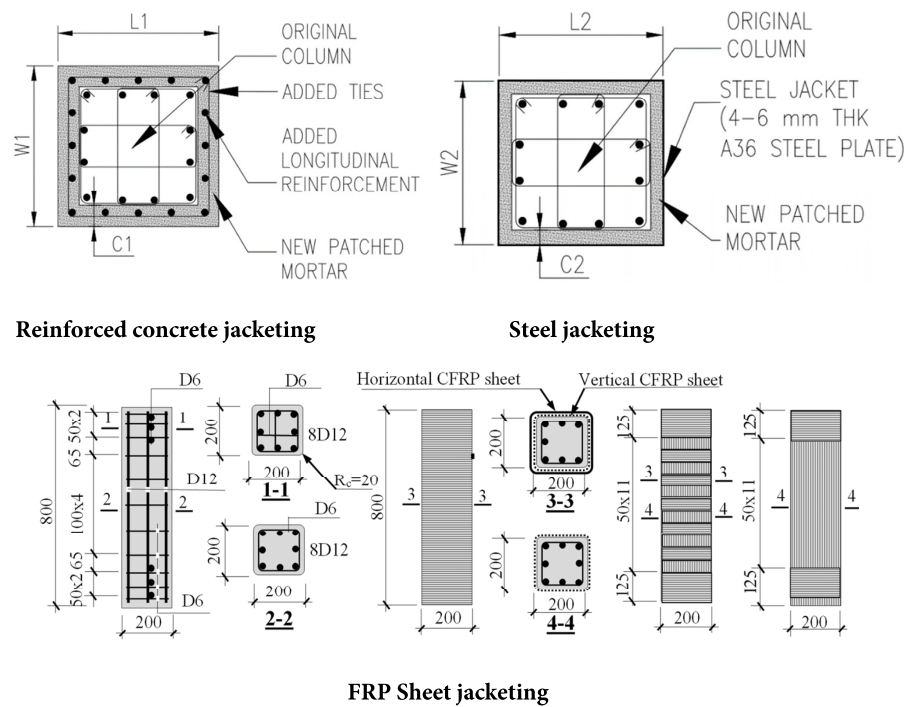


Figure 1: Illustration of jacketing techniques [9,10]. Adapted with permission from Refs. [9,10]. Copyright ©2022, MDPI.

1.3 Objective of the Present Review Paper

This review aims to give a summary and comparison of the main key findings from recent research on retrofitting columns using different jacketing methods such as, reinforced concrete jacketing, external steel jacketing, FRP jacketing, fiber reinforced cementitious matrix (FRCM), and ECC jacketing, steel jacketing, hybrid jacketing, seismic retrofit of RC columns, and confinement models for concrete. This study encompasses a range of experimental, analytical, and numerical investigations, to compile and analyze their results. The primary focus is the rehabilitation of reinforced concrete columns through jacketing techniques, presenting methods applicable to columns of any shape by coating the existing element in a robust jacket system. These techniques are important because they can significantly enhance the load-bearing capacity, strength, and stiffness of columns, while requiring minimal skilled labor and avoiding complex installation processes [10]. Despite the numerous reviews, which explored the effectiveness of different jacketing methods, there is still some limited information on the detailed comparison of these methods and under different conditions such as different applied loading conditions and environmental exposure. This paper focuses on the gaps by examining both mechanical performance and the durability under major loadings and extreme environmental conditions of various jacketing techniques. Moreover, the paper investigates the economic and cost-effective implications of each method, providing practical recommendations for their application in both developed and developing regions.

2 Review Methodology

2.1 Review Design and Objective

This study reviewed existing research on various jacketing techniques for reinforced concrete (RC) column repair and rehabilitation. This review study aims to provide a performance-based comparison on the mechanistic interpretation, and research gap identification for the different strengthening systems including

reinforced concrete (RC) jacketing, steel jacketing, fiber-reinforced polymer (FRP), fiber-reinforced cementitious matrix (FRCM), engineered cementitious composites (ECC) and hybrid systems. The methodology was prepared to ensure transparency, reproducibility, and analytical synthesis beyond descriptive reporting.

2.2 Literature Search Strategy

A comprehensive and structured literature review was conducted to ensure wide coverage and technical relevance of studies related to different jacketing techniques for reinforced concrete (RC) columns. The search was primarily performed using major scientific databases including Scopus, Web of Science, ScienceDirect, and the ASCE Library. Google Scholar was additionally used to identify supplementary studies and recently published articles not yet indexed in other databases. The search period covered publications was from 2000 to 2025 with emphasis placed on experimental, analytical and numerical investigations addressing structural performance, confinement behavior, seismic retrofitting, durability and constructability of jacketing systems.

To get all the relevant strengthening approaches, a combination of keywords was applied using Boolean operators (AND/OR). The main search terms were including: RC column jacketing, FRP confinement, FRCM strengthening, ECC jacketing, steel jacketing, hybrid jacketing, seismic retrofit of RC columns and confinement models for concrete. Additional filtering was applied to focus on peer-reviewed journal articles and conference proceedings reporting quantitative performance indicators such as axial strength enhancement, ductility ratio, stiffness modification, shear capacity improvement, or confinement efficiency.

3 Types of Jacketing Techniques

3.1 External Steel Jacketing

3.1.1 Materials and Installation Methods

Steel jacketing is a method used to reinforce or repair concrete or masonry structures by wrapping them with steel plates or sheets. This technique enhances the structural integrity and durability of the building, especially in seismic zones or areas prone to corrosion. Steel jacketing typically consists of steel plates or sheets made from materials such as carbon steel or stainless steel. These plates are usually pre-fabricated to fit the specific dimensions of the structure being reinforced [11]. The installation process of steel jacketing includes surface preparation (concrete surface should be clean and all debris should be removed with preparing rough surface for better adhesion), apply adhesive (bond agent should be applied to ensure strong bond between steel jacketing and concrete substrate), placement of steel jacketing (placing the steel plate of sheets onto the surface with applying mechanical fasteners to cover the overlapping area), sealing joint (any gaps or joint between plates should be sealed to prevent moisture and corrosive substance from penetrating) and surface finishing (painting the surface or coating to give additional protection to the steel from corrosion or environmental damage) [ASTM A36/A36M-14, ACI 562-16] [12,13].

3.1.2 Advantages and Limitations

Steel jacketing offers many advantages for reinforcing and repairing concrete. One of the main advantages is enhancing structural strength. Structural strength can be enhanced significantly by steel jacketing improving the load bearing capacity and structural integrity of concrete structure. This strengthening is particularly beneficial for earthquake-prone areas or for building subjected to heavy loading [14]. Other advantages for using steel jacketing include durability and corrosion resistance, versatility in application and rapid installation. Steel—especially stainless steel—provides excellent durability and resistance to corrosion, ensuring long-term performance of the strengthened structure even under harsh environmental conditions [15]. Recent studies have demonstrated the effectiveness of stainless-steel jacketing in improving

both axial and seismic performance of reinforced concrete members, highlighting its suitability for modern strengthening applications [16]. Steel jacketing can be applied to various structural elements which make it a solution for reinforcing different parts of building also, the application of steel jacketing takes shorter time compared to the other reinforcement methods such as concrete encasement which result in less time of disruption of the building and operations [17]. As steel jacketing is giving the structure many advantages, still there are some limitations should be considering when using this method to be strengthening the building such as the additional weight on the structure which should be analyzed to ensure that the building can support the increased load. Also, the installation and application will require some additional space around the structural element to be retrofitted while the steel will require maintenance is required to ensure long-term performance for the jacketing system [18].

RC columns are mostly retrofitted using external steel jacketing, particularly in seismic zones where the need for enhanced ductility and load-bearing capacity is paramount. Column's structural integrity and resistance to lateral load is improved by wrapping with steel plates or sheets. Degradation due to corrosion is not a concern with stainless steel jacketing, especially in coastal and industrial environments, where carbon steel is not fit for use [19]. Further improvements in steel jacketing have been made by the innovative use of hybrid steel composites containing FRP layers within the steel jacket. This reduces the overall weight and makes construction process easy. Thus, the common drawbacks associated with the system are addressed, issue such as space requirement and excessive weight, making the technique more viable in space-constrained applications [20].

3.1.3 Case Studies Demonstrating the Effectiveness of External Steel Jacketing

Chong et al. [21] investigated the impact of seismic loading on a structural frame damaged by earthquakes and subsequently retrofitted using steel jacketing. Their study involved testing a half-scale, single-span, two-story precast concrete (PC) frame subjected initially to pseudo-static loading until severe damage was reached. After retrofitting with steel jacketing, the frame was retested under pseudo-static loads. Both the original and retrofitted frames developed plastic hinges at the beam ends, indicating a similar mode of damage progression. The steel jacketing effectively reduced crack widths in the strengthened areas. The retrofitted frame demonstrated an 85% increase in yield load and a 72% increase in peak load compared to the original. However, the hysteresis curve of the retrofitted specimen showed a pinching effect caused by extensive shear cracks at the beam midspan and progressive failure of the steel angle anchors at the beam ends and column base due to weld damage. This pinching was not observed in the original specimen, resulting in lower energy dissipation in the retrofitted frame. The failure mode before and after applying the steel jacketing is shown in Fig. 2.

Villar-Salinas et al. [22] examined the effects of seismic loading on a six-story reinforced concrete building in Cartagena de Indias, Colombia, which was retrofitted using steel jacketing. The applied steel jacketing technique significantly enhanced the columns' axial strength and flexural capacity by 187% and 261%, respectively. Additionally, the lateral strength was improved through the stiffening of joint frames, resulting in increases in resistance of 127% and 74% in the X and Y directions. Fig. 3 illustrates the story drift at different strength levels for all six stories.

The use of steel jacketing has proven to be very effective in a case like Colombia where earthquake is common. Over 180% increase in column axial load capacity and significant increase in lateral stiffness was achieved [22]. However, while steel jacketing contributed to the performance of columns, the extra dead load contributed to the structure remains a major concern, particularly in older structures, where the underlying foundation may need to be reinforced to support the added mass [22].

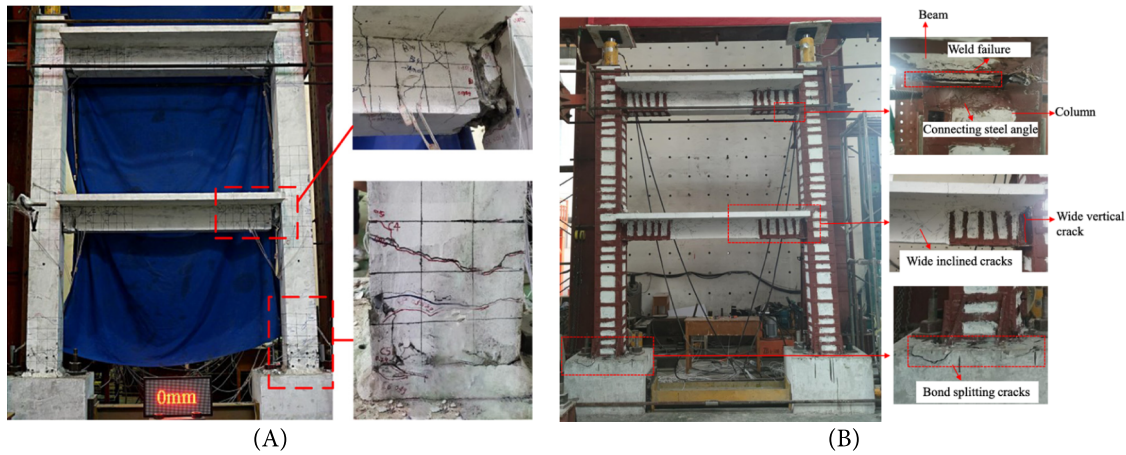


Figure 2: Failure mode of the 2-story frame. (A) without steel jacking, (B) with steel jacking [21]. Adapted with permission from Ref. [21]. Copyright ©2024.

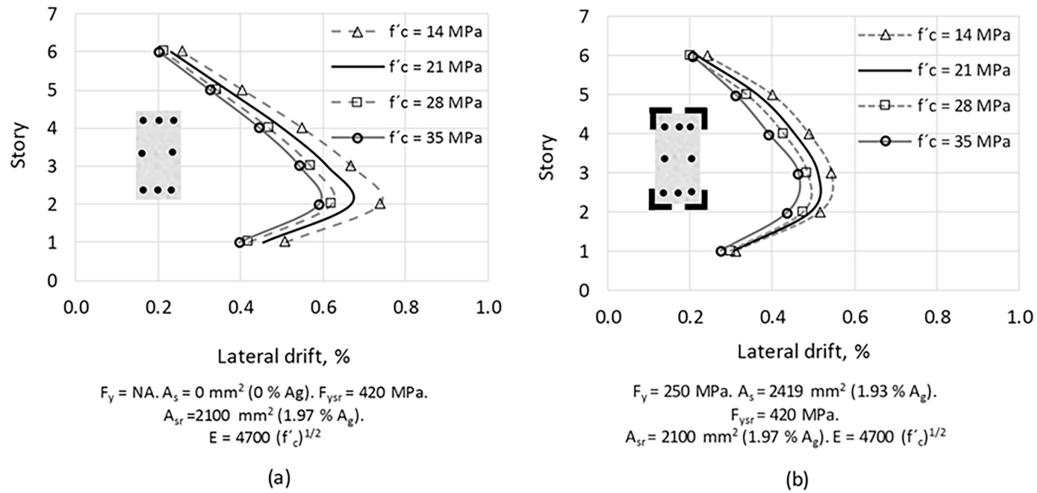


Figure 3: Comparison between the story drift with different concrete compressive strength. (a) Original building (b) Retrofitted building [22]. Adapted with permission from Ref. [22]. Copyright ©2021.

3.2 Fiber Reinforced Polymer (FRP) Jacketing

3.2.1 Types of FRP Materials Used for Jacketing

FRP jacketing is a technique employed to strengthen and retrofit concrete structure by wrapping the structure element with composite materials composed of high-strength fibers. The fiber materials used in FRP jacketing are carbon fibers, glass fibers or aramid fibers. The fiber materials will be embedded within a polymer resin matrix and use to enhance the structure performance and durability for various structure elements such as, beams, columns and bridges. Pham and Hao [23] examined the axial impact resistance of concrete columns confined with carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer by using a drop-weight apparatus, they found out that concrete columns confined with GFRP demonstrated better impact resistance and ductility compared to those confined with CFRP. Although GFRP has lower properties in tensile strength and elastic modulus than CFRP, its significantly higher rupture strain was identified as the main factor behind its superior performance. Xiao and Shen [24] studied the behavior of concrete filled steel tube (CCFT) columns confined with CFRP subjected to axial

impact loading. Their findings indicated that the external FRP jacket provided effective lateral confinement, thereby mitigating concrete damage. Moreover, an increase in impact energy was found to prolong the impact duration. Shan et al. [25] have examined the resistance of concrete-filled tubular (CFT) columns and confined concrete-filled tubular (CCFT) columns under axial impact loading using high-speed gas gun. Their results showed that external FRP jacketing offers efficient lateral confinement and significantly enhancing the impact resistance of CFT columns. High-strength reinforced concrete (RC) columns in particular deserve special attention because they tend to exhibit more brittleness and reduced deformation capacity compared to normal-strength concrete columns making them more vulnerable to sudden impact and dynamic loading. Consequently, effective confinement systems such as FRP jacketing play a critical role in improving their ductility, energy absorption capacity, and failure mode under impact conditions. In addition, fibers manufactured from recycled plastic bottles, such as polyethylene naphthalate (PEN) and polyethylene terephthalate (PET), have attracted considerable attention in recent studies due to their tensile rupture strains exceeding 5%, which are significantly higher than those of conventional FRPs, including CFRP (1.5%), GFRP (2.5%), and AFRP (3%). The relation between the tensile stress and tensile strain are shown in Fig. 4 [26].

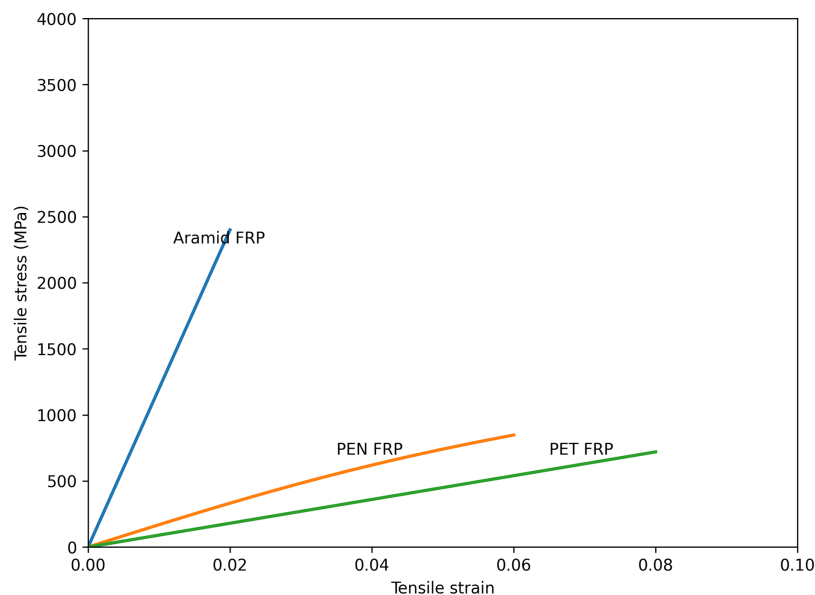


Figure 4: Stress–strain relationships of different FRPs [26]. Adapted with permission from Ref. [26]. Copyright ©2021, MDPI.

3.2.2 Application Techniques and Considerations

Installing the FRP strengthening in the RC structure requires preparation for the structural element for the application. These preparations generally are surface preparation, adhesive or primer bonding material, installation of FRP jacketing and sealing and finishing. FRP installation can take many different methods, for example, Zhang et al. [27] introduced a new FRP anchor designed for near surface mounted (NSM) FRP shear-strengthened beams, constructed using a rectangular FRP sheet via a wet lay-up method. The FRP sheet, serving as the anchoring device, was divided into two segments: one encircled the end of the FRP bar/strip, while the other adhered to the top or bottom concrete surface. This innovative FRP anchor effectively prevents interfacial debonding between the concrete and NSM FRP, as well as side concrete cover separation, leading to a potential 45% increase in beam load capacity. However, this anchor necessitates precise manufacturing and installation to avoid potential interfacial debonding issues. Consequently, while

this anchor shows promise, its effectiveness is contingent upon meticulous manufacturing and installation procedures. Moreover, existing anchoring techniques for NSM FRP shear-strengthened beams are hindered by their limited ability to mitigate the separation of concrete cover and by their complex manufacturing and installation processes. Additionally, most research focuses on T-shaped beams, as rectangular beams are typically integrated with RC slabs to form T-shaped beams in practical engineering applications.

3.2.3 Performance Evaluation and Case Studies of FRP Jacketing

Yang et al. [28] studied the compressive behavior of RC columns with corroded reinforcement strengthened using basalt fiber reinforced polymers (BFRP) in ultra-high-performance concrete (UHPC) was studied. The BFRP sheet wrappings remained intact throughout loading, even when reaching 80% of the peak load capacity. In specimens with a BFRP-UHPC jacket, residual strength was maintained beyond ultimate failure due to the significant confinement provided by the BFRP wrapping. Adding a 20 mm thick UHPC jacket enhanced the RC column peak load RC by 74.6% to 96.5%, while the combined BFRP-UHPC jacket further enhanced the peak load by an additional 1.06% to 18.92%. Under certain conditions, the ultimate strain of square RC columns reinforced with UHPC jackets and BFRP wrapping more than doubled compared to unstrengthened columns. In contrast, circular RC columns showed only slight increases in ultimate strain with the same strengthening. While UHPC jackets alone reduced ductility, the combined BFRP-UHPC jacketing restored ductility to levels comparable to those of non-corroded RC columns. Li et al. [29] evaluated the enhancement of concrete when applying GFRP, and the most significant decreases, amounting to 57.2% in compressive strength and 41.5% in ultimate axial strain, are observed when the replacement ratio reaches 25%, in comparison to control cases devoid of recycled GFRP short rebars.

3.3 Reinforced Concrete Jacketing

3.3.1 Types of Concrete Used for Jacketing

The repair and rehabilitation of damaged concrete structures have become pivotal construction endeavors worldwide. Reinforced concrete (RC) structures often require strengthening due to several factors such as deterioration, seismic damage, construction flaws, design deficiencies, and altered functionality. Reinforced concrete jacketing is widely adopted technique, stands out as the most favored method for repairing and reinforcing RC columns [30]. Strengthening and repairing jacketing methods employ materials such as ordinary concrete, self-compacting concrete, steel, ferrocement, and FRP. However, each approach has its drawbacks. For example, reinforced concrete jacketing reduces usable space and requires a lengthy construction period. Steel jacketing suffers from poor corrosion resistance. Meanwhile, FRP jacketing is primarily effective for previously repaired cracked RC columns, with its performance degrading under freeze-thaw cycles and temperature fluctuations [30].

3.3.2 Construction Methods, Considerations and Case Study

RC jacketing is widely used to strengthen and repair deficient or damaged RC columns. The traditional methods for reinforced concrete jacketing involve casting a new layer of reinforced concrete or mortar around the column (partially or the entire length) to increase its cross-sectional area. This new section is connected to the original column using high-strength bolts or anchor rebars. Although this method mainly improves the column's performance against seismic loading, it also enhances the axial load capacity, flexural strength, and ductility. It is often costly and time-consuming because of the required formwork installation. Additionally, the improvement in ductility is limited because the jacketing material (concrete) is brittle. Moreover, altering the cross-sectional area of the column changes the mass and stiffness of the structure,

leading to a reduction in its natural period and subsequently higher seismic demands. Therefore, high-performance RC materials have gained prominence in recent years for jacketing purposes to strengthen or repair the specimen without altering its cross-sectional size. Below is a summary of improvements and developments in RC/mortar jacketing techniques [31]. Lehman et al. [32] have used fresh cast concrete, headed reinforcement and mechanical couplers to repair a circular RC column had moderately to severely damage. While the repairs successfully restored strength and ductility, stiffness was only partially recovered in moderately damaged columns, and in case of severely damaged specimens the repairs were ineffective. Vadoros and Dristos [33] have used RC jackets with welded stirrup ends to improve the strength and ductility of RC columns. However, surface bonding treatment was inadequate at the interface led to separation between the jacket and the original column. Chang et al. [34] made a comparison between the effectiveness of RC jacketing and wing wall installation, concluding that RC jacketing provided greater improvements in energy dissipation and ductility for deficient RC columns. In Fig. 5 illustrates a comparison among a normal reinforced column, a reinforced column with RC jacketing, and one strengthened with wing wall jacketing. Liu et al. [35] proposed using a single asymmetric concrete section to strengthen RC columns, reducing occupancy disruption. This method significantly increased ductility and ultimate strength of retrofitted specimens while minimizing initial stress differences and maintaining structural usability. Ou and Troung [36] suggested strengthening the first weak story of the existing building by adding flanges in the weak axis of RC column. Although this resulted in enhanced lateral strength and ductile failure modes, the strength of retrofitted specimens was lower than monolithic specimens due to discontinuity in longitudinal reinforcement.

In recent times, high-performance materials have enhanced durability compared with conventional materials which spurred their increased adoption for the repair and strengthening of RC columns. Cho et al. [37] have enhanced the performance of plastic hinge region of the columns by utilizing high-performance fiber-reinforced cementitious composite (HPFRCC) mortar, revealing that HPFRCC mortar application have reduced the bending and shear cracks and also enhanced the overall force-displacement behavior, stiffness degradation, and energy dissipation. Similarly, Meda et al. [38] proposed the repair of corrosion-damaged RC columns by using high-performance fiber-reinforced concrete (HPFRC), resulting in a reasonable increase in column strength. Dagenais et al. [39] observed that jacketing deficient lap splice columns in RC bridges with self-compacting ultra-high-performance fiber-reinforced concrete (UHPFRC) eliminated bond failure and concrete damage in plastic hinge regions. Other high-performance materials like engineered cementitious composites (ECCs) and ferro-cement jackets were employed to strengthen short RC columns. ECC, a mortar-based composite reinforced with fibers, exhibited superior ductility, energy dissipation, and inelastic deformation compared to ferro-cement jacketing. Also, specimens with ECC-jacketed have displayed enhanced seismic performance at high axial load ratios [40]. Conversely, Abdullah and Takiguchi [41] noted stable cyclic response and improved ductility in columns with ferro-cement jackets, albeit without a noticeable increase in flexural strength. Rodrigues et al. [42] repaired severely damaged RC columns by replacing damaged concrete in the plastic hinge region with high-strength micro-concrete and welding ruptured longitudinal bars. Testing revealed that this repair technique fully restored column strength and ductility, though stiffness remained lower than in the original specimens. Recently, Li et al. [43] suggested using textile-reinforced concrete, which is made up of bundles of carbon and glass fibres as shown in Fig. 6 to wrap corrosion-damaged RC columns. Although the extent of the improvement was dependent on the initial corrosion ratio—higher initial corrosion ratios were associated with less behaviour enhancement—this repair method enhanced seismic performance in terms of yield load, ultimate bearing capacity, ductility, and energy dissipation.

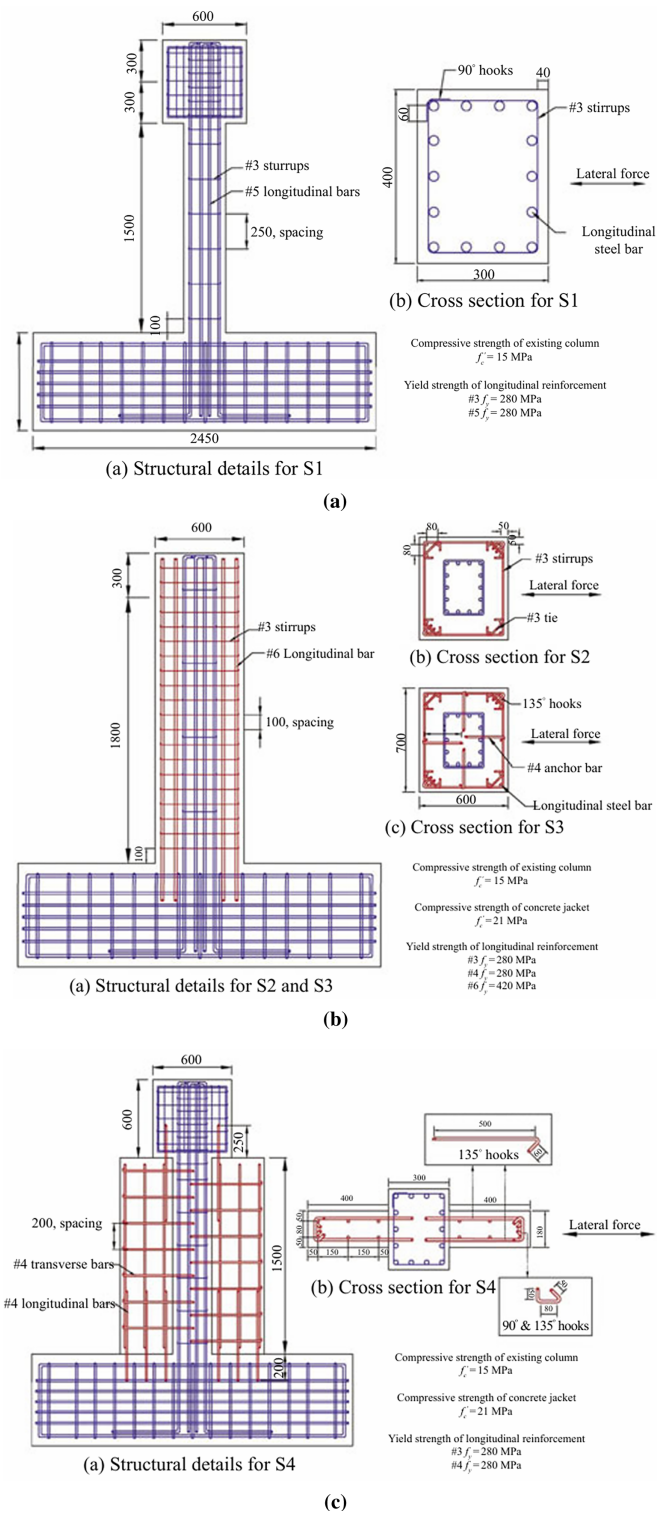


Figure 5: Comparing between (a) normal reinforced columns, (b) reinforced column jacketing and (c) wing wall reinforced jacketing. Adapted with permission from Ref. [26]. Copyright ©2021, MDPI.

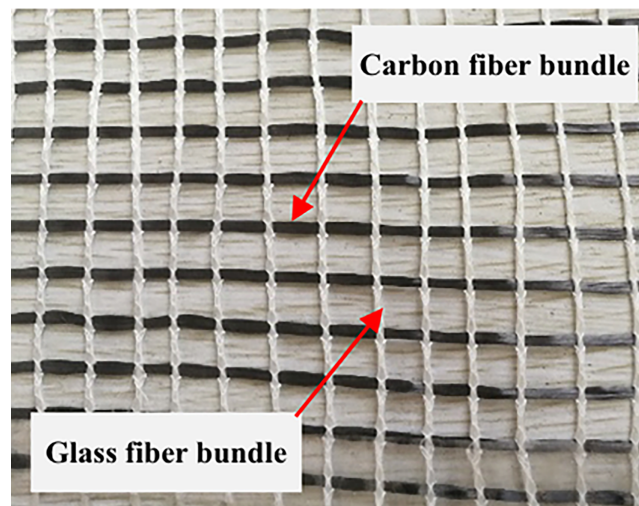


Figure 6 : Carbon and glass fibers bundles. Adapted with permission from Ref. [43]. Copyright ©2019, Elsevier.

However, there are limitations associated with reinforced concrete jacketing. Like the steel jacketing, reinforced concrete jacketing also contributes to added weight which leads to increased overall stiffness of the structure. The introduction of fiber-reinforced concrete (FRC) is a potential to the aforementioned limitations. It provides a balance between reduced mass and strength of concrete. Similarly, the construction done with high performance concrete in jacketing components exhibits an improvement in seismic resistance by enhancing both the ductility and energy absorption capacity of the retrofitted columns [44].

3.4 Fiber Reinforced Cementitious Matrix (FRCM) Jacketing

3.4.1 FRCM Materials and Their Properties

Fiber Reinforced Cementitious Matrix (FRCM) jacketing composites have become widely used for retrofitting existing RC structures that were originally under-designed. Fiber reinforced systems have attracted significant research attention since the early 1970s, although their broad adoption occurred only in more recent years [45]. Recently, composite materials used for rehabilitating concrete or masonry structures were mainly applied with organic, typically epoxy-based, matrices. This approach significantly improved the resistance and ductility of the strengthened elements. However, epoxy resins in FRP systems have several drawbacks, including poor fire resistance, challenges in application on wet surfaces, limited substrate breathability, low reversibility, and high sensitivity to UV radiation [45,46]. These factors have contributed to a decreased adoption of FRP systems, prompting the exploration of new, more compatible, and durable alternatives. One such alternative emerged by replacing epoxy matrix made with organic material with inorganic cement-based matrix, commonly referred to as Fiber Reinforced Cementitious Mortar (FRCM) or Textile Reinforced Mortars (TRM). Similar to FRP systems, FRCMs have recently seen widespread use in enhancing the flexural and shear strength of beam elements, as well as improving the axial strength and ductility of concrete or masonry columns through confinement [45–47].

FRCM entails an inorganic matrix comprising textile layers enclosed within cementitious mortar layers. Most of existing studies examined the performance of reinforced concrete short columns reinforced with poly-paraphenylene-benzobisoxazole (PBO) FRCM, carbon FRCM (C-FRCM), and glass FRCM (G-FRCM) [47–50]. Younis and Ebead [51] investigated the bonding characteristics of three types of carbon FRCM (C-FRCM), PBO-FRCM, and glass FRCM (G-FRCM). Tensile tests were performed on all three,

and the modulus of elasticity was determined from the results. During these tests, C-FRCM and PBO-FRCM specimens failed due to fabric slippage, while G-FRCM specimens exhibited brittle failure caused by fabric rupture. Following this, 18 concrete prisms were wrapped with FRCM sheets and subjected to double shear tests to examine failure modes, bond capacity and deformation. The number of fabric layers, bond length, and mesh type were among the variables that were changed during the study. Because G-FRCM has a propensity to rupture during tensile tests, the bond length was left unchanged. According to the results, the bidirectional mesh geometry caused weaker mortar bonding, which is why C-FRCM specimens primarily failed by debonding within the matrix. Most PBO-FRCM specimens failed by debonding at the matrix-concrete interface, due to strong internal matrix bonding from higher fabric density along the wrap direction. As bond length increased, PBO-FRCM specimens transitioned to matrix rupture failure, reflecting stronger matrix-concrete bonding. The main cause of failure for G-FRCM specimens was matrix rupture. PBO-FRCM had the highest bond capacity of the three, followed by C-FRCM and G-FRCM. Using carbon and basalt textiles, Kim et al. [50] investigated the bond properties between the matrix and textile in FRCM composites. To improve bond strength, the matrix was made to be resistant to alkali. Pull-off tests assessed the bond performance at the matrix-textile interface, whereas pull-out tests evaluated the bond between the textile and matrix. The results of the pull-out tests showed that, in comparison to basalt FRCM (B-FRCM), carbon FRCM (C-FRCM) had an elastic modulus and bond strength that were roughly 169% higher. Similarly, in line with the results of the pull-out tests, the pull-off tests verified that C-FRCM had better bond performance. These results of bond strength are shown in Fig. 7.

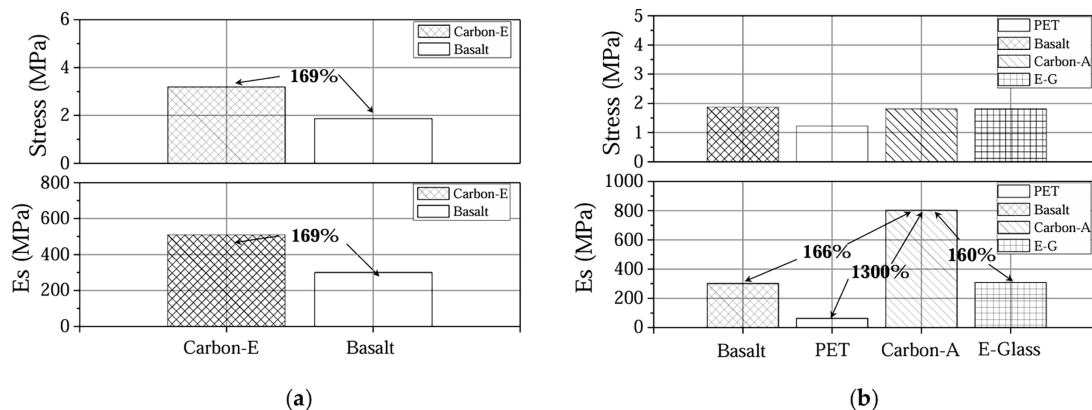


Figure 7: Pull-out specimens' analysis: (a) textile type; (b) weaving type. Adapted with permission from Ref. [50]. Copyright ©2020, MDPI.

Zhu et al. [48] carried out research on carbon FRCM (C-FRCM), concentrating on how the material bonds to the matrix at the fabric-mortar interface. Bidirectional C-FRCM fabric was used in this investigation. An upper cut intersected the carbon yarn in the middle of the asymmetric test setup, while two additional cuts preserved the integrity of the middle carbon yarn. Each specimen was made up of upper and lower blocks, with the anchorage length of the lower block being longer to guarantee strong and sufficient anchorage. In order to prevent local failure, CFRP sheets were applied to each specimen end after both ends were clamped. A displacement-controlled pullout test was performed on the specimens at a loading rate of 0.2 mm/min. According to the test results, specimens with longer upper block lengths experienced slippage along with partial carbon yarn rupture, whereas specimens with shorter upper block lengths failed only as a result of carbon yarn slippage. The failure mode is shown in Fig. 8.



Figure 8: Failure mode observed in pull out tests with 30 mm embedded length. Adapted with permission from Ref. [48]. Copyright ©2021, Elsevier.

D'Ambrisi et al. [52] examined the connection between concrete and PBO-FRCM strengthening materials. They performed a double-face shear test on every sample and changed the bond length and quantity of FRCM layers in the specimens. The findings showed that matrix rupture and debonding at the fiber interface were the main causes of the specimens' failure. Interestingly, they discovered that the bond length had no effect on the ratio of debonding strain. Other researchers explored how the technique of strengthening with FRCM can be integrated with other existing techniques to protect concrete structures from corrosion [53].

3.4.2 Columns Strengthened with FRCM Properties

The performance of FRCM strengthened RC columns loaded concentrically [54–56] and eccentrically [57] has been explored by several studies. In the studies, numerous parameters, such as subjecting the member to pre-damage prior to testing, cross-section type, spacing of transverse reinforcement, type of FRCM system, and the number of FRCM system layers. Table 1 provides a comprehensive summary of the experimental programs and key findings from all the previous studies mentioned in this literature review regarding columns. FRCM jacketing's superior performance in cyclic and monotonic loadings has been demonstrated in studies. In this technique, the ductility and axial load capacity of the member is improved, with no substantial impact on the structural mass. However, the application process requires careful surface preparation and curing to ensure proper bonding, which can increase labor costs and installation time.

Colajanni et al. [56] carried out an experimental investigation by using square prisms and cylindrical specimens reinforced with PBO-FRCM. In order to test their effects on capacity and ductility, the study used various parameters such as specimen length, cross-section type, reinforcement ratio, number of FRCM layers and overlapping length. Monotonic loading tests were performed on all specimens. The results showed, with increasing the number of FRCM layers and overlapping length the strength and ductility have increased. Surprisingly, square cross-section specimens showed enhanced strength post-wrapping, contrary to expectations. The cylindrical specimens that are confined with three PBO-FRCM layers, demonstrated the maximum capacity increase of approximately 64%. Failure modes included prism specimens failing because of FRCM rupture at the corners and cylindrical specimens failing because of FRCM rupture after the FRCM textile developed large vertical cracks.

Table 1: Literature review summary of FRCM strengthened columns.

Reference	Test Type	Pre-Damage	Comp. Strength (MPa)	Cross Section Shape	Type of FRCM System	No. of FRCM Layers	Comp. Strength Increment (%)
Colajanni et al. [56]	monotonic loading	No	25	Circular	PBO	2–3	2% to 64%
Colajanni et al. [58]	monotonic loading and cyclic loading	No	17	Rectangular	Carbon	2–3	14% to 49%
Toska et al. [45]	monotonic loading	No	16	Circular Rectangular	Carbon	1–2	0% to 24%
Feng et al.	cyclic loading	Yes	44	Circular	Carbon	2–3	15% to 33%
Villar-Salinas et al. [22]	monotonic loading	Yes	21	Circular Rectangular	Carbon	2	0% to 34%
Zhu et al. [48]	monotonic loading	Yes	42	Circular	Carbon	1	0% to 37%
Ombres and Verre [57]	monotonic loading	No	24 & 40	Rectangular	PBO	1–2	20% to 39%

Colajanni et al. [58] studied the behavior of cylindrical and prismatic specimens reinforced with carbon FRCM (C-FRCM) under both monotonic and cyclic loading. The prismatic specimens' cross-section shape, number of C-FRCM layers, and corner radius were all varied during the investigation; each specimen had an overlap length of 100 mm. The results showed that C-FRCM considerably improved strength and ductility in all specimens, with cylindrical specimens showing the largest improvement, at roughly 49%. Strength was further increased by adding more C-FRCM layers, but ductility decreased for all specimen types. Faleschini et al. [54] investigated the axial behavior of RC columns strengthened with carbon FRCM (C-FRCM). They cast 12 columns with either circular or square cross-sections, with the square columns having rounded corners. Some columns were left unconfined as controls, while others were confined with one or two layers of C-FRCM. The tie spacing was also varied across specimens. All columns were tested under displacement-controlled loading at a rate of 0.3 mm/min. The study found that, despite the rounded corners, square columns still experienced stress concentrations. Additionally, increasing the number of C-FRCM layers improved load capacity, especially in circular columns, which showed a maximum capacity increase of approximately 24%. Feng et al. [55] studied the behavior of corroded circular RC columns strengthened with carbon FRCM (C-FRCM) under cyclic loading. Seven specimens with identical dimensions, concrete strength, and reinforcement were cast, including one uncorroded control. Corrosion was accelerated by submerging the columns in water for 12 h daily over 360 days, with 3% NaCl added by cement weight to the concrete mix. The specimens were then wrapped with either two or three layers of C-FRCM. For cyclic testing, hydraulic actuators with capacities of 2000 kN (horizontal) and 5000 kN (vertical) were used at the column caps. Three displacement cycles were applied, beginning at 2 mm amplitude and increasing by 4 mm increments. The highest capacity was achieved by the specimen wrapped with three C-FRCM layers with increase of 33% subjected to a high axial compression ratio. Zhu et al. [59] investigated RC columns confined with carbon FRCM (C-FRCM) and rehabilitated using ICCP-SS, a novel method for repairing sea-sand concrete columns. Corrosion was induced by adding sodium chloride (NaCl). Nine columns were cast and divided into five groups: control columns; one column with NaCl and no repair; two columns with

NaCl repaired using ICCP only (without C-FRCM); one column with NaCl repaired solely by structural strengthening (SS); and three columns with NaCl repaired by combined ICCP-SS. After curing, columns exposed to NaCl underwent accelerated corrosion for 270 days, followed by 250 days of cathodic protection for the ICCP-repaired specimens. All columns were then subjected to compressive testing. Results showed that columns retrofitted with ICCP-SS achieved a maximum capacity increase of about 37%. The study also proposed a confinement model based on these findings. Ombres and Verre [57] examined the structural behaviour of rectangular concrete columns strengthened with PBO-FRCM under eccentric loading with different eccentricity-to-height ratios and reinforcement ratios. Two ratios of reinforcement were employed: 0.8% and 1.4%. For each ratio, three columns were cast: one unstrengthened, one strengthened with a single PBO-FRCM layer, and one reinforced with two layers. Eccentricity was varied across all specimens. Prior to applying the PBO-FRCM, the columns were sandblasted 28 days after casting and then left in ambient conditions for 7 days. All column corners were rounded to a 20 mm radius. Compressive tests showed that the confined columns experienced strength increases ranging between 20% to 39%. The strength gain increased with higher reinforcement ratios but decreased as eccentricity values increased.

3.4.3 Installation Methods and Considerations

FRCM installation methods for RC columns typically involve the following steps:

1. **Surface Preparation:** Concrete surface of the concrete column needs to be prepared thoroughly before applying to the FRCM. This includes cleaning the surface to remove dust and any existing coatings, as well as roughening the surface to improve FRCM bonding with the concrete surface.
2. **Priming:** A suitable bonding agent is required to be applied on the concrete surface to enhance the adhesion between the substrate (concrete surface) and the FRCM system. The primer helps to promote a strong and stable bond to improve the overall performance of the reinforcement.
3. **Application of FRCM Mortar:** The FRCM mortar consists of cementitious material mixed with embedded fibers, is applied to the prepared surface of the concrete column. This can be achieved using by various methods such as spraying, troweling, or manually applying the mortar onto the surface.
4. **Embedding Reinforcement:** Additional reinforcement maybe such as carbon or glass fiber sheets may be embedded into the wet FRCM mortar to enhance the structural performance of the column. These reinforcement layers are usually applied in multiple layers to achieve the desired strength and ductility.
5. **Curing:** After the application of FRCM mortar and reinforcement layers, the system needs to be cured properly to allow for the hydration of the cementitious materials and ensure adequate strength development. Curing methods can be either air curing, moisture curing, or the use of curing compounds.
6. **Finishing:** After the curing of the FRCM system, finishing touches can be applied such as smoothing the surface or applying protective coatings to improve the aesthetic appearance and durability of the column.

Additionally, one efficient way to increase the strength and ductility of existing RC columns is to confine them with FRCM jackets. This confinement mainly enhances the peak load resistance. However, improving overall ductility requires more complex calculations to evaluate the column's capacity to withstand drift and rotation without suffering a notable loss in strength [ACI 549]. Thus, the purpose of this section is to increase the column's effective ultimate compression strain in order to improve flexural ductility. The following illustrates the process for axial strengthening an RC column under pure compression.

- **Mesh reinforcement properties:** The FRCM material system should be approved by the International Code Council Evaluation Service (ICC-ES), ensuring compliance with established standards and regulations. Additionally, its geometrical and mechanical properties must align with those specified in the corresponding ICC-ES Research Report. This ensures the reliability and consistency of the FRCM

system's performance and allows for confidence in its structural enhancement capabilities. It must be noted that the properties reported such as area of mesh reinforcement by unit width, tensile modulus of elasticity, ultimate tensile strength and ultimate tensile strain.

- The comparison between bonded and unbonded confinement reveals the following conclusions:
 - (a) Fabric-reinforced cementitious matrix-confining jackets lead to significant improvements in compressive strength and deformation capacity. For instance, the increase in ultimate capacity compared to unconfined specimens ranges from 25 to 75 percent, depending on factors such as mortar type, number of reinforcement layers, and specimen cross-section type.
 - (b) Depending on the mortar's tensile strength, the extent of this improvement increases as the number of mesh layers increases. Whether the jacket fails due to debonding or fiber fracture is determined by the tensile strength.
 - (c) Failure of FRCM jackets occurs due to the gradual fracture of individual fiber strands, indicating a progressive failure mechanism.

3.4.4 Case Study Highlighting the Benefits of FRCM Jacketing and Shape Effect

Two case study conducted by Tello et al. [60,61] has examined how the number of PBO-FRCM layers and the shape of the column cross-section affect how well PBO-FRCM systems work to increase the ductility and strength of RC columns that have already been damaged as well as those that have not. Total of 10 columns with a clear height of 800 mm and a longitudinal reinforcement ratio of 1.5%, were cast and tested. The columns were subjected to monotonic loading until failure and divided into three groups: unwrapped controls, wrapped with two layers of PBO-FRCM, and wrapped with four layers. The experimental results showed that strengthening pre-damaged RC columns with PBO-FRCM effectively restored and improved their original capacity, with capacity increasing in proportion to the number of layers applied. Circular columns experienced the most significant gains, with ultimate capacity improvements ranging from 38% to 71%. Additionally, the ductility of short RC columns strengthened with PBO-FRCM increased substantially, between 19% and 82%. Theoretical ultimate capacities calculated using the ACI 549.4R-13 code closely matched experimental values, confirming the code's reliability for estimating the capacity of short RC columns reinforced with PBO-FRCM.

Proposed two section shaped circular and rectangular as designment shown in Fig. 9.

- Concrete with a compressive strength of about 30 MPa was to be used to cast all of the columns.
- PBO-FRCM, a bidirectional PBO fiber mesh with 70 g/m² in wrap and 18 g/m² in weft, is utilized to wrap the cast columns. Its fiber density is 1.56 g/cm³, its elongation at rupture is 2.5%, its tensile strength is 5.8 GPa, and its elastic modulus is 270 GPa. A sample of PBO-FRCM fibers is shown in Fig. 10.
- Properties of the PBO-FRCM bidirectional mesh according to the manufacturer's datasheet as shown below:

Properties of the Bidirectional Mesh	PBO-MESH GOLD 70/18
Weight of PBO fibers in the mesh	88 g/m ²
Equivalent thickness of dry fabric in the direction of the wrap	0.0455 mm
Equivalent thickness of dry fabric in the direction of the weft	0.0115 mm
Tensile strength of the wrap per unit of length	264.0 kN/m
Tensile strength of the weft per unit of length	66.5 kN/m
Weight of the mesh (support + PBO fibers)	110 g/m ²

- Properties of the PBO-FRCM inorganic matrix according to the manufacturer's data sheet as shown below:

Properties of the Inorganic Matrix	PBO-MESH GOLD CALCESTRUZZO
Water per 100 kg of dry premix	26–28 liters
Consistency of the mortar (EN13395-1)	175 ± 10 mm
Specific weight of fresh mortar (EN 1015-6)	1.80 ± 0.05 g/cc
Volume of fresh mortar for 100 kg of dry premix	About 71 liters
Compression resistance at 28 days (EN12190)	≥ 40 MPa
Bending resistance at 28 days (EN 196-1)	≥ 4 MPa
Elastic modulus at 28 days (EN 13412)	≥ 7 GPa

- Effect of cross-section: The results indicated that wrapped square columns exhibited a greater increase in ductility compared to circular columns. Specifically, the ductility of square columns increased by 31% to 35%, while that of circular columns increased by roughly 19% when wrapped with two layers of PBO-FRCM. Similarly, square columns showed a significantly larger increase in ductility, ranging from 80% to 82%, whereas circular columns showed a gain of roughly 45% to 51% when wrapped with four layers. The effect of columns shape is illustrated in Fig. 11.
- Effect of number of PBO-FRCM layers: Every column strengthened with four PBO-FRCM layers demonstrated significantly greater ductility than those reinforced with two PBO-FRCM layers; the difference in ductility increases between square columns reinforced with two and four PBO-FRCM layers was 26%–32%, while for circular columns it reached 45%–51%. The effect of number of PBO-FRCM layer is illustrated in Fig. 12.

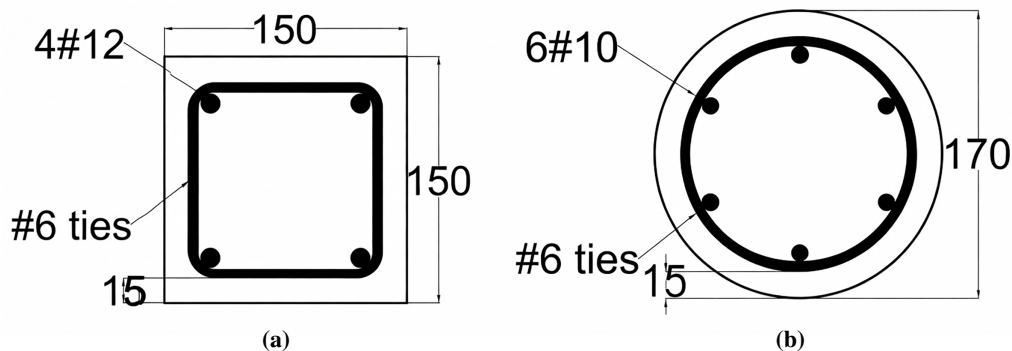


Figure 9: Cross-sectional details of (a) square column (b) circular column [60,61]. Adapted with permission from Refs. [60,61]. Copyright ©2021, Elsevier.

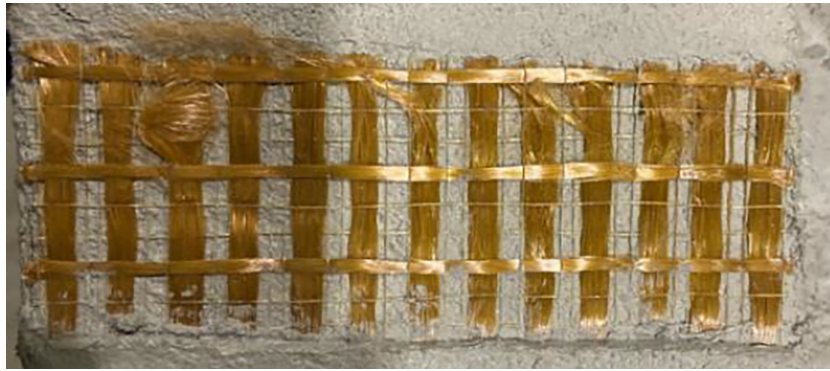


Figure 10: Sample of PBO-FRCM [62]. Adapted with permission from Ref. [62]. Copyright ©2022, ASCELibrary.

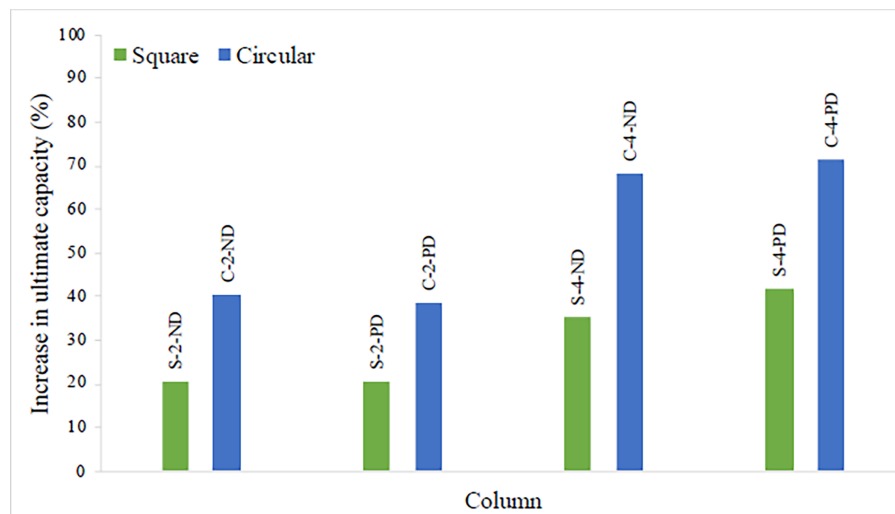


Figure 11: Columns with different cross-sections comparison in ultimate capacity [60,61]. Adapted with permission from Refs. [60,61]. Copyright ©2021, Elsevier.

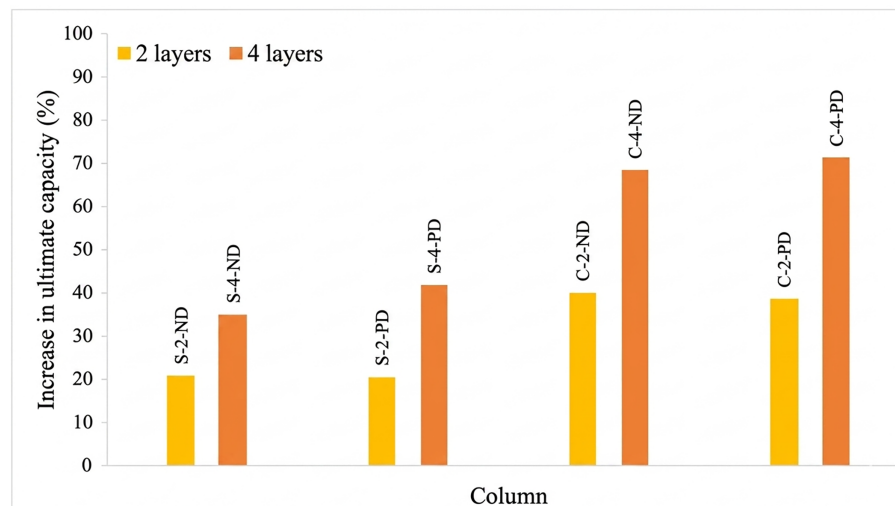


Figure 12: Comparison between columns wrapped with a different number of PBO-FRCM layers and its ultimate capacity [60,61]. Adapted with permission from Refs. [60,61]. Copyright ©2021, Elsevier.

3.5 Engineered Cementitious Composites (ECC) Jacketing

3.5.1 ECC Materials and Their Properties

Engineered Cementitious Composites (ECC) are increasingly used as an advanced strengthening and retrofitting technique for reinforced concrete (RC) columns due to their high tensile ductility and controlled microcracking behavior. When applied as an external jacket or overlay around existing columns, ECC significantly enhances confinement, shear capacity, ductility, and energy dissipation under axial and seismic loading as shown in Fig. 13 [63]. Unlike conventional concrete jackets, ECC forms multiple fine microcracks instead of large brittle cracks, this helps the structure to maintain integrity and improve load redistribution after cracking. Its superior bond performance with existing concrete and reinforcing steel ensures effective composite action, while its strain-hardening behavior increases deformation capacity and delays failure. As a result, ECC jacketing provides a lightweight, durable, and crack-resistant solution for upgrading deficient RC columns, particularly in seismic regions and infrastructure rehabilitation projects. The Table 2 [63] have summarized the main materials used in Engineered Cementitious Composites (ECC) and explains their specific roles in strengthening reinforced concrete (RC) columns. It highlights how each component contributes to the mechanical performance and durability of the ECC jacket. The binder materials (OPC and fly ash) provide strength and matrix stability, while fine silica sand ensures proper fiber dispersion and crack control. PVA fibers are the key element responsible for strain-hardening and multiple microcracking behavior, which enhances ductility and energy absorption. Admixtures such as superplasticizers improve workability and bonding, ensuring effective composite action between the ECC layer and the existing column. Overall, the Table 2 demonstrates how the optimized combination of materials enables ECC to serve as a high-ductility, crack-resistant, and durable strengthening solution for RC columns [63].

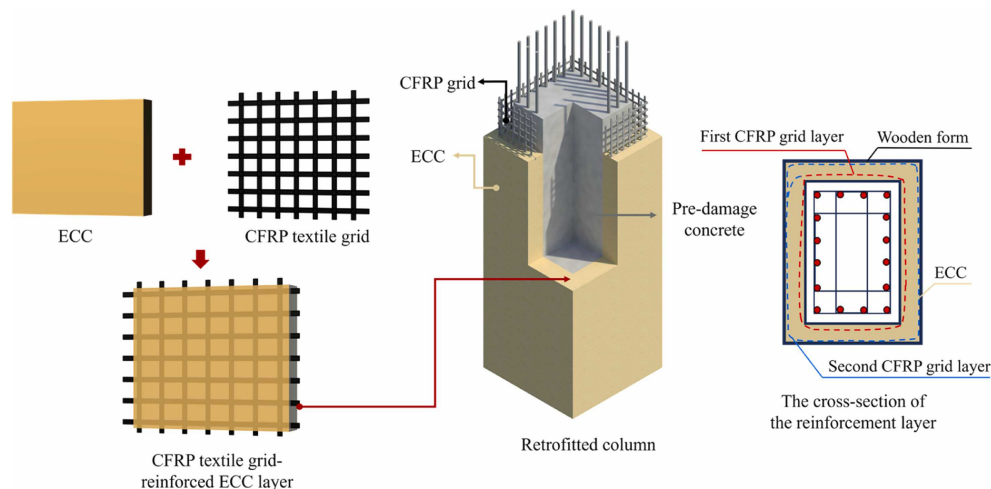


Figure 13: ECC jacketing system for strengthening RC columns [63]. Adapted with permission from Ref. [63]. Copyright ©2023, Elsevier.

Table 2: Comparative evaluation of ECC materials and their applications [63].

Material	Function in ECC	Application in RC Column Strengthening
Ordinary Portland Cement (OPC)	Primary binder	Provides compressive strength and matrix formation

(Continued)

Table 2 (continued)

Material	Function in ECC	Application in RC Column Strengthening
Fly Ash (Class F)	Supplementary cementitious material	Improves ductility, reduces heat, enhances durability
Silica Sand (Fine Aggregate)	Filler material (no coarse aggregate)	Enhances fiber distribution and crack control
PVA Fibers (~2% volume)	Crack-bridging reinforcement	Enables strain-hardening and microcrack control
Superplasticizer (HRWR)	Improves workability	Ensures proper casting and bonding around column
Water	Hydration medium	Controls workability and strength development
Bonding Agent (if required)	Surface preparation	Enhances adhesion between old concrete and ECC jacket

3.5.2 Columns Strengthened with ECC Materials

Engineered Cementitious Composite (ECC) jacketing has been increasingly investigated as an advanced strengthening technique for RC columns due to its unique strain-hardening and multiple microcracking behavior, which fundamentally differs from conventional confinement-based systems. While Zhang et al. [64] provided a comprehensive experimental study on high-strength ECC (HS-ECC) under cyclic loading see Fig. 14. Similar findings have been reported in other independent studies, confirming the consistency of ECC performance. Deng et al. [40] demonstrated that ECC jackets significantly improve shear resistance and cyclic stability of RC columns through distributed crack control rather than localized failure. Likewise, Meda et al. [38] and Beschi et al. [18] reported that high-performance fiber-reinforced cementitious composites, including ECC-type materials, enhance both strength and ductility by improving confinement and delaying concrete spalling. Dagenais et al. [39] further showed that ultra-high-performance fiber-reinforced cementitious systems (UHPFRC), which share similar micromechanical principles with ECC, significantly enhance seismic performance and energy dissipation capacity. Additionally, Cho et al. [37] confirmed that fiber-reinforced cementitious jackets applied in plastic hinge regions effectively improve deformation capacity and damage tolerance. More recently, Chen et al. [63] reported that ECC-based composite jackets improve both axial and seismic performance of damaged columns, supporting the applicability of ECC in rehabilitation scenarios.

ECC is typically developed by incorporating high-performance cementitious matrices with synthetic fibers such as polyethylene (PE) or polyvinyl alcohol (PVA), enabling tensile strain capacities far exceeding conventional concrete. As reported by Zhang et al. [64], HS-ECC achieved compressive strength of approximately 78 MPa, tensile strength of about 12.5 MPa, and tensile strain capacity up to 7.9%, significantly higher than conventional fiber-reinforced concrete systems. In comparison, high-performance mortar (HPM) and high-strength fiber-reinforced concrete (HSFRC) exhibit limited tensile strain capacity ($\approx 0.3\%$) and strain-softening behavior, resulting in lower ductility and more brittle failure modes. The superior performance of ECC is attributed to its ability to form multiple fine cracks with controlled crack widths, which enhances stress redistribution, delays localization, and improves confinement effectiveness. In terms

of structural performance, ECC jacketing consistently demonstrates significant improvements in ductility, energy dissipation, and post-peak behavior. Zhang et al. [64] reported that full-height ECC jacketing increased ductility by approximately 67.7% and cumulative energy dissipation by nearly 395% under cyclic loading. These findings are supported by Deng et al. [40], who observed enhanced shear stability and reduced stiffness degradation, and by Dagenais et al. [39], who highlighted improved seismic resilience in columns strengthened with fiber-reinforced cementitious materials. Compared to FRP and FRCM systems, ECC does not rely solely on external confinement but instead improves structural performance through intrinsic material ductility and crack control mechanisms, resulting in more stable and damage-tolerant behavior.

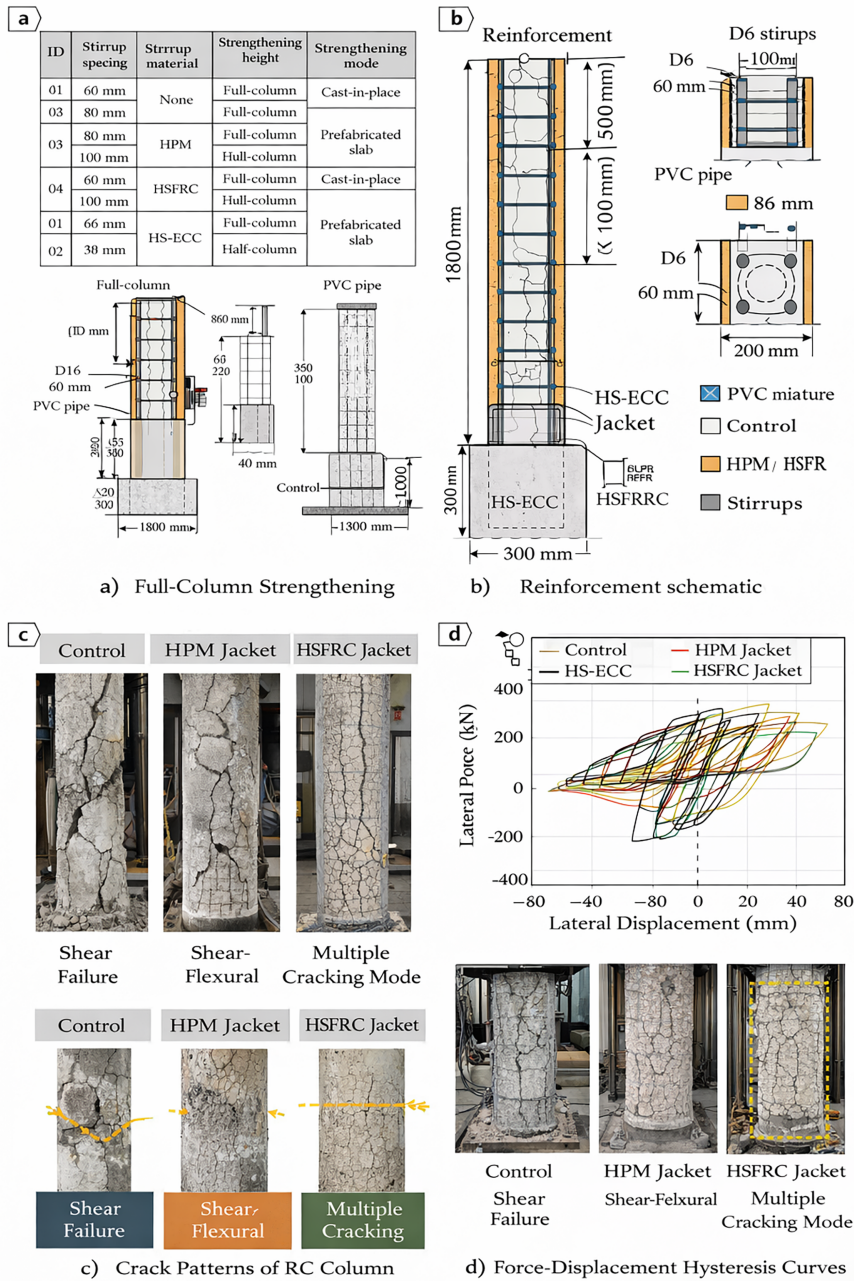


Figure 14: HS-ECC jacketing system and cyclic performance of strengthened RC columns. Adapted with permission from Ref. [64]. Copyright ©2023, Elsevier.

3.6 Hybrid Jacketing System

3.6.1 Structural Performance and Application

Hybrid jacketing system for reinforced concrete (RC) columns can enhance structural performance by combining section enlargement with active confinement. Typically, a thin reinforced concrete (or shotcrete) jacket is added on the existing column to increase the cross-sectional area and adding additional longitudinal and transverse reinforcement. This enlargement directly improves axial load capacity and flexural strength by increasing the load-carrying area and the internal lever arm between compression and tension forces becomes larger [65]. The shear resistance is also increased by the added transverse reinforcement in the jacket and also improves the confinement of the core concrete. To further enhance performance, an external fiber-reinforced polymer (FRP) wrap is applied around the jacketed column. The FRP provides strong lateral confinement, which restrains the lateral expansion of concrete under compression. This confinement increases the effective compressive strength of the concrete and significantly improves ultimate strain capacity. As a result, the column becomes more ductile and less prone to brittle crushing or sudden failure. Under seismic loading, the improved confinement delays spalling, enhance energy dissipation, and improves overall stability and cyclic performance as illustrated in Fig. 15. The combined action of the concrete jacket and FRP wrap creates a synergistic effect. The concrete jacket primarily increases strength and stiffness, while the FRP enhances ductility and confinement efficiency. Together, they improve axial capacity, flexural performance, shear resistance, and seismic behavior more effectively than using either method alone. This makes hybrid jacketing a highly effective solution for upgrading deficient, aging, or under-designed RC columns where improved strength, safety, and durability are required without complete structural replacement [65].

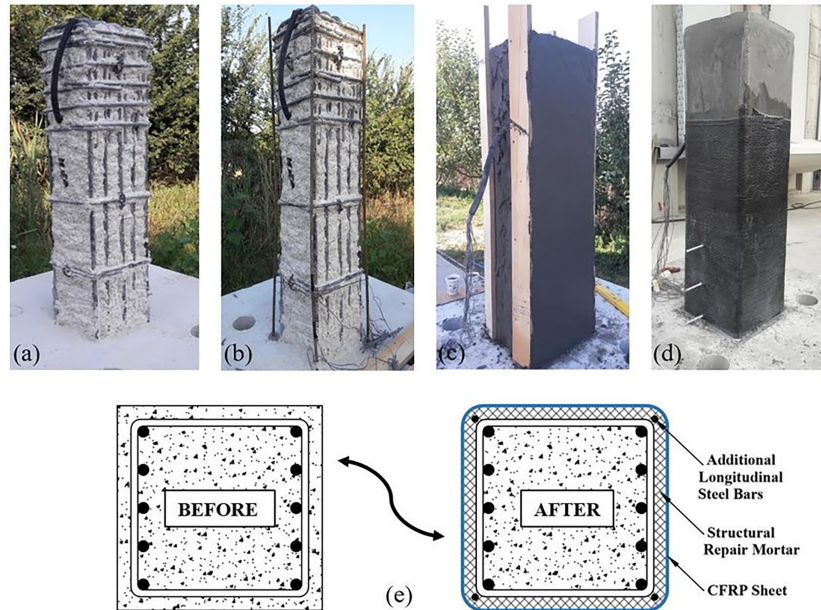


Figure 15: Application of the proposed hybrid thin jacketing method: (a) removal of concrete cover, (b) anchorage of additional longitudinal reinforcement, (c) application of structural repair mortar, (d) CFRP jacketing, and (e) cross-sectional demonstration of the method. Reproduced from Ref. [65].

3.6.2 Cost-Effectiveness and Constructability

Hybrid thin jacketing systems e.g., repair mortar, added bars and FRP eliminate heavy formwork and reduce transverse steel usage, since confinement is provided by FRP. Studies such as Narlitepe et al. and Fakharifar et al. [65,66] show that hybrid systems achieve of 40%–50% strength improvement with minimal section enlargement, reducing material volume and labor. Based on experimental and state-of-the-art studies, hybrid jacketing systems for RC columns demonstrate strong advantages in terms of cost-effectiveness and constructability when compared with conventional RC jacketing or FRP-only strengthening. Conventional RC jacketing typically requires full section enlargement, dense transverse reinforcement cages, extensive formwork, and significant concrete volume, which increases labor intensity, material consumption, and construction time. In contrast, hybrid thin jacketing systems—such as those combining structural repair mortar, additional longitudinal reinforcement, and external CFRP wrapping [65,66] achieve substantial improvements in strength and ductility while maintaining nearly the original column dimensions. Experimental results have reported approximately 40%–50% increases in lateral strength and ductility using hybrid systems, achieved with limited material addition and without the need for heavy reinforcement cages or thick concrete jackets. This results in a more favorable performance-to-cost ratio, as the hybrid approach strategically uses the material for its most efficient role: repair mortar and added steel bars enhance axial and flexural capacity, while FRP provides effective confinement and ductility improvement. From a constructability perspective, hybrid systems eliminate complex formwork and reduce reinforcement congestion, simplifying installation work operations. The application sequence covers removal, anchorage of additional bars, repair mortar application, and FRP wrapping is relatively faster and requires lighter equipment compared to conventional jacketing. Furthermore, since the increase in cross-sectional is minimal, changes to the building's mass and stiffness are low, reducing the need for additional foundation strengthening and minimizing disruption to occupants. Consequently, literature consistently indicates that hybrid jacketing provides a technically efficient, economically balanced, and practically constructible solution for seismic upgrading of deficient RC columns. Table 3, summarizing the findings of these papers.

Table 3: Cost-effectiveness and constructability percentage comparison for jacketing techniques for RC column strengthening methods [65–68].

Parameter (Compared to Original Column)	RC Jacketing	FRP Jacketing	Hybrid Jacketing
Axial Strength Increase	Moderate	Low	Moderate
Flexural Strength Increase	Moderate	Low	Moderate
Shear Strength Increase	Moderate	Low	Moderate
Ductility Improvement	Low	Moderate	Moderate
Stiffness Increase	Moderate	Low	Low
Increase in Section Size	Low	Low	Low
Increase in Structural Mass	Low	Low	Low
Construction Time (Relative Reduction)	(baseline)	Moderate	Low
Labor Intensity (Relative Reduction)	(baseline)	Moderate	Moderate
Overall Cost Efficiency (Performance per Cost Gain)	Moderate	Moderate	High

4 Performance-Based Comparative Synthesis

4.1 Axial Load Enhancement Capacity

The axial load enhancement capacity of jacketed RC columns is governed by two primary mechanisms: section enlargement (RC and steel jacketing) and confinement-based strengthening (FRP, FRCM, ECC, and hybrid systems). For consistent comparison, performance is best interpreted using normalized indicators such as strength gain relative to added mass and confinement efficiency. RC jacketing provides reliable strength increases typically in the range of 40% to 80% through composite action and additional reinforcement [57,69], while steel jacketing can achieve increases exceeding 100% due to active confinement and yielding behavior [70]; however, both methods are associated with significant increases in structural mass and stiffness, reducing efficiency when evaluated on a weight basis. In contrast, FRP systems provide axial strength improvements of approximately 10% to 25% for rectangular columns and up to about 70% for circular columns [22,71], while FRCM systems achieve strength gains ranging from 0% to about 60% depending on textile configuration and bond performance [72,73]. These confinement-based systems introduce negligible additional mass, making them highly efficient in terms of strength to weight ratio, although their performance may be limited by debonding (FRP) or lower tensile capacity and bond behavior (FRCM). ECC jacketing, based on strain-hardening and microcrack control mechanisms, has been reported to provide strength enhancements of approximately 60% to 80%, while significantly improving post-peak behavior and stability [55,74]. Hybrid jacketing systems, which combine limited section enlargement with external confinement, typically achieve axial strength increases of about 35% to 70% with a relatively low mass increase of approximately 5% to 12%, resulting in improved structural efficiency [75,76]. Overall, RC and steel jacketing maximize absolute strength capacity, whereas FRP and FRCM systems provide superior efficiency, ECC enhances structural stability, and hybrid systems offer the most balanced trade-off between strength enhancement, added weight, and constructability.

4.2 Ductility and Deformation Capacity

Ductility and deformation capacity are primarily governed by the effectiveness of confinement and crack control mechanisms. These should be evaluated in relation to failure mode and energy dissipation. RC jacketing provides limited ductility improvement typically in the range of 20%–50%, as its contribution is mainly associated with increased confinement from transverse reinforcement and section enlargement rather than intrinsic deformation capacity [57,69]. Steel jacketing offers higher ductility enhancement, generally exceeding 50%, due to active confinement and yielding behavior that maintains lateral pressure at large strains [70]. FRP systems provide significant ductility improvements ranging from approximately 40% to 100%, particularly in circular columns where confinement is more uniform [22,71], although performance is reduced in rectangular sections due to stress concentration effects. FRCM systems demonstrate moderate ductility enhancement typically between 20% and 80%, with improved post peak behavior resulting from progressive matrix cracking and fiber slippage rather than sudden rupture [72,73]. ECC jacketing provides the highest deformation capacity, with ductility increases exceeding 60% and energy dissipation improvements reaching under cyclic loading conditions due to strain hardening and distributed microcracking behavior [55,74]. Hybrid systems achieve balanced ductility improvements in the range of 40% to 80%, combining confinement and section enlargement to improve cyclic stability and delay stiffness degradation [75,76]. Overall, ECC and hybrid systems provide the most effective enhancement in deformation capacity, FRP offers high ductility efficiency with minimal weight, while RC jacketing remains less effective in improving ductility despite its strength benefits.

4.3 Shear Enhancement and Confinement Efficiency

Shear enhancement and confinement efficiency depend on the ability of the jacketing system to control diagonal cracking and provide sustained lateral confinement, particularly under seismic loading conditions. RC jacketing increases shear capacity by approximately 30% to 60% through the addition of transverse reinforcement and section enlargement [57,69], while steel jacketing provides comparable or higher improvements with enhanced confinement efficiency due to active restraint and yielding behavior [70]. FRP systems improve shear capacity by approximately 25% to 50% through externally bonded transverse fibers that resist diagonal tension forces [22,38,71], offering high efficiency due to negligible mass addition but with sensitivity to bond performance and anchorage. FRCM systems provide moderate shear strength improvements with values generally within a similar range but slightly lower than FRP, while offering improved ductility and progressive failure behavior due to matrix cracking and fiber slip mechanisms [72,73]. ECC jacketing enhances shear performance primarily through distributed microcracking and crack width control rather than direct shear reinforcement, resulting in improved shear stability and energy dissipation under cyclic loading [74]. Hybrid systems provide the most balanced performance, achieving shear capacity increases of up to approximately 70% by combining internal shear reinforcement with external confinement [75,76]. Overall, RC and steel jacketing maximize absolute shear strength, while FRP, FRCM, and hybrid systems provide more efficient and ductile shear enhancement, particularly under seismic conditions.

4.4 Structural Mass and Stiffness Modification

The modification of structural mass and stiffness introduces a critical trade-off between local strengthening and global structural response, particularly in seismic applications where increased stiffness and mass may amplify demand. RC jacketing results in significant mass increases of approximately 20% to 45%, along with substantial stiffness enhancement due to cross-sectional enlargement and additional reinforcement [66,69], which may reduce displacement demand but increase seismic forces. Steel jacketing also increases mass and stiffness, although typically to a lesser extent than RC jacketing depending on thickness, while still influencing global structural behavior [70]. In contrast, FRP systems introduce negligible mass increase, typically less than 2%, with minimal effects on stiffness, making them highly efficient for maintaining the original dynamic characteristics of the structure [22,71]. FRCM systems introduce slightly higher mass than FRP but remain significantly lighter than RC jacketing, with moderate influence on stiffness while providing improved durability and fire resistance [72,73]. ECC jacketing introduces moderate increases in mass and stiffness. However, structural behavior improves by reducing stiffness degradation through crack control mechanisms [55,74]. Hybrid systems provide controlled mass increase of approximately 5% to 12%, while achieving meaningful improvements in strength and stiffness through combined mechanisms [75,76]. Overall, FRP and FRCM systems offer the highest efficiency in terms of performance gain per added mass, RC and steel jacketing are suitable when maximum strength is required despite global effects, and hybrid systems provide the most balanced solution for practical retrofitting applications.

5 Evaluation of Jacketing Techniques

5.1 Structural Analysis and Design Considerations

5.1.1 Load Carrying Capacity and Flexural Behavior

Structural jacketing is a method used to enhance the load-carrying capacity and the flexural resistance of existing structural elements such as beams, columns and slabs. The amount of enhancement in the load carrying capacity can vary depending in many factors such as the material used for the jacketing (concrete, steel, FRP or FRCM), the method of application, cross section of jacketing, bond strength and load

distribution. For reinforced concrete jacketing the increase of cross section area of the reinforced section will improve the load capacity. The load capacity enhancement of the capacity depends on the concrete strength and dimensions of jacketing. For steel jacketing the enhancement can be made by adding more thickness of the steel cross section by adding steel plate and bond it with the old steel section. Mostly the bond between the steel structure and the steel plate used for jacketing are bolting or welding. For FRP jacketing it has an advantage of light-weight material which will not add some load into the structure and it is very useful against seismic retrofitting since it is easy to apply and not adding weight to the structure.

The increase of axial load capacity for columns can be increased using the following formula Eq. (1) [70]:

$$P_{u,new} = P_{u,old} + A_j f'_{cj} + A_{sj} f_{yj} \quad (1)$$

where:

$P_{u,new}$: new axial load capacity

$P_{u,old}$ = original axial load capacity

A_j : Area of jacketing materials

f'_{cj} = compressive strength of jacketing materials

A_{sj} : Area of additional steel reinforcement

f_{yj} : Yield strength of new steel.

The increase of flexural capacity for concrete beams can be increased by the following formula see Eq. (2) [70]:

$$M_{u,new} = M_{u,old} + Z_{new} f_{cnew'} + f_{snew} A_{snew} \quad (2)$$

where:

$M_{u,new}$: new moment capacity

$M_{u,old}$: original moment capacity

$f_{cnew'}$: strength of new concrete

Z_{new} : section modulus of new cross-section

f_{snew} : Yield strength of new steel

A_{snew} : area of new steel reinforcement

5.1.2 Shear Strengthening and Confinement Effects

Shear strengthening involves increasing the shear capacity of structural elements (beams, columns, and slabs) to prevent shear failure, which typically manifests as diagonal cracking and eventual collapse. Shear can be strengthened by reinforced concrete jacketing, steel jacketing and FRP jacketing. For reinforced concrete jacketing the increase on the shear resistance by the additional concrete cross-section. The bond between the old and new concrete should be strong enough to transmit the load for the entire new section. The new capacity of shear resistance can be estimated using the following formula see Eq. (3) [70]:

$$V_{u,new} = V_{u,old} + V_{s,new} \quad (3)$$

where:

$V_{u,old}$: original shear capacity

$V_{u,new}$: shear capacity provided by the new concrete

$V_{s,new}$: shear capacity provided by the new transverse reinforcement

In case of steel jacketing, steel plate and straps are bolted onto the side of structural element. The new steel jacketing should be properly anchored to transmit the load and should be designed against buckling from the shear load. The additional shear resistance capacity from steel plate can be estimated using the following formula see Eq. (4) [70]:

$$V_{u,new} = V_{u,old} + V_{steel} \quad (4)$$

where:

V_{steel} : shear capacity provided by the steel plates.

Shear capacity can be also increased by using FRP jacketing which has high-strength and wrapped around the structural element to enhance the shear strength. FRP should be properly placed to utilize its full capacity with the existing structure with good bonding material as well as the orientation and direction of the fibers. The additional shear resistance added by the FRP can be estimated using the following formula see Eq. (5) [70]:

$$V_{u,new} = V_{u,old} + V_f \quad (5)$$

where:

V_f : shear capacity provided by the FRP wrap.

Another advantage of jacketing is the increase of the confining effect which give the structure more resistance under lateral loads and prevent dilation under compressive loads. The confining effect vary depend on the method of jacketing used. Jacketing materials should be bonded properly to give full potential of confinement. The confining effect for (concrete, steel and FRP) jacketing can be estimated using the following formula see Eqs. (6)–(8) [70]:

$$f'_{cc} = f'_c \left(1 + k \frac{f_l}{f'_c} \right) \quad (6)$$

$$f_l = \frac{2f_{y,st}A_{st}}{sd} \quad (7)$$

$$f'_{cc} = f'_c \left(1 + \frac{kE_ft_f}{df'_c} \right) \quad (8)$$

where:

f'_c : unconfined concrete strength

f_l : effective lateral confining pressure

k : confinement effectiveness coefficient

$f_{y,st}$: yield strength of steel

A_{st} : cross sectional area of steel jacket

S : spacing of steel hoops

d : diameter of confined core

E_f : modulus of elasticity of FRP

t_f : thickness of FRP wrap

5.1.3 Durability Considerations

The durability of jacketing plays a critical factor in the success of structural jacketing to ensure long-term effectiveness and integrity of the enhanced element. Structure is exposed to many environmental exposures such as moisture, temperature variations and chemical exposure. These factors can cause corrosion and degradation of the concrete and FRP jacketing system and thermal expansion. To avoid these problems the materials compatibility between old structure and the jacketing system is achieved. Jacketing materials should have similar thermal expansion in order to avoid any cracking and desponding. Chemical compatibility prevents any reaction between different materials that can lead to deterioration. Bond strength also plays very important role to ensure the composite will prevent delamination.

5.2 Performance Assessment and Retrofitting Strategies

5.2.1 Non-Destructive Testing Methods for Assessing Jacketed Structures

Jacketed structures can take various forms and, when executed correctly, can significantly extend their lifespan [22]. This not only conserves raw building materials but also saves capital, labor hours, and addresses issues related to construction disposal waste and recycling. However, a critical aspect is ensuring that the effectiveness of the jacketing technique is evaluated to confirm that it has restored the properties or achieved the intended intervention goals [73,77]. Given the diversity in structural design and material usage, effective restoration is not always a simple undertaking. Modern diagnostic techniques are increasingly applied to assess the jacketed structures and overall structures. Non-destructive testing of building materials is a key aspect of this diagnostic field. Materials such as concrete, fiber-cement, and steel undergo testing for various reasons, typically during construction and throughout their service life. For this, a variety of investigative techniques are used, which are divided into destructive, semi-destructive, and non-destructive techniques according to their intrusiveness [72]. A general classification of techniques for diagnosing buildings and building materials is shown in Fig. 16.

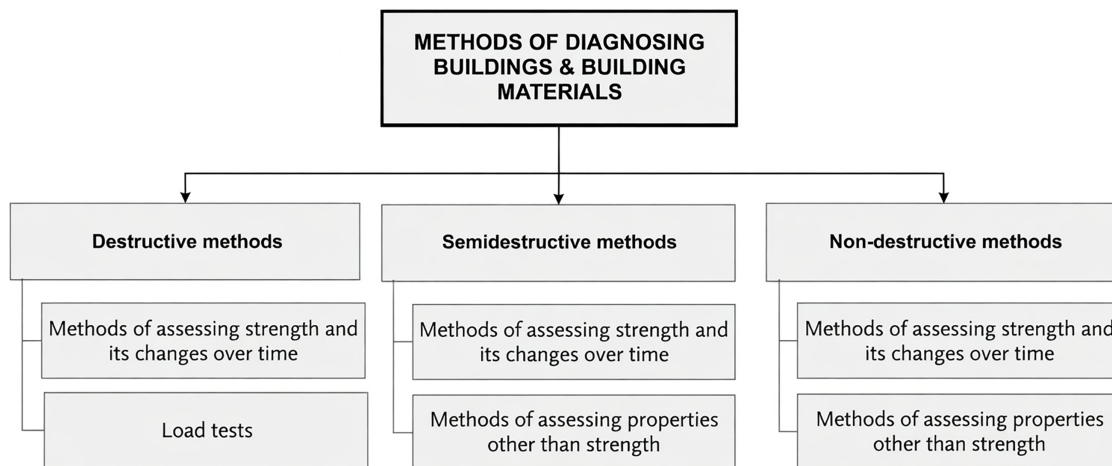


Figure 16: General classification of investigative methods useful for diagnosing jacketed structures and building materials [72]. Adapted with permission from Ref. [72]. Copyright ©2019, MDPI.

It is clear to distinguish that semi-destructive methods typically cause limited and surface-level damage to the material under examination, whereas non-destructive methods do not induce any damage. This non-invasive characteristic of non-destructive techniques makes them particularly well-suited for analyzing extensive surfaces and delving into significant depths, which is advantageous for construction and overall

assessment purposes. Furthermore, the ability to repeat measurements with non-destructive methods enables the verification and validation of test outcomes [22,72,73,77]. A general classification of non-destructive methods that are useful for diagnosing buildings and building materials [5] is presented in Figs. 17 and 18, provides an in-depth categorization of non-destructive methods that are beneficial for diagnosing buildings and building materials.

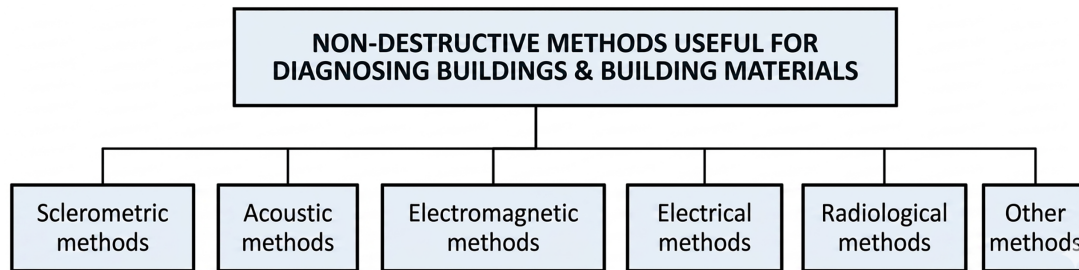


Figure 17: General classification of non-destructive methods useful for diagnosing jacketed structure and repairing building materials [72]. Adapted with permission from Ref. [72]. Copyright ©2019, MDPI.

5.2.2 Retrofitting Strategies Based on Structural Assessment Results

The most effective retrofitting strategies are determined by evaluating the results of the structural assessment, available repair resources, and the time available for repairs. These conducted assessment aims to enhance the performance of jacketed structures affected by the main causes that determined during the assessment stages [1]. Recognizing the best retrofitting strategies are mainly involved in the following considerations:

- Establishing the comprehensive approach or blueprint for remedying the damage or deterioration within a structure.
- A systematic investigation report is indispensable.
- A meticulous evaluation of the structure's condition should encompass:
 - Identifying the root cause of damage or loss of protection.
 - Assessing the extent and speed of deterioration.
 - Anticipating the progression of damage over time.
 - Understanding the impact of damage on structural behavior and serviceability.

Additionally, it proposes that the repair strategy is contingent upon several factors, including:

- Cause and extent of damage: Understanding what caused the damage and how extensive it is.
- Consequences of the damage: Assessing whether the damage impacts the structural safety or merely the appearance of the structure.
- Appropriate time for intervention: Determining if immediate repairs are necessary or if they can be deferred due to the slow rate of damage.
- Economic aspect: Evaluating the cost-effectiveness of the chosen repair method.
- Operational constraints: Considering any limitations or logistical challenges that may affect the repair process.
- Durability, feasibility, and desired service life of the structure: Ensuring that the chosen repair method aligns with the long-term goals for the structure's lifespan and functionality.

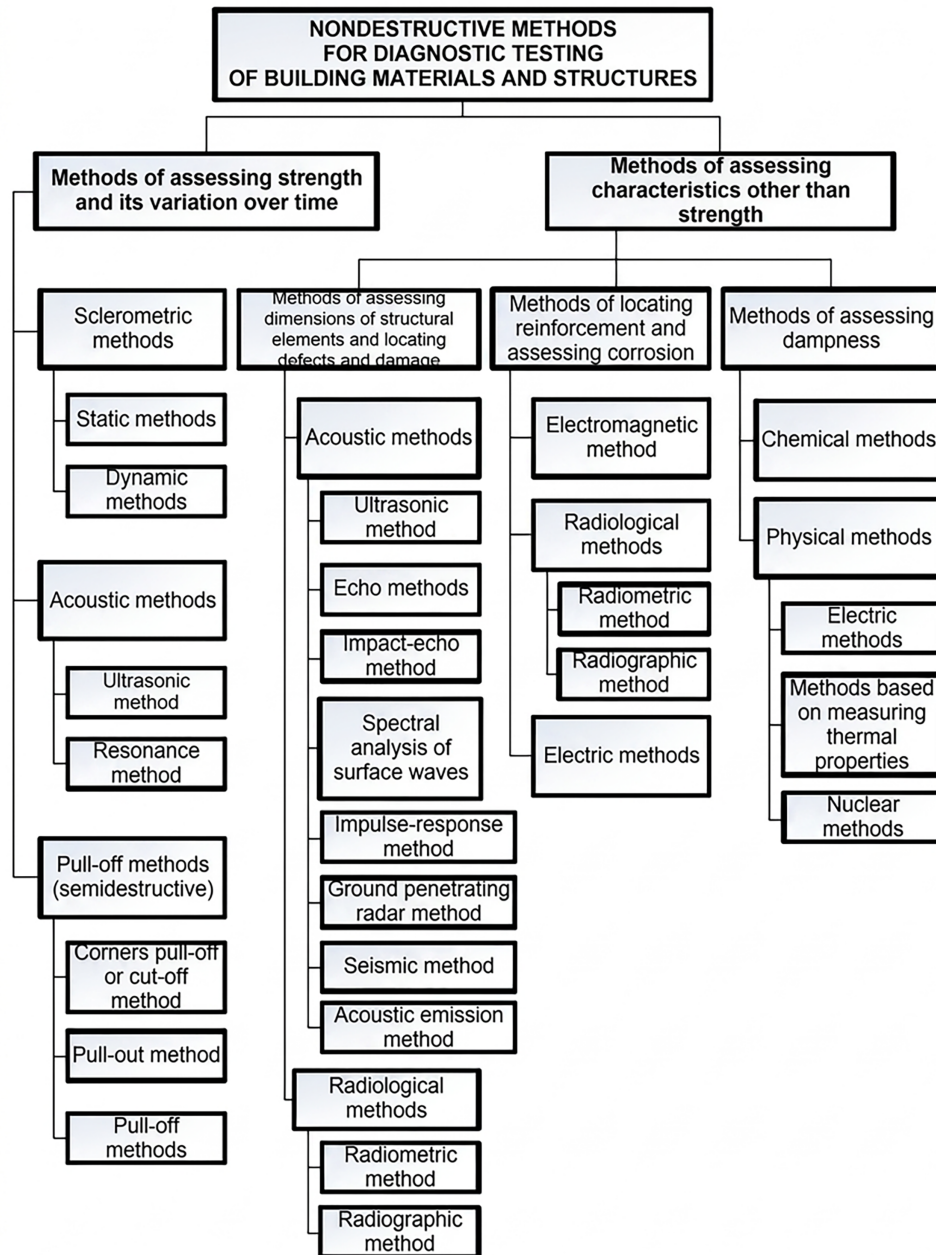


Figure 18: Non-destructive methods useful for diagnosing building structures and building materials [72]. Adapted with permission from Ref. [72]. Copyright ©2019, MDPI.

5.2.3 Long-Term Performance Evaluation of Jacketed RC Column Structures

In order to evaluate the long-term performance of jacketed RC columns, performance monitoring should be conducted. As a case study conducted by Shamim [1]. In the mid-1990s, GFRP was used to repair a number of columns in different bridges that were mainly damaged by steel corrosion in and around Toronto as shown in Fig. 19 below.



Figure 19: Damaged highway bridge columns [1]. Adapted with permission from Ref. [1]. Copyright ©2007.

One of these bridges crosses Leslie Street on Highway 401. According to the lab study, the loss of concrete cover and steel corrosion caused the damaged columns' axial load carrying capacity to drop by roughly 20%. Three types of grouts were used to build the columns to their original shape before wrapping them with GFRP. The grouts used were based on regular cement, non-shrink cementitious materials, or expansive cement. The repaired columns have performed without problems over the course of more than 11 years of observation. During this time, there has been no discernible degradation of the columns or the GFRP. Corrosion monitoring revealed a significant reduction in both corrosion rates and associated risks in the GFRP-repaired columns over time. Field measurements of strain, corrosion rates, and physical inspections over the eleven-year period confirmed the effectiveness and durability of the retrofit techniques applied to the columns. Column 1 is depicted in the Fig. 20 prior to, immediately following, and in 2006. There was no evidence of any deterioration, and there is now less chance of corrosion in the future. Furthermore, none of the columns repaired over eleven years ago required re-repair. In order to prevent potential long-term alkali-related damage to the GFRP, a thin polyethylene sheet was applied in some columns during this initial GFRP repair project as a barrier to keep the new mortar or concrete away from the GFRP. Since then, GFRP sheets' exceptional long-term durability in alkaline environments has been validated by extensive testing. Consequently, future GFRP repairs can be performed without using such barriers. While the barrier is not essential for protecting the glass from alkalis, it may have contributed to the observed reduction in corrosion activity within the columns.



Figure 20: GFRP jacketed columns before and after repair [1]. Adapted with permission from Ref. [1]. Copyright ©2007.

In modeling the behavior of retrofitted columns accurately, several advanced structural analysis techniques, such as finite element analysis (FEA), are needed. With the tools, engineers can perfectly simulate the impact of retrofitting under different load conditions and revealing the stress concentration points and potential failure modes in the members. In Table 4, Jacketing techniques were evaluated in multiple factors.

Table 4: Comparative evaluation of jacketing techniques.

Technique	Strength Gain	Ductility Gain	Added Weight	Durability	Cost	Construction Disruption	Suitability
RC Jacketing	High	Moderate	High	High	Very High	High	Heavily damaged or deteriorated RC
Steel Jacketing	Very High	High	High	Moderate (unless SS)	High	High	Seismic retrofitting, industrial zones
FRP Jacketing	High	High	Low	Low (sensitive to UV/fire)	Moderate	Low	Seismic retrofit, confined spaces
FRCM Jacketing	Moderate–High	High	Low–Moderate	High	Moderate	Moderate	Repair with high durability demands
Ferrocement Jacketing	Moderate	Moderate	Moderate	Moderate	Low	Moderate	Economic repair in developing regions

6 Research Gaps and Future Challenges and Directions

6.1 Research Gaps

Although a substantial body of research has addressed jacketing techniques for strengthening reinforced concrete (RC) columns, the distribution of experimental and analytical efforts remains uneven across key structural parameters. Based on the surveyed literature, most of experimental studies focus on short columns subjected to concentric or near-concentric axial loading [33,75,78]. However, there is a relatively limited

experimental database for studies investigating combined axial–flexural behavior or eccentric loading, despite the fact that eccentric loading conditions are more representative of real column behavior in buildings and bridges, especially under seismic actions [56,57]. A similar imbalance is observed with column geometry: more than 60% of reported experimental database focus on circular columns, while rectangular and square column, which are the most existing building stock, are less frequently reported in published studies [74,75]. This disparity limits the general applicability of confinement models and design recommendations, especially for FRP and FRCM systems, where stress concentrations at corners and non-uniform confinement significantly influence strengthening efficiency [56,57]. Furthermore, experimental studies considering pre-damaged or corrosion-affected columns remain relatively limited, even though deterioration and corrosion are among the primary motivations for column rehabilitation in practice [38,55].

Another research gap is related to the limited quantitative evaluation of long-term durability and environmental exposure effects on jacketed RC columns. Short-term mechanical performance under monotonic or cyclic loading is well documented, but, less published studies explicitly investigate the influence of high temperature, freeze–thaw cycles, sustained humidity, or ultraviolet exposure on the residual strength and ductility of strengthened members [67]. This shortfall is particularly evident for FRP and hybrid jacketing systems, where degradation of epoxy matrices, bond deterioration, and reduced fire resistance may govern long-term performance [67,75]. Although FRCM and ECC jacketing techniques are frequently proposed as more compatible and fire-resistant alternatives, few available studies provide direct, quantitative comparisons of durability-related strength retention or ductility degradation relative to conventional FRP or steel jacketing [56,57,64]. In addition, economic considerations remain largely qualitative; few studies report normalized cost metrics, construction time, or performance-to-cost indices, limiting objective comparison and informed decision-making for practical applications [65,66]. These quantified observations highlight the need for future research that integrates realistic loading conditions, durability-oriented performance indicators, and lifecycle-based economic assessments to support performance-based selection of jacketing techniques.

6.2 Limitations and Challenges Associated with Jacketing Techniques

The seek to develop effective strengthening and repair techniques for RC columns has been a significant focus for researchers over the past few decades. Balancing structural requirements like enhancing strength, ductility, and drift with various non-structural considerations such as cost, minimal disruption during implementation, aesthetics, durability, and safety is paramount [1]. However, there are challenges associated with strengthening and repairing. For instance, localized changes in member stiffness resulting from repair interventions can alter the dynamic properties of the structure. Consequently, this can shift seismic demands to individual elements or the entire building, necessitating careful consideration and analysis during the repair process [1]. The challenges in jacketing technique for retrofitting and strengthening of RC column have been categorized based on the impact on strength, ductility, stiffness, cost, aesthetics, and the impact on occupants. The latter specifically refers to the effect on building occupants during the implementation of strengthening and repair techniques. Tables 5–7, summarizes the drawbacks and effectiveness of each technique within each category with each Criteria of comparison. It's important to remember that the performance levels shown in Table 4 are only broad generalizations based primarily on the observations and results of the individual studies described in the sections above. Depending on the particulars of each case, the difficulties associated with each strengthening or retrofitting technique will vary.

Table 5: Drawbacks summary of the different jacketing techniques for repair and strengthening RC column.

RC Jacketing	- Costly, requiring significant labor and time, primarily due to the installation of formwork. - Changing the cross-sectional size can result in variation to stiffness and seismic demands. - Ductility increase is low due to brittle nature of concrete - Disruption of occupancy
Steel Jacketing	- Labor intensive and expensive. - Rusting and corrosion - Heavy weight
Externally bonded FRP Jacketing	- Higher cost material: however, transportation and installation cost are low. - Low efficiency (30%–35%) due to debonding - Poor properties on exposure to high temperature and wet environment
Near-Surface mounted FRP or Steel reinforcement	- Higher cost material: however, transportation and installation cost are low. - Requires more labor than externally bonded FRP but less than steel and RC jacketing. - Slight increase in ductility

Table 6: Criteria of comparison between jacketing techniques.

Criteria	RC Jacketing	Steel Jacketing	FRP	FRCM	Ferrocement
Structural Strength	High	Very High	Moderate	Moderate	Low
Ductility Improvement	Moderate	High	High	High	Low
Seismic Performance	Moderate	Very High	High	High	Low
Environmental Durability	Moderate	Moderate	Low	High	Moderate
Installation Complexity	High	High	Moderate	Moderate	Low
Cost Efficiency	Low	Low	Moderate	Moderate	High
Aesthetic Impact (Column Size)	××	×	✓✓✓	✓✓✓	×

Table 7: Comparison of the different jacketing techniques for repair and strengthening RC column.

Strengthening Method	Effect on Strength	Effect on Ductility	Effect on Strengthening	Cost of Strengthening	Aesthetics/Impact to Floorplan	Impact to Occupants
RC Jacketing	Increase	Increase	Unchanged/increased	Very high	Poor	Very high
Steel Jacketing	Significant increase	Significant increase	Unchanged/increased	Very high	Moderate	High
Externally bonded FRP Jacketing	Significant increase	Significant increase	Unchanged	Moderate	Good	Moderate
Near-Surface mounted FRP or Steel reinforcement	Significant increase	Increase	Unchanged	Moderate	Good	High

In comparison, RC jacketing and steel jacketing usually employ cost-effective construction materials with straightforward load transmission mechanisms. However, they are often labor-intensive and time-consuming, making them less cost-effective overall. On the other hand, externally bonded FRP and near-surface mounted FRP tend to have lower material costs, but their effectiveness in terms of cost is influenced by factors such as labor and time. Although the cost of externally bonded FRP and near-surface mounted FRP is higher compared to RC jacketing and steel jacketing, the overall cost-effectiveness is typically greater due to cheaper transportation and installation costs. Furthermore, these techniques are often considered superior in terms of aesthetics and their impact on the floor plan. Externally bonded FRP and near-surface mounted FRP or steel reinforcement result in minimal changes to the column cross-section, making them more favorable from a visual and floor plan perspective. In contrast, RC jacketing tends to significantly increase column dimensions, thereby having a more pronounced impact on aesthetics and the overall floor plan of a building.

6.3 Emerging Trends and Advancements in Jacketing Materials and Methods

In term of recent advancement in jacketing materials and method, researchers [67] have been exploring the development of new hybrid FRP composites, which combine two different types of fiber materials. By integrating these distinct fibers, the resulting hybrid material can lead to the benefits of each individual component. This approach aims to capitalize on the unique properties of each fiber type, thereby enhancing the overall performance and capabilities of the composite material. Fakharifar et al. [66] proposed an innovative hybrid jacketing method for the quick and lightweight repair of earthquake-damaged bridge piers. As illustrated in Fig. 21, this method entails applying prestressing strands externally and wrapping the damaged reinforced concrete (RC) column internally with a thin sheet of cold-formed steel. The damaged concrete was also replaced with repair grout. This technique was used by the researchers on a large, inferior RC column that was common in construction prior to the 1970s. When a constant axial load and cyclic lateral forces were applied, the column first suffered damage until its strength dropped by 25%. Afterward, the proposed retrofitting technique was implemented to repair the column. Experimental results were promising, showing that the hybrid confinement method notably improved both the flexural strength and ductility of the damaged column.

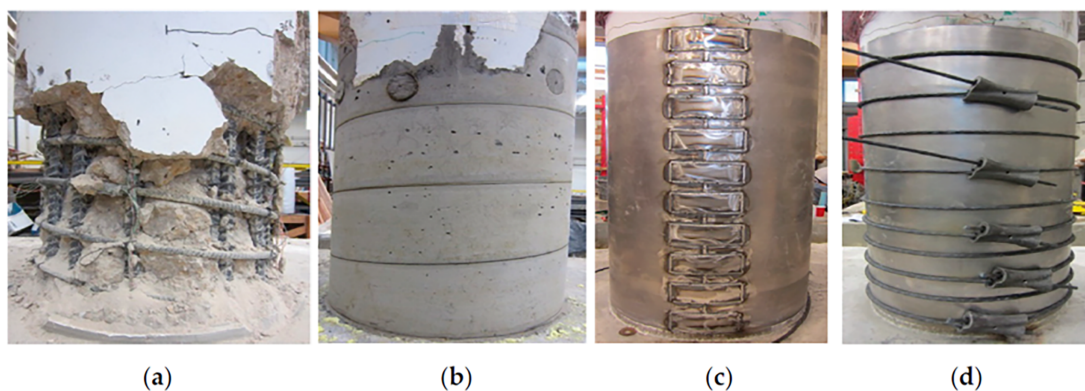


Figure 21: Hybrid confining jacketing repairing procedure: (a) Initially damaged column; (b) Patched column with repair grout; (c) Metal sheet wrapping; (d) Installation of prestressing strands [66]. Adapted with permission from Ref. [66]. Copyright ©2015, Semantic Scholar.

7 Conclusions and Future Recommendations

7.1 Conclusions

This review has examined the state of practice and recent developments in jacketing techniques for the repair and rehabilitation of reinforced concrete (RC) columns. Reinforced concrete jacketing, steel jacketing, FRP systems, FRCM composites, ECC, and hybrid solutions were reviewed and compared based on their strengthening mechanisms, structural performance, constructability, durability, and cost implications. The collected evidence confirms that jacketing methods can enhance column performance when appropriately selected and designed. Conventional RC and steel jacketing remain reliable options in severely deficient columns to restore their strength; however, their application is often accompanied by increased structural mass, changes in stiffness, and practical challenges related to construction and space limitations.

In contrast, composite-based systems have demonstrated clear advantages in situations where lightweight solutions and minimal geometric alteration are required. FRP jacketing provides efficient confinement and notable improvements in ductility, particularly for circular columns, although its effectiveness is reduced in non-circular sections and in aggressive environmental conditions. FRCM systems have emerged as a more compatible alternative, offering improved fire resistance and substrate compatibility while exhibiting a more gradual and progressive failure response. Recent studies on ECC jacketing highlight its strong potential for seismic strengthening applications, as the strain-hardening behavior and controlled microcracking of ECC significantly enhance deformation capacity and energy dissipation under cyclic loading. Hybrid jacketing systems, which combine thin cementitious jackets with external FRP confinement, appear to offer a practical balance between strength enhancement, ductility improvement, and constructability, making them especially attractive for retrofitting substandard or space-constrained RC columns.

Despite the substantial body of research reviewed, several important gaps remain. Existing experimental data are still largely concentrated on short, circular columns subjected to concentric loading, while fewer studies address eccentric loading, realistic seismic demand, or columns affected by prior damage or corrosion. In addition, long-term durability performance under environmental exposure, as well as quantitative cost and lifecycle assessments, remain insufficiently explored, particularly for emerging systems such as FRCM, ECC, and hybrid jacketing. Addressing these limitations through targeted experimental programs, durability-focused investigations, and performance-based design frameworks will be essential for improving the reliability and wider adoption of advanced jacketing techniques. Overall, this review provides a consolidated technical reference for researchers and practitioners, while also outlining clear directions for future work aimed at achieving safer, more durable, and economically efficient rehabilitation of RC column structures.

7.2 Future Recommendations

Despite the significant progress achieved in the development and application of jacketing techniques for the repair and rehabilitation of reinforced concrete columns, the reviewed literature reveals several unresolved challenges and research gaps. Addressing these issues through targeted experimental, analytical, and durability-focused investigations is essential for improving the reliability, applicability, and long-term performance of existing and emerging jacketing systems. Accordingly, the following recommendations are proposed to guide future research efforts in this field.

- Future experimental studies should place greater emphasis on RC columns subjected to eccentric and combined axial–flexural loading, as these conditions more accurately represent real structural behavior in buildings and bridges, particularly under seismic actions.

- Additional investigations are needed on rectangular and square RC columns, which dominate existing building stock, to improve the applicability of confinement models and design recommendations beyond circular sections.
- More research should focus on pre-damaged and corrosion-affected RC columns, as deterioration and reinforcement corrosion are among the primary drivers for rehabilitation in practice, yet remain underrepresented in current experimental databases.
- Long-term durability performance of jacketed columns under environmental exposures such as elevated temperature, freeze–thaw cycles, ultraviolet radiation, and high humidity should be evaluated, particularly for FRP, FRCM, and hybrid jacketing systems.
- Quantitative comparisons of durability-related strength retention and ductility degradation among different jacketing techniques are required to support performance-based material selection, especially for emerging systems such as FRCM and ECC.
- Future studies should incorporate lifecycle cost analysis, including construction time, maintenance requirements, and performance-to-cost indices, to enable objective economic comparison among jacketing techniques.
- Advanced numerical modeling and finite element analysis should be further developed and validated to simulate complex failure mechanisms, stress concentrations, and long-term behavior of jacketed RC columns under realistic loading scenarios.
- Greater attention should be given to hybrid jacketing systems that combine steel, FRP, cementitious composites, or prestressing elements, as these systems show strong potential for balancing strength enhancement, ductility improvement, constructability, and durability.
- The integration of non-destructive evaluation techniques and data-driven approaches, including structural health monitoring and artificial intelligence, is recommended to assess in-service performance and optimize retrofit design strategies.

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