Publisher: Engineering College, Al Muthanna University

Open Access

DOI:10.52113/3/eng/mjet/2026-14-02-/77-90, Vol. (14), Issue (2), (2026)

Muthanna Journal of Engineering and Technology
MJET

Submitted 13 March 2026, Accepted in revised form 11 April 2026, Published online 02 May 2026

Traditional and Modern Techniques for Strengthening RC Columns under Seismic Loads: A Review

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Abstract

Reinforced concrete (RC) columns are fundamental components in structural systems. Vertical loads are transferred from the top of the structure to the foundation. Due to exposure to various environmental and structural factors such as bearing capacity, seismicity, and corrosion of rebars, columns are susceptible to performance degradation or loss of load-bearing capacity. Therefore, the application of strengthening techniques has become crucial for restoring column efficiency and improving their structural behavior. Recent years have witnessed significant advancements in strengthening methods, including the utilize of advanced combined like fiber-reinforced polymer (FRP), in addition to ferrocement and other strengthening techniques. These modern methods offer an attractive alternative to traditional methods involving concrete and steel jackets. All these techniques increase the column's resistance to compressive, shear, and buckling forces, and also aim to improve the ductility and stiffness of the element as a whole. Environmental conditions, the nature of the damage, design requirements, feasibility of implementation, and cost are important factors in selecting the appropriate techniques. This review aims to study traditional and modern techniques used in RC columns, analyze the operating principle of each technique, and examine the factors affecting its effectiveness. Its performance and usage limits provide a knowledge base that contributes to improving design and engineering decisions in this vital field. The literature shows that modern reinforcement technologies, especially using FRP, fundamentally transform the seismic response of RC columns by promote lateral confinement, increasing energy dissipation and ductility, while transforming the failure pattern from brittle attitude to safer ductile attitude, but their efficiency remains limited by the quality of bonding with concrete and the effects of the environment, where the separation (Debonding) is the most prominent challenge in long-term performance.

Keywords: *Column, Jacketing, Modern, Seismic, Strengthening, Techniques.*

1. Introduction

Earthquakes are among the most devastating naturalistic phenomena. They release enormous energy, subjecting structures to dynamic stresses and intense ground movements. This causes deformations in structural elements that are often greater than their design capacity. The vulnerability of (RC) buildings to resist such seismic demands can result in catastrophic failures. Historical seismic events have demonstrated widespread collapses and damage. Historical seismic events have revealed widespread collapse and severe damage to numerous RC buildings and other infrastructures in various locations around the world for instance, U.S.A. (San Fernando Valley, 1971) Mexico (Mexico City, 1985); Japan (Kobe, 1995); India (Bhuj, 2001); Haiti (2010) [1]. Furthermore, Turkish earthquakes (Kocaeli 1999, Duzce1999, Bingol2003) demonstrated that insufficient ductility and strength of (RC) columns as a result of inadequate transverse reinforcement detailing can result in significant constructional damage which may lead the frame buildings to collapse [2].

As a result, most areas prone to earthquakes now acknowledge that the existing buildings present a significantly greater seismic risk than new constructions. This is due to the fact that older structures were built either prior to the introduction of a seismic risk requirements or according to outdated seismic Codes, which are currently recognized as insufficient. In Greece, approximately 80% of buildings considered old (based on the 1985 cutoff year for distinguishing between old and new structures, due to a significant revision of the seismic code that year) are at risk[3]. In addition, the older buildings had been made from low compressive strength concrete (about 15–20 MPa), that means they do not comply with present design codes of seismic. Columns of such concrete structures under seismic loading exhibit a significant reduction in their capacity to bear lateral loads after the peak load and demonstrate limited deformation ductility [4].

Recent years have witnessed a significant increase in the number of studies examining earthquake-damaged structures. These studies have focused on analyzing structural deficiencies that contribute to the poor performance of these structures. Among the most prominent of these deficiencies are the use of low-quality concrete, inadequate end-beam enclosures, failure to implement the strong column-weak beam principle, the emergence of short column behavior, insufficient bond lengths, and poor detailing of passenger hooks. Collectively, these factors reduce the structure's ability to resist seismic loads [5]. Seismic design has advanced quickly, leading to new reinforced concrete (RC) structures that are more likely to behave satisfactorily in the event of an earthquake. Nonetheless, advances in seismic design methodologies have led to some uncertainty about whether existing RC buildings exhibit adequate seismic behavior The primary cause of the collapse of these reinforced concrete buildings was the failure of columns. This failure was linked to insufficient details (hoops spaced too far apart and open hooks) in transverse reinforcement, in addition to inadequate anchoring of main (longitudinal) reinforcement [4].

On the other hand, it is increasingly common for construction work to involve repairing and rehabilitating existing structures. Some estimates suggest that, globally, in 2010 maintenance and repair expenditures accounted for approximately 85% of total construction spending. Thus, the creation of repair/retrofit methods that are both economical and durable can Reduction of maintenance requirements, improving safety’s, extending the operational of concrete's life structures.[6]. Thus, the necessity for seismic strengthening arises in numerous scenarios. Determining the most appropriate technique for reinforcing a particular structure, however, represents a complex challenge. The engineer is tasked with evaluating and choosing from a range of potential strategies and methodologies, some of which may be unfamiliar or require specialized expertise for effective application [3]. Traditional methods such as steel jackets and concrete jackets enhance the seismic performance of structures by increasing the column's cross-sectional area, Subsequently, researchers have been proposing and evaluating new techniques that introduce minor structural engineering modifications while also enhancing structural strength. Although, the numerous benefits of traditional techniques, the modern techniques (with many different types) have been used. One of these modern techniques was employing of Fiber-reinforced polymers (FRPs), which are widely considered an attractive alternative to traditional strengthening techniques, and significant international research efforts have been dedicated to investigating various aspects of FRP strengthen e.g. [7] [8][9][10]In a study, light ceramist concrete (FLWCC) was used to strengthen reinforced concrete columns in order to improve their seismic resistance, where periodic load tests were carried out on seven columns, one of which is a reference and the rest are reinforced under different conditions. The results showed a significant improvement in seismic performance, with an increase in endurance by more than 100%, improved ductility and energy dissipation, as well as reduced damage. Epoxy was also more effective than cement mortar, while increased axial load led to reduced displacement and ductility. A numerical model was also developed and its accuracy verified; a reliable equation was proposed to calculate the seismic capacity of reinforced columns. [8].

Wang et al. [9] designed and tested a wedge tensioning instrument that permits to the reinforcement RC columns of square section using multilayer CFRP prestressed fibers. Experiments were carried out on nine columns against the impact of steady axial load and periodic horizontal loads, with changing axial compression ratios, prestressing levels, the number of layers and the area of packaging. The results showed a significant improvement in the ductility and energy dissipation capacity of the reinforced columns. It was also shown that an increase in prestressing significantly affected the stiffness and endurance, while an increase in the number of CFRP layers had a greater effect in enhancing energy dissipation. It was noted that the complete fiber wrapping significantly increased the maximum drift by 167%, and the power dissipation capacity increased by 6.5 times compared to unsupported columns.

While addressing the difficulty of achieving a balance between ductility, drift reduction and cost using FRP systems. Lu et al. [10] has developed a multi-objective optimization framework that combines a finite element model with an evolutionary algorithm to maximize performance and minimize cost. The accuracy of the model was verified by comparing it with the results of periodic experiments, during which balanced optimal solutions were obtained. The analysis showed that the power dissipation ratio was the most important factor in reducing the residual drift. The results also showed that ECC with BFRP enhanced ductility, while CFRP systems reduced drift, while BFRP economical options remained effective.

Despite the remarkable progress in reinforced concrete column strengthening technologies using traditional and modern methods, there is still a research gap represented by the limitation of comprehensive comparative studies under real seismic loads, poor representation of dynamic behavior in numerical models, especially with regard to the effect of strain rate and interface interaction between concrete and reinforcing materials such as FRP. The lack of Applied Studies in extreme environments also limits the popularization of these technologies. Accordingly, this study aims to provide a comprehensive and systematic scientific review of the assessment and comparison of the efficiency of various strengthening methods under the influence of seismic loads, by analyzing the experimental and numerical results available in the literature. Additionally, the study examines new advancements in reinforcement materials and technologies, including fiber-reinforced polymer (FRP) encapsulation, reinforcement with shape memory alloys (SMA), and composite systems that strike a balance between structural effectiveness and economic sustainability.

2. Reasons for strengthening reinforced concrete columns

RC columns are pivotal constructional parts in concrete structures, as they carry out the task of transferring vertical and horizontal loads to the soil, achieving the overall stability of the facility [11], [12]. However, during their service life, these elements are exposed to various factors that degrade their performance, which necessitates strengthening interventions to restore their ability to withstand loads, especially seismic ones. These reasons can be classified into four main categories. Firstly, the shortcomings of the old design constitute one of the most prominent motives for the stiffeners. Many existing facilities, especially those built before the seventies of the last century, were designed according to building codes that did not adequately take into account the requirements of earthquake resistance [13] [14]. This shortcoming is most often manifested in insufficient transverse armament and its poor detailing, such as the use of 90-degree open collars instead of 135-degree closed collars, and a large spacing between them [15]. This deficiency reduces the column's ability to confine concrete, limiting its ductility and shear resistance, and makes it vulnerable to sudden collapse under seismic loads [16] [17]. Priestley and Park in their fundamental study noted that insufficient details of the armament lead to a bombing failure of the columns under seismic loads [17].

Secondly, environmental degradation erodes the capacity of the columns over time. Corrosion of rebar caused by the penetration of chlorides into coastal installations or the carburization of concrete are the main reasons for this deterioration [18][13]. Corrosion causes a lack of area of the rebar section and deterioration of its mechanical properties, and the expansion of rust products leads to cracking and fragmentation of the concrete cover, which weakens the bonding between iron and concrete and negatively affects the bearing capacity and rigidity of the Shaft [13][15]. In addition, freezing and thawing cycles in cold climates negatively affect concrete, causing its cracking and loss of cohesion, which aggravates the weakness of the column [13].

Thirdly, natural disasters, especially earthquakes, are a direct cause of the need for strengthening. Exposure to an earthquake may cause local damage to the columns, such as shear cracking, longitudinal rebar dents, or concrete fragmentation in the node areas [13]. Such damage, even if it did not lead to total collapse, reduces the efficiency of the origin to resist future tremors [19]. Studies have shown that installations located in harsh environments and prone to corrosion are more prone to collapse, which makes their strengthening a top priority to ensure public safety [13][14].

Fourthly, a change in the use of the building leads to an increase in the loads on the columns beyond what they were originally designed for [15]. These changes include adding new roles to the building, shifting its use from residential to commercial which increases live loads, or even adding new loads such as installing heavy equipment on roofs [15] [16]. In such cases, it becomes necessary to strengthen the columns to raise their bearing capacity to meet the requirements of new loads and avoid over-stress that may lead to structural failure [11][12].:

3. Mechanisms of seismic response of RC columns

The reinforcement of reinforced concrete columns is mainly aimed at improving their seismic performance by modifying their response mechanisms to periodic loads. These mechanisms can be summarized in four main points. Firstly, improving the ductility and increasing the energy absorption capacity is one of the fundamental goals of potentiation processes [12] [16]. Ductility is the ability of a column to withstand significant deformations in the plasticity range without collapse, which is a crucial property of earthquake resistance [17]. Reinforcement systems, such as steel jackets or fiber-reinforced polymer caps, confine concrete, increasing its maximum reactivity and improving its behavior under stress [18] [12]. Laboratory results show a significant increase in ductility up to 100-200% compared to its value in non-reinforced samples, with a parallel improvement in the amount of energy that the column can absorb and dissipate in the form of heat during repeated loading Cycles [18] [14].

Some studies have shown an increase in absorbed energy exceeding 50-60% when using hybrid systems combining FRP fibers and shape memory alloys [18] [14]. Secondly, the stiffener serves to change the failure pattern from a bombardment breakdown to a plastic failure [16] [20]. Poorly cross-armed columns are prone to sudden and very serious bombing failures [15][17]. Strengthening strategies, such as the addition of outer jackets, significantly raise the shear resistance of the shaft, increasing it by 30% to 80% according to recent studies [18][14]. This transformation transforms the nature of the collapse from a violent collapse that lacks any advance warning to a gradual failure accompanied by obvious cracks and deformations that alert the users of the building before the disaster occurs [16] [20]. A study by Hou et al. has shown that the use of vests of high-strength cement compounds armed with a fabric can effectively change the failure pattern [21]. Thirdly, strengthening contributes to addressing the weakness of the philosophy "weak column - strong bridge" [16]. In many old constructions, the columns are weaker than the bridges connected to them, which leads to a concentration of damage and the formation of spandex joints in the columns during an earthquake, and this may cause a complete collapse of the facility [13][19].

Reinforcement techniques, such as increasing the dimensions of the column or adding side elements such as retaining walls, raise the resistance and rigidity of the column, redistributing forces and ensuring that plastic joints are formed in Bridges first, thus realizing the philosophy of modern seismic design "strong column - weak bridge" [19] [16]. The study of Xiao et al. confirmed the effectiveness of the addition of retaining walls in achieving this goal [19]. Fourthly, the performance of the stiffener is significantly influenced by the level of axial load on the Shaft [11] [16]. Studies have shown that the effectiveness of stiffening systems varies depending on the ratio of axial load. Under low axial loads, the improvement of ductility and energy absorption is very noticeable [12]. Under high axial loads, the effectiveness of the grouting is more important to maintain the integrity of the concrete and prevent premature Dent of the reinforcing steel, however, the amount of improvement in ductility may be reduced in comparison with the case of low loads [11][16]. Therefore, the stiffening system must be designed taking into account the expected axial load level to ensure balanced and safe performance [12][16]. The study of Amin et al. showed that the performance of steel jackets filled with concrete varies depending on the level of axial load [11]..

4. Research contribution

This research seeks to contribute to the scientific field by:

1. Analyze modern research trends in strengthening concrete columns against earthquakes, compare the effectiveness of various technologies.
2. Identify research gaps in previous studies that still need to be explored and developed. Assessment of mechanical and dynamic performance of advanced technologies under the influence of various seismic loads.
3. Propose practical recommendations that can help engineers and researchers choose the most suitable method of reinforcement based on the characteristics of the origin and its environmental conditions.
4. Promote sustainability and economy in the design of reinforcement systems by integrating modern materials and smart technologies.
5. Providing a reliable knowledge base that forms a scientific reference in the development of practical methods for strengthening concrete columns' resistance seismic loads and reduce structural and human damage.

5. Strengthening strategies and Methods

There are many strengthening methods used to RC columns both before and after construction. Due to seismic disasters and the urgent need to strengthen columns and structures, researchers have focused on studying strengthening methods. These methods can be divided into traditional and modern approaches. Researchers have focused on adopting sustainable materials like FRP (Fiber-Reinforced Polymer) and lightweight, high-strength materials in recent years. The following strengthening techniques, both traditional and modern, will be discussed:

5.1. Traditional strengthening methods

RC members can be strengthened using a variety of techniques, such as adding new components that improve their structural performance and strength or fixing damaged parts to return them to their initial load-bearing capability. The following is a summary of the most popular methods used to enhance reinforced concrete constructions [22].

5.1.1. Steel jacketing

The technology of RC concrete columns using steel sheathing is one of the oldest and most common methods of enhancing their capacity and improving their behavior, especially in cases of limited ductile (non-ductile) columns. Various forms of this technology have been developed, including different types of packaging, such as steel plates, outer hoops, partial or complete packaging, as well as the use of various steel segments, for raising the endurance and the efficiency of the column. The basic configuration of this system is based on welding transverse (horizontal) steel sheets along the shaft at regular distances, fixing longitudinal steel corners or U-shaped segments (channels) in the corners of the shaft. To ensure a higher effectiveness of this casing, the narrow space between the surface of the shaft and the steel casing is filled with high-quality mortar (epoxy or special cement). The transfer of stresses between the mortar layer and the original concrete column can be enhanced by using additional reinforcing steel, which improves the structural integrity of the system. Figure (1) shows a comparison of a reference concrete column (not reinforced) with various styles of reinforcement with steel sheathing, such as reinforcement with steel corners with collars, with U-shaped segments, and with steel plates. This technique is widely used to improve the seismic performance of ductile limited columns, as it contributes to increasing their shear resistance and improving their ductility under periodic loads [23][24][5].

The behavior of strengthened RC columns utilizing steel jacketing techniques has been the subject of several studies. The impact of various steel section types on the strengthening performance of RC columns was investigated experimentally by Belal et al.[25]. Seven columns (200 × 200 × 1200 mm) were tested: five strengthened specimens grouped by jacketing arrangement and two as controls. The first group employed three or six horizontal steel straps along with four longitudinal steel angles (50 × 50 ×

5 mm). The third group used four longitudinal steel plates (200 × 2.4 mm) on all sides, whereas the second group used two longitudinal steel channel sections (260 × 50 mm) with the identical two-strip configuration. The findings showed that angle sections performed better than channel and plate sections, and that steel jacketing greatly increased load-carrying capability. The strength of the jacketed columns was further enhanced by adding more horizontal straps.

For enhancing the response of reinforced concrete columns, Ezz-Eideen [26]] conducted an experimental study to assess several steel jacketing designs. Five straightened control specimens measuring 120 × 160 mm in cross-section and 1000 mm in height were used in the investigation. They were examined at different eccentricity ratios (e/t 6.3%, 12.5%, 18.75%, and 25%). In accordance with the jacketing layout, twelve more columns were separated into three groups. On both the compression and tension faces, the first group used four longitudinal steel angles (20×20×2 mm). The second set used smaller angles on the tension side (20x20x2 mm) and larger ones on the compression side (40x40x4 mm). Even greater angles (60x40x4 mm on the compression side and 60x20x2 mm on the tension side) were used by the third group. Five transverse steel straps (20 x 2 mm) were used to restrain each strengthened column. The results showed that while adding more horizontal straps successfully prevented the steel angles' buckling, extending the longitudinal steel sections increased the columns' load-bearing capability

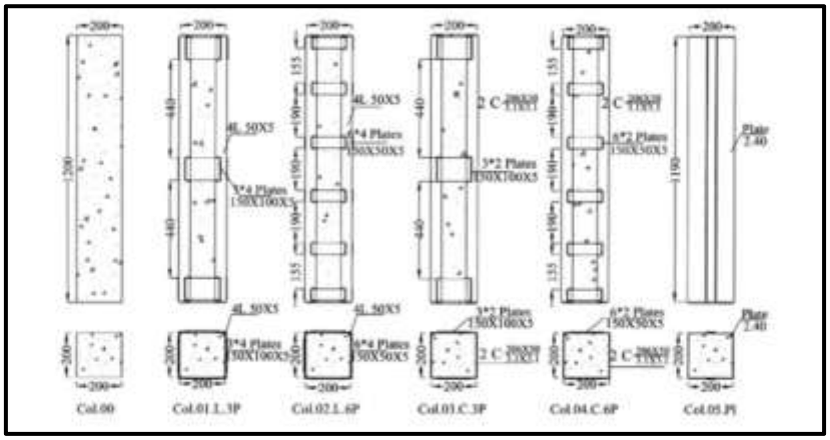

Fig 1: Details of full steel jacketing types[25].

For severely damaged RC columns, Fakhar far et al. [27] developed a fast-strengthening technique using lightweight prestressed steel jackets to minimize changes in column shape, mass, and stiffness. Using this novel method, a thin steel sheet was restrained by several prestressed strands and then wrapped around the column to create a jacket in less than 12 hours. While the sheet itself stopped the strands from penetrating the damaged concrete, the prestressed strands successfully kept the steel sheet from buckling. According to experimental results, this strengthening technique brought the retrofitted columns' ultimate strength and ductility back to roughly 115% and 140%, respectively, of the original as-built examples. Nevertheless, only roughly 80% of the initial rigidity was recovered.

The seismic response of circular reinforced concrete (RC) columns reinforced with full and split prefabricated steel wrapping jackets was recently studied by Choi et al. [28] . According to their findings, the split-type jacket outperformed the full jacket in terms of cost efficiency and convenience of installation while achieving almost the same improvement in seismic performance. A cable attached to a cross device was used in their experimental program to apply the steel wrapping system's external confining pressure. In a similar vein, Pudjisuryadi et a. [29] compared specimens constrained by external steel angle collars placed uniformly along the column height with specimens fitted with traditional stirrups. The findings showed that, in contrast to specimens confined with conventional stirrups, those with steel angle collars showed extremely ductile behavior and failed at greater drift ratios.

5.1.2. Concrete jacketing

Reinforced concrete jacketing is a commonly adopted technique for strengthening or rehabilitating reinforced concrete columns that have experienced severe damage or are located in seismic regions. In this method, an additional layer of reinforced concrete consisting of a steel reinforcement cage and additional concrete material is applied around the existing column. To achieve sufficient bonding and ensure composite behavior (that is, the integrity of the structural work) between the original column and the concrete layer added later (jacket), binders (bonding agents) or mechanical fasteners such as anchor bolts are usually used [23][30][31]. In this context, several studies have dealt with the reinforcement of reinforced concrete columns using concrete sheathing (jacket) techniques.

The study of Sayed et al. [32] studied the effect of increasing the ratio of longitudinal reinforcing steel on the performance of concrete columns coated with a concrete jacket, as shown in Figure (2). The study involved the manufacture of fifteen columns distributed into three categories: five square columns with dimensions (200 × 200 × 1200) mm, five rectangular columns with dimensions (160 × 250 × 950) mm, five round columns with a diameter of 160 mm. The first and second groups were reinforced using reinforced concrete jackets with a thickness of 50 mm, with variable longitudinal reinforcement (4Ø126 ،Ø128 ،Ø12) ، while the round columns were supported by 50 mm thick concrete jackets also but with longitudinal reinforcement (4Ø106 ،Ø10 ، 8Ø10). To improve the strength of adhesion (fastening) between the surface of the old shaft and the new jacket, anchor bolts and chemical epoxy (Kemapoxy) were used. The results showed that the use of reinforced concrete Jackets led to a noticeable increase in the maximum bearing capacity of the columns, and it also turned out that this capacity raises with an increase in the amount of longitudinal reinforcing steel.

The study of Tayeh et al. [33] investigated the effectiveness of various types of concrete Jackets used in the rehabilitation of deteriorated concrete columns. Forty-five columns of ordinary resistant concrete were tested in this study. Nine columns were used as reference samples, which included three uncoated columns and six columns coated with jackets of ordinary resistant concrete of two different thicknesses (25 mm and 35 mm). The remaining thirty-six columns were rehabilitated using reinforced concrete jackets with additional longitudinal Bars (4Ø10), with thicknesses of 25 mm and 35 mm, and made either from high-performance self-compacting fiber-reinforced concrete (UHP-SCC) or from ordinary resistant concrete (NSC). To enhance the adhesion of the jacket to the original Shaft, various surface processing methods were applied, including mechanical wire brushing, mechanical scraping (scratching), and the use of shear screws (or shear joint). The results revealed that the columns coated with UHP-SCC concrete achieved higher maximum load capacities compared to those coated with NSC concrete. It was also noted that increasing the thickness of the jacket leads to additional lifting at maximum load capacity. In addition, the use of shear screws showed superior performance in fastening strength compared to other surface treatment methods.

In general, it turns out that the maximum loading capacity is greatly influenced by the characteristics of the jacket material. Common materials in this technique are: high-performance fiber-reinforced self-compacting concrete (UHP-SCC), fiber-reinforced concrete, and ordinary resistant concrete (NSC). previous research has shown that UHP-SCC is the most effective material. The study of Wibowo et al. [34] within the framework of a study that addressed sustainable aspects, Wibowo et al. investigated the possibility of using bamboo rods as an alternative to steel reinforcing bars in concrete packaging technologies. The experimental work involved 18 samples that were reinforced using different numbers of bamboo rods (4 and 8 rods) with dimensions of (10 × 10) mm and (5 × 10) mm, and using canes (stirrups) of bamboo or steel and with varying distances (70, 100, 140) mm. The results showed that the use of bamboo rods contributed to an improvement in the maximum load capacity of the poles. It was also noted that the best performance in terms of maximum load capacity is achieved when using a combination of longitudinal bamboo rods with steel Canes (stirrups).

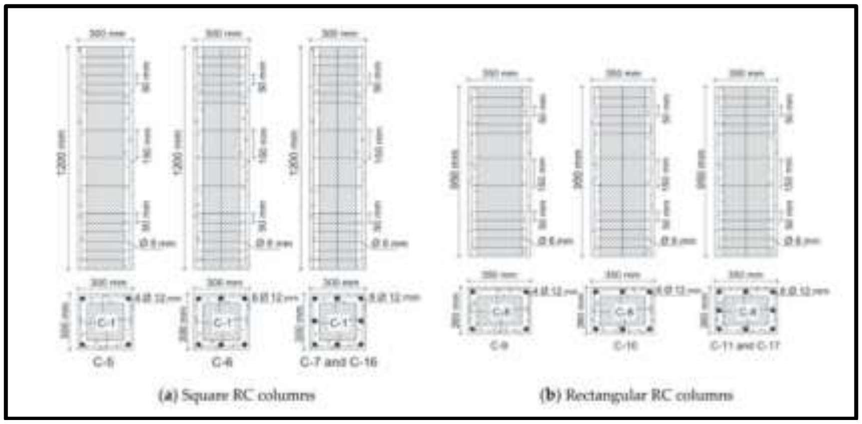

Fig 2: Illustrates the detailed configuration of the reinforced concrete (RC) columns that were strengthened using the full (complete) RC jacketing technique[32].

Vandoros and Dristos [35] investigated the use of reinforced concrete (RC) jackets in which the stirrup ends were welded. This configuration effectively improved the RC columns' ductility and strength of the RC columns. However, they observed that, in some cases, separation occurred between the original column and the jacket, attributed to insufficient surface preparation or inadequate bonding treatment at the interface. The welding of stirrup ends was found particularly beneficial in restraining the buckling of longitudinal reinforcement. To minimize interference with building occupancy during strengthening works, Liu et al. [36] introduced an innovative technique employing a single asymmetric concrete section attached to the existing column. The new section was connected to the original one using anchor rebars or high-strength bolts. The results of the experiments showed a significant improvement in the reinforced specimens' ultimate strength and ductility. Additionally, it was demonstrated that this method decreased the initial stress differential between the newly added and old sections. Another benefit of this approach is method is that most of the strengthening operations can be executed externally, preserving the space's usability without requiring the relocation of equipment or furniture.

5.2. Modern strengthening methods

A number of cutting-edge reinforcing methods have been created recently as substitutes for traditional concrete and steel jacketing. These contemporary techniques concentrate on enhancing structural performance by utilizing cutting-edge composite materials, lightweight systems, and effective bonding technologies that provide greater durability and shorter intervention times. They also make use of sustainable material.[37][38][39][40].

5.2.1. Ferrocement jacketing

For retrofitting reinforced concrete (RC) columns, the ferrocement jacketing technique is seen to be an effective solution. This method involves covering the column surface with a thin coating of cement-sand mortar reinforced by one or more layers of woven or welded wire mesh. This arrangement offers an affordable substitute for traditional reinforcing techniques like concrete or steel jacketing. The structural performance and efficacy of ferrocement jacketing in improving the strength and ductility of RC columns have been the subject of numerous studies in recent years[23][41].

Mourad et al. [6] experimentally examined ten small-scale square reinforced concrete (RC) columns under axial stress using a preloading technique applied at different ultimate load levels (0%, 60%, 80%, and 100%). The damaged specimens were repaired using high-strength ferrocement jacketing strengthened with two layers of steel mesh after the initial loading phase, and they were then retested until they failed. The specimens' overall structural reaction was evaluated in terms of lateral displacement, axial deformation, and load-carrying capability. Figure 3 below, clarify the correlations between axial and lateral displacements and the corresponding load capacities for the tested columns which include control specimens (SC-2), jacketed specimens (SJ-0-2), strengthened preloaded specimens (SJ-60-1 and SJ-80-1), and the strengthened failed specimen (SJ-100-1). In comparison to the control specimens, the experimental results showed that the use of high-strength ferro-cement jacketing increased axial load capacity by about 33% and axial stiffness by about 26%. Furthermore, it was discovered that rehabilitating preloaded and failing columns with the same ferro-cement jacket almost restored their initial stiffness and load capacity. Furthermore, compared to the control columns, the restored specimens showed better energy absorption capacity and ductile failure behavior, indicating a notable increase in their overall seismic performance.

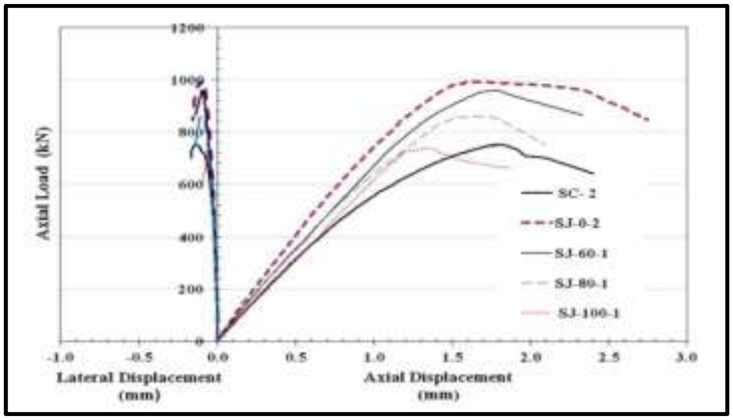

Fig 3: The load–displacement curves obtained from the tested specimens[6].

A semi-automated ferrocement jacketing technique was used in an experimental study by Kaish et a.[42] to repair reinforced concrete (RC) columns. As seen in Figure (4), this technology used automated procedures to construct the jackets under regulated laboratory settings. Nut-and-bolt connections were used to carry out the installation procedure on-site. Four enhanced specimens using semi-automated ferrocement jackets with either L-shaped or C-shaped configurations were included in the investigation, along with two control specimens of square RC columns (150 × 150 × 300 mm) having a compressive strength of 20 MPa. Bolted joints and cement grout were utilized to enhance the bond between the concrete core and the jacket.

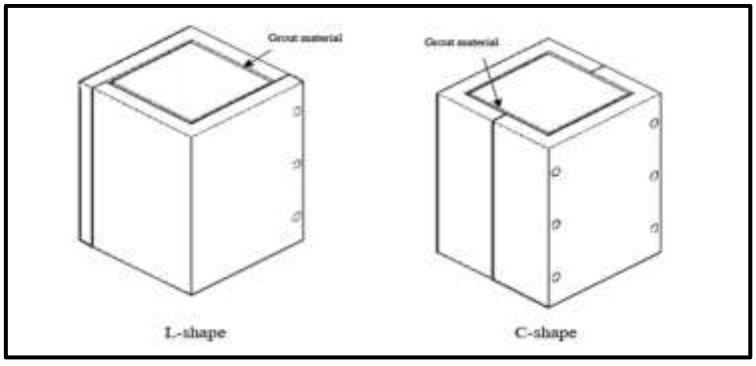

Fig 4: The prefabricated specimens strengthened with ferrocement jacketing. [42].

This innovative semi-automated ferrocement jacketing approach offers several benefits, including shorter fabrication duration, superior quality control, and lower labor demand. Owing to these advantages, the method has strong potential for widespread implementation in the construction sector.

Similarly, Xiong et al. [43] devised two alternative strengthening systems for RC columns, they were ferrocement-based and called mat–mortar (BM) and ferrocement–steel bar (FS) , as clarified in Figure (5). Their experimental program involved producing 33 circular columns, each with a 105 mm diameter and 450 mm height. Specimens retrofitted with BM and FS systems were confined using one to four layers of wire mesh. The results revealed that for the FS method, incorporating steel bars significantly improved the column's ultimate capacity, while for the BM method, increasing the number of mesh layers improved the overall ductility of the strengthened columns.

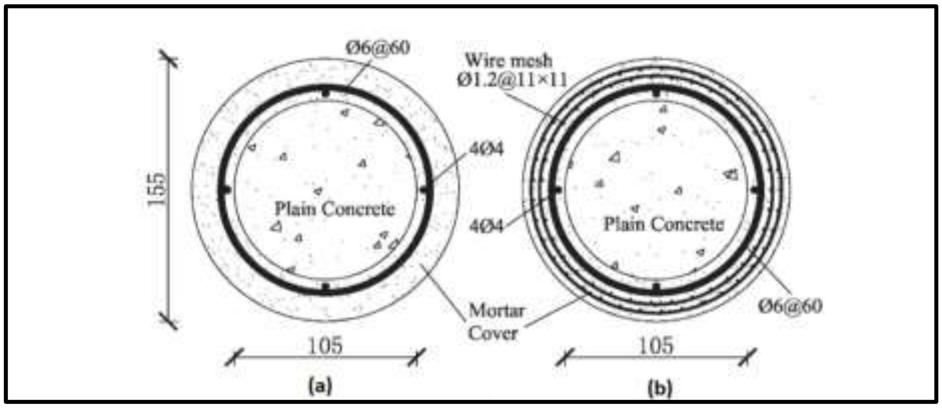

Fig 5: Cross-sectional views for the alternative ferrocement-based methods (unit: mm): (a) BM-confined, (b) FS-confined[43].

5.2.2. Externally bonded fiber-reinforced polymer (frp) jacketing

Use of Fiber Reinforced Polymer has Significantly has gained popularity in strengthening applications over the past few years .used Fiber polymer fabrics to Enhance bending, shear and axial capacities of the columns and beams may be manufactured from various materials such as carbon, glass and aramid Without an increase in the volume of the strengthened member, considerable advancements can be achieved in the capacity and ductility characteristics of the element[5][7][44].

A. CFRP Strengthening

The effect of CFRP strengthening on the overall behavior and failure mechanisms of strengthened RC columns has been the subject of numerous investigations. By avoiding brittle shear failure, defective RC columns retrofitted with external CFRP jacketing demonstrated a stable flexural response with enhanced ductility and energy dissipation capability, according to Ma et al. [5]. Similarly, Ye et al. [45] discovered that CFRP sheets can increase the shear strength of an RC column with insufficient transverse reinforcement. Additionally, it was found that the shear resistance mechanism of CFRP sheets was comparable to that of reinforcing hoops, where it became effective following diagonal shear cracking of concrete. In a different investigation Ye et al. [46] found that when the strong shear and weak flexure factors are greater than 1, the confinement effect of CFRP can enhance the ductility of RC columns. Haroun and Elsanadedy [47] indicated that CFRP strengthening enhanced ductility from limited to moderate levels and effectively prevented brittle shear failure. Abdel-Mooty et al.[48] indicated that wrapping exhibited greater effectiveness in square columns compared to rectangular ones. In contrast, Ghosh and Sheikh [49] found that FRP confinement had a more significant effect in circular columns than in square columns. Moreover, it was highlighted that for columns that were previously damaged, the efficiency of FRP strengthening is influenced by the extent of the prior damage.

B. Basalt Fiber-Reinforced Polymer (BFRP)

Basalt fiber-reinforced polymer has lately drawn interest for structural strengthening applications due to its comparatively inexpensive cost when compared to CFRP, as well as its advantageous properties like strong resistance to fire and chemical corrosion. In this regard, Ouyang et al. [50] compared the performance of externally bonded CFRP and BFRP wraps and discovered that columns reinforced with BFRP sheets performed on par with or even better than those reinforced with an equivalent number of CFRP sheets. Additionally, it was stated that BFRP sheets were just 20% more expensive than CFRP and promising alternative for strengthening purposes.

C. Near-Surface Mounted (NSM) Fiber-Reinforced Polymer (FRP) Jacketing

To increase the column's flexural resistance, these bars are usually positioned longitudinally [22][51][52][53]. A hybrid strengthening system is frequently created by combining the NSM technique with externally bonded FRP (EB-FRP) jacketing. Three partially broken reinforced concrete (RC) stub columns were used in an experimental investigation by Hasan et al. [54] to evaluate the relative effectiveness of NSM rebar repair and CFRP wrapping. The results showed that, in comparison to specimens covered with CFRP laminates, those reinforced with NSM rebars demonstrated better energy dissipation, increased ductility, and greater load-bearing capacity. On the other hand, specimens wrapped with CFRP had more controlled crack onset and propagation. The scientists explained this discrepancy by pointing out that CFRP laminates primarily improve performance in the tension zone, whereas NSM reinforcement adds to both compression and tension resistance.

5.2.3 Shape Memory Alloy (SMA) Wire Jacketing

Shape memory alloys (SMAs), known for their remarkable super elasticity, durability, and self-recovery characteristics, have been increasingly investigated for structural strengthening applications. Owing to their unique mechanical properties, SMAs present an attractive alternative to FRP retrofitting systems, offering advantages such as the absence of adhesive requirements, straightforward installation, and the elimination of debonding risks[55][56][57][58].The effectiveness of two types of SMA wire jackets—nickel-titanium-niobium and nickel-titanium alloys—for the seismic strengthening of RC columns was investigated by Choi et al. [59] . The concrete surface was mechanically secured to the SMA jackets. According to experimental findings, SMA-retrofitted columns with lap splices had extremely ductile behavior and occasionally even performed better than columns without lap splices. Additionally, the study found that because nickel-titanium-niobium alloys operate steadily throughout a larger temperature range than nickel-titanium alloys, they are better suited for civil engineering applications.

5.3. Composite techniques

The integration of more than one material into reinforced concrete column reinforcement systems is one of the modern trends in seismic engineering, as it allows achieving integration in the mechanical properties of each material, such as combining high rigidity, ductility, energy dissipation ability, and durability. This composite approach helps to overcome the limitations of using a single material, by developing hybrid reinforcement systems capable of improving seismic performance more efficiently and sustainably [60], [61], [62]. In the study of Cao et al., [60] a composite reinforcement system was used combining steel pipes filled with self-compacting concrete and coated with carbon fiber (CFRP), where tests were carried out on several columns under the influence of periodic loads. The results showed a high structural compatibility between the reinforcing elements and the original column, with a clear improvement in hysteresis curves and power dissipation capacity. Numerical modeling using the ABAQUS program also showed good agreement with the experimental results, which confirms the efficiency of this composite system in improving seismic performance.

Liu et al. [61] introduced an innovative system of composite columns of steel-reinforced concrete reinforced with carbon fiber (CSFRCC), with the aim of achieving a recoverable structure with low damage. The results showed that the addition of steel fibers reduced the development of cracks and significantly increased the durability, ductility and energy dissipation. A numerical model was also verified using the Diana program, with the proposal of a retrospective power model and a new arithmetic equation reflecting the nonlinear behavior of these columns. In the study of Hong et al. [62], encapsulation techniques were adopted using ultra-high-performance fiber reinforced concrete (UHPFRC) with or without fabric reinforcement, as this method proved high efficiency in reinforcing columns and reducing the thickness of the casing. The histologically enhanced system (TR-UHPFRC) showed greater improvement in ductility as a result of changing failure patterns. The effectiveness of the shear bonding between the casing and the original concrete was also demonstrated, in addition to clarifying the mechanisms of force transfer through the behavior of arches (Arch Action), which enhances the shear resistance of the reinforced columns.

6. **Comparison between Strengthening Techniques**

The comparison between the traditional and modern techniques used to strengthening the existed RC columns needs to understand the advantage, disadvantages and some factors. Table 1 illustrate summary for understanding the advantage and disadvantage of the previous techniques with some factors which consider hindrance in implementing this technique in site.

Table 1: A comparison between Jacketing Techniques

Method	Advantages	Disadvantages	Factor affecting design	Scope of applicability
Steel Jacket	▪ The most suitable method for or non-ductile, undamaged columns and columns with poor strip arrangement (partial steel jacketing with steel ties). It helps to reduce construction time, minimal increase column dimensions, and lower costs.	▪ In corrosive and fire-prone environments, Steel jackets are likely to deteriorate significantly, resulting in an unsightly appearance, especially when large steel sizes are used. Reinforcement only improves shear strength in cases of partial steel jacketing.	▪ Area of covering. ▪ Column head connection. ▪ Types of grout material. ▪ Horizontal straps.	▪ Non-ductile and undamaged column. ▪ Poor Columns with strip arrangement. ▪ columns in non-corrosive environments or areas not exposed to fire.
Concrete Jacket	▪ The structural stiffness is increased by the concrete jacketing technique. ▪ It also improves the seismic performance of the column in terms of flexural strength, ductility, and axial load-bearing capacity.	▪ It requires skilled labor. ▪ More expensive. ▪ Take a long time. ▪ It causes enlargement in the column sections and add extra weight.	▪ The spacing of the stirrups. ▪ The thickness of the jacketing. ▪ The connection to the slab and footing. ▪ Surface roughness. ▪ The longitudinal steel bars.	▪ Columns exposed to severe damage. ▪ Columns exposed to earthquakes and fires.
Ferrocement jacket	▪ This technology does not require highly skilled workers. ▪ It is easy to implement. ▪ It improves ultimate load capacity, earthquake resistance, fire and corrosion resistance. ▪ The maintenance costs are low.	▪ It adds extra weight. ▪ It is increasing the column cross-section.	▪ The shape, materials. ▪ Thickness of the thin mortar wall. ▪ The bonding strength. ▪ Number of wire mesh layers.	▪ Earthquake-resistant columns. ▪ Columns in potential fire zones. ▪ Severely damaged columns. ▪ Ductile columns
CFRP jacket	▪ CFRP composites are lightweight materials that are easy to install on-site. ▪ Highly resistant to chemical attacks. ▪ Do not suffer from corrosion problems like steel jacketing. ▪ They are protective in locations exposed to fire.	▪ The cost is high.	▪ The design is influenced by the type of resin used, the volume and direction of the fibers, and the corner-rounding radius.	▪ Ductile columns. ▪ Fire zones. ▪ To strengthen earthquake resistant columns.
Externally Bonded FRP Jacketing	▪ Easy and quick to install. ▪ It also boasts high corrosion resistance. ▪ high durability, and a high strength-to-weight ratio. ▪ It improves the work safety and minimal risk.	▪ It is an expensive material (the overall cost is low due to lower transportation and installation costs), ▪ Its properties deteriorate when exposed to high temperatures and wet environments. ▪ The increase in strength is relatively small.	▪ The quality of the surface of the original column and the extent of its preparation. ▪ The type of FRP used. ▪ The thickness of the layers, the direction of the fibers, and the method of gluing them with resin. ▪ Bond connection between FRP and concrete. ▪ Column section and shape. ▪ The influence of the environment on adhesion and life span.	▪ Existing concrete columns need to be strengthened quickly without a significant increase in Section or significant interference to the functioning of the building. ▪ Installations in medium to high seismic zones. ▪ Restoration or upgrade of old or designed columns with requirements lower than current standards.
Near-Surface Mounted (NSM) (FRP) Jacketing	▪ This technique preserves the structure's aesthetics while significantly enhancing its strength.	▪ It's an expensive material (low overall cost). ▪ It requires a comparatively more labor intensive, compared to externally bonded FRP, but less than RC and steel jacketing.	▪ The depth and length of the groove and how to fill it. ▪ The type of FRP used (bars, rods, fibers) and their number. ▪ The connection between FRP and concrete.	▪ Columns need to be strengthened, but with minimal changes in the outer section, or in narrow places that do not allow large packaging. ▪ Existing installations where strengthening is intended to be carried out without significant

Method	Advantages	Disadvantages	Factor affecting design	Scope of applicability
		▪ The increase in plasticity is minimal.	▪ Interference with the original reinforcement and its dissection. ▪ The influence of climatic changes and heat on adhesion. ▪ The extent of the effect of activation (pressing) or pre-tightening of FRP rods, if used.	disruption or apparent engineering change. ▪ Situations where higher resistance to corrosion or environmental aggressions is preferred, or where long-term performance is important.
Shape Memory Alloy (SMA) Wire Jacketing	▪ This technology is fast to install. ▪ It requires no adhesive. ▪ It offers exceptional elastic and durability. ▪ It is increasing both strength and durability.	▪ The material is very expensive. ▪ Its strength improvement is relatively small. ▪ It has ineffective composite action with concrete	▪ Choose the type of SMA based on the required properties. ▪ The pre-tensile ratio or stimulation of the SMA, and the way it is distributed around or inside the column. ▪ Interaction bond or mechanical linkage between the SMA and the original concrete/reinforcement, ensuring properties. ▪ Seismic situation and climate / environment.	▪ Columns located in seismically critical structures need not only a higher load capacity, but also reduced residual noise after earthquakes. ▪ Columns inserted into joints or areas where it is acceptable to have concentrated reinforcement (plastic hinge). ▪ Columns with a non-soft design and need improvement. ▪ advanced cases where budget and engineering evaluation allow the use of innovative technologies. alternative

7. Conclusion

This study concludes that techniques for strengthening and rehabilitating reinforced concrete columns have developed significantly. The effectiveness of each technique varies depending on its mechanical properties and application requirements. The review showed that the choice of the appropriate method depends on the condition of the structural element, the type of loads applied to it, and the surrounding environmental conditions. Traditional Methods: Reinforced concrete and steel encapsulation techniques have demonstrated high effectiveness in restoring the strength of damaged columns and improving their structural behavior under axial and lateral loads. Steel encapsulation offers more stiffness and greater resistance to shear and buckling, as long as good bonding between the new layer and the original element is achieved through appropriate surface treatment. Concrete encapsulation is distinguished by its low cost and ease of implementation. However, these conventional approaches take longer to adopt and require more planning. Additionally, they increase the concrete section's size and self-weight, which makes them less appropriate for projects that need to be lightweight or have limited space. Modern Methods (Ferrocement and FRP): Ferrocement jacket technology has proven to be a cost-effective and successful substitute for concrete column rehabilitation. It is distinguished by its low maintenance costs compared to conventional techniques, ease of application, lightweight design, and strong resistance to impact, fire, and corrosion. Fiber-reinforced composite materials (FRP), like CFRP, have demonstrated remarkable effectiveness in enhancing ductility and energy absorption capacity in addition to improving compressive, shear, and buckling resistance. CFRP sheets are a great option for strengthening elements exposed to challenging conditions because of their high strength- to-weight ratio and superior resistance to corrosion and environmental variables. The findings demonstrate that, as compared to conventional techniques, contemporary technologies—particularly ferro and FRP—offer more effective and sustainable solutions because of their superior mechanical qualities and ease of installation and upkeep.

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