Improving the Dynamic Performance of Reinforced Concrete Columns with Jacketing Techniques

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Abstract

This paper studies the retrofitting and strengthening of reinforced concrete (RC) columns with an emphasis on sustainability, safety, and resilience, particularly for aging infrastructure and natural disaster risks. It reviews methods such as RC and steel jacketing and newer techniques like fiber-reinforced polymers (FRPs) and ferrocement jacketing. Each method presents unique benefits and challenges, from resource-intensive RC jacketing to lightweight but debonding-prone FRP jacketing. The paper advocates for customized solutions based on load-bearing capacity, ductility, and seismic resistance. By analyzing various studies, it offers guidance for structural engineers and highlights the need for ongoing research to ensure sustainable and resilient RC structures.

Keywords: Retrofitting, Jacketing, Seismic, Reinforced Concrete Column, Fiber Reinforced Polymer.

1. Introduction

The focus on infrastructure sustainability has led to certainty on rehabilitating and strengthening reinforced concrete (RC) structures. These methods increase performance to meet modern standards, providing a more sustainable alternative to destruction and reconstruction by conserving resources and decrease carbon emissions.

Extensive research on seismic retrofitting and RC column strengthening addresses the need for repair after earthquakes, as columns absorb significant seismic energy. Structures constructed before the 1970s are especially vulnerable due to inadequate seismic detailing, requiring upgrades to meet modern codes.

Strengthening and repairing RC columns are also necessary due to aging infrastructure, concrete deterioration, changes in building use, errors of design, corrosion of reinforcement, and construction errors. Old methods like steel jacketing and concrete encasing enhance seismic performance but increase the column's cross-section. New techniques, such as fiber-reinforced polymers (FRPs), increase capacity with minimal structural changes. Hybrid jacketing, combining various methods, is increasingly popular for strengthening RC structures.

Columns are critical structural components, bearing loads and transferring them to the foundation. In high-rise buildings, their performance is crucial; failure can cause abrupt collapses.

Replacing damaged elements is challenging and risks overall structural integrity. Repairing compromised RC elements aims to restore their original strength and stiffness.
A column is an important structural element that transfers building loads to the foundation, supporting floors, slabs, and beams against lateral and axial forces. Failure can cause to building collapse, particularly in tall structures. To prevent that, retrofitting and strengthening techniques improve columns' resistance to seismic forces. Retrofitting enhances existing structures using advanced materials like composites. Older methods such as concrete and steel jacketing have been standard for reinforced concrete (RC) structures.

These traditional methods are important for strengthening columns, but newer approaches include:
- Jacketing with reinforced concrete.
- Steel Jacketing.
- High-tension materials jacketing with like glass fiber, carbon fiber, or aramid fiber.
- Jacketing by ferrocement.

2. Literature Review

(Dingorkar and Srivastava, 2016) “Retrofitting – Comparative Study of R.C. Jacketing and FRP Wrapping” this study compares the strength increase by two retrofitting methods: reinforced concrete jacketing and FRP wrapping, evaluating their effectiveness. The study goals to assist in assessing the better technique for reinforcing weakened structural elements, helping engineers in selecting the most suitable method to achieve necessary strength improvements.

(Fukuyama et al., 2000) “Studies on repair and strengthening methods of damaged reinforced concrete columns” researchers study to verify the effectiveness of jacketing in repairing or strengthening RC columns damaged during the 1995 Hyogoken-Nanbu earthquake in Japan. They tested 8 column specimens to evaluate shear strength and ductility improvements. Results showed that jacketing significantly increase both shear strength and ductility, surpassing the columns' pre-damage condition.

Additionally, specific formulas derived to evaluate the maximum shear strength of columns repaired or strengthened with RC jacketing, steel plates, or carbon fiber sheets.(Ahmed, 2021)

(Mahjoub et al., 2016) “The use of kenaf fiber reinforced polymer to confine the concrete cylinder” the study explained Kenaf fiber, a natural fiber and biomaterial, as an alternative to FRP. Concrete specimens were tested, with one without retrofitted, another retrofitted with GFRP, and the third with Kenaf fiber. Results gave that GFRP had higher tensile strength than Kenaf fiber; specifically, Kenaf fiber withstood 540 kN compared to GFRP's 1120 kN and no-retrofitted concrete's 470 kN. The study suggests that increasing Kenaf fiber thickness could improve its strength, highlighting the need for further research on how thickness affects performance in retrofitting applications of both Kenaf and glass fiber.

(Micelli and Modarelli, 2013) “Experimental and analytical study on properties affecting the behavior of FRP-confined concrete” an experimental study tested 128 specimens, with 89 wrapped in CFRP and GFRP, and the rest left as plain concrete. They measured compressive load, axial load, and hoop strain to analyze the stress-strain relationship. Results showed that confinement effectiveness decreases as concrete strength increases, but FRP increased compressive strength by 64% to 95% for concrete strengths of 38 MPa to 28 MPa. Retrofitting column corners ensured full strength. External FRP confinement enhanced strength, ductility, and energy absorption capacity.

(Sen, 2017) “Behavior and strength of RC columns retrofitted with steel angles and strips under eccentric axial loads” an experimental study on six steel-jacketed RC columns under eccentric loads used steel angles and strips. The results showed that steel jacketing performed well under both concentric and eccentric loading, increasing the capacity by about 240% compared to un-strengthened columns under concentric loads. However, the ultimate capacity decreased by approximately 15% as the eccentricity ratio increased from 0 to 0.45 of the column width. Eccentricity also affected the ductile behavior of the jacketed columns.

(Vandoros and Dritsos, 2008) “Concrete jacket construction detail effectiveness when strengthening RC columns” the study investigated strengthening full-size concrete columns, halved in height, using three different concrete jacketing methods. It compared their effectiveness and examined construction procedures for practicality and ease of implementation. Seismic performance was assessed based on strength, stiffness, and hysteretic response, providing a comprehensive view of how well these methods enhance structural integrity and seismic resilience.

(Ou and Truong, 2018) “Cyclic behavior of reinforced concrete L- and T-columns retrofitted from rectangular columns” a proposed seismic retrofit technique aimed to convert first-floor rectangular columns into L- and T-shaped columns to address weak-story vulnerability. Experimental results showed these retrofitted columns displayed ductile behavior governed by flexure under cyclic loading, with no cracking or detachment at the retrofit interface. This method increased load capacities by 120%. Despite reduction in lateral strength due to interrupted longitudinal reinforcement at the base, the retrofitted columns demonstrated ductility and less damage. A pushover analysis model, accounting for reinforcement discontinuity, accurately predicted initial stiffness, lateral strength, and post-peak behavior, indicating this technique effectively addresses weak-story issues.

3. Materials and Methods

3.1 Reinforced Concrete/Mortar Jacketing

Jacketing by reinforced concrete is a common method for strengthening and repairing reinforced concrete columns. It includes enlarging the column's cross-section with a layer of reinforced concrete or mortar, attached using anchor rebars or high-strength bolts. This technique enhances seismic performance by increasing capacity of axial load, flexural strength, and ductility. However, it is expensive, time-consuming due to formwork installation, and provides limited ductility improvement because brittleness of concrete.

Jacketing by reinforced concrete also changes the cross-sectional area of the column, which influence the structure's weight and stiffness, potentially modify its natural period and increasing seismic demands.

More recent applications of RC jacketing use high-performance materials to strengthen or repair columns without clearly changing their cross-sectional size.

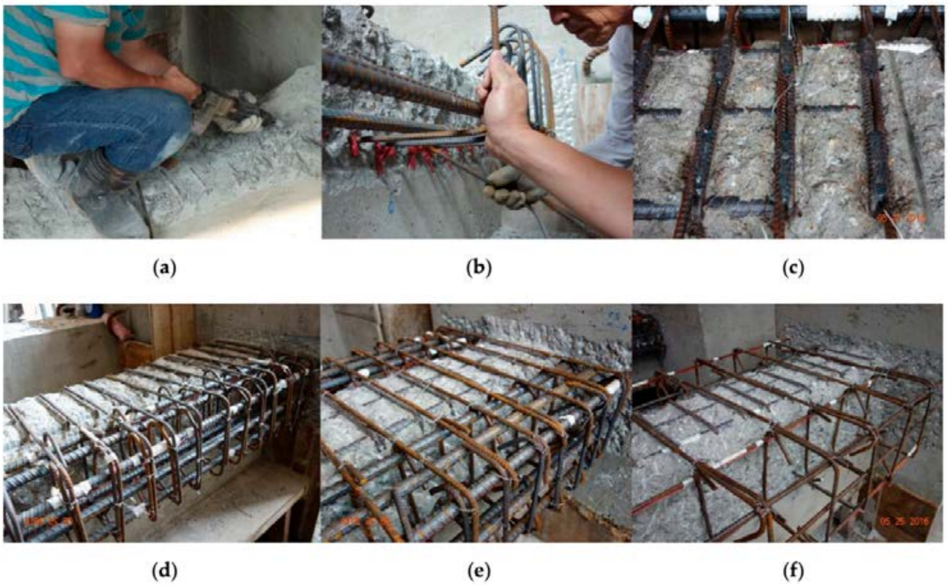


Figure 1 illustrates the steps involved in repairing with RC jacketing:

(a) Begin by removing the cover concrete and roughening the surface for better bonding. (b) Add transverse reinforcement to the structure. (c) Weld the transverse reinforcement to secure it in place. The figure also shows reinforcement cage configurations for different column types: (d) An L-shaped column, (e) A T-shaped column, and (f) A T-shaped column with wall-type reinforcement (Ou and Truong, 2018).

3.2 Steel Jacketing

Strengthening concrete columns with steel jackets is one of the oldest methods for reinforcing non-ductile columns. Steel jackets come in various forms, such as plates, external ties, partial or complete encasements, and diverse profiles, enhancing column resilience. A common setup includes longitudinal steel angles or channel sections at each corner, with horizontal steel sheets welded at intervals. There is a small gap between the column and jacket allows for the infusion of special mortar, improving effectiveness. Further reinforcement can be integrated to certain the smooth transfer of stress between the mortar layer and the column (Naji et al., 2021).

Figure 2. Steel jacketing of column

The technique of steel jacketing is used for strengthening and repair reinforced concrete columns. It involves encase of the column in a steel frame, typically made of steel plates, angles, or strips, which are fastened around the column. Jacketing provides additional support and confinement, enhancing the column's load-bearing capacity, ductility, and seismic resistance.

Generally, the process includes the following stages:

Preparation: clear any damaged concrete or corrosion from the column's surface and clean it smoothly.

Steel components installation: set steel plates, angles, or strips around the column to create a jacket. These components are often anchored with bolts or welded for stability and rigidity.

Connection Reinforcement: steel jacket is often designed to be continuous through column joints, providing a strong connection to the rest of the structure.

Concrete Fill (optional): In some cases, the space between the column and the steel jacket is filled with concrete or grout to improve the column's strength and stiffness.

Steel jacketing is useful because it enhances the structural integrity of columns without importantly increasing their cross-sectional area, allowing for increase disruption to the building's layout. It is widely used for seismic retrofitting and strengthening of structure due to its effectiveness and flexibility.

3.3 Fiber-Reinforced Polymer (FRP) jacketing

Fiber Reinforced Polymer (FRP) jacketing strengthens, and retrofits reinforced concrete structures, especially columns and beams, by wrapping them with composite materials made from high-strength fibers like carbon, glass, or aramid, in a polymer resin. This method is accepted for its high strength-to-weight ratio, flexibility, simple of installation, and influence impact on original geometry and aesthetics.

Jacketing with FRP offers an easy installation process, need less labor and equipment than traditional methods like steel or concrete jacketing. Its lightweight and corrosion resistance ensure durability, making FRP increasingly familiar for seismic retrofitting and strengthening infrastructure.

FRP jacketing has disadvantages, including high material and installation costs and potential effectiveness due to premature debonding if improperly applied. It is also influenced by high temperatures and extreme weather, affecting long-term performance. Despite these disadvantages, FRP remains popular for retrofitting due to versatility and minimal disruption to structures.

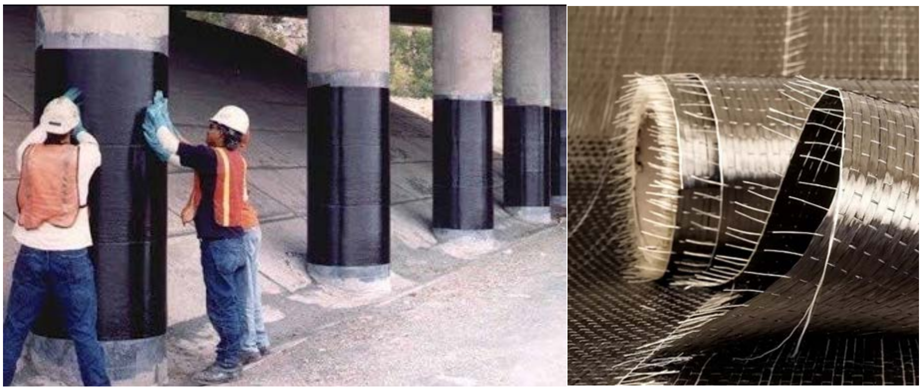


Figure 3. Jacketing of columns fiber reinforced polymer

3.4 Ferrocement jacketing

Ferrocement jacketing strengthens reinforced concrete columns by applying them in a thin layer of high-strength mortar reinforced with fine steel wire mesh or steel rods with small-diameter. This way enhances column strength and ductility without big changes to their dimensions, making it favored for seismic retrofitting and repairing aging or damaged RC columns.

The process begins with cleaning and smoothing the existing concrete surface for better adhesion. Steel wire mesh or thin steel rods are wrapped around the column to create a supportive structure for the high-strength mortar. This mortar is applied over the mesh to form a strong, thin jacket. Proper curing is essential to get the required strength and durability of the jacket.

Ferrocement jacketing improv load-bearing capacity and ductility with minimal impact on column geometry. It's cost-effective and acceptable to various shapes and sizes, though labor-intensive and sensitive to application quality. Proper curing is essential for optimal results, constructing ferrocement jacketing an effective alternative for strengthening RC columns while preserving their aesthetics and structural integrity.

Figure 4. Fiber Reinforced Polymer jacketing for columns (Koutas and Bournas, 2020).

4. Results and Discussion

The following summaries are the key points from each reviewed work, focusing on the topic of increasing the dynamic behavior of reinforced concrete columns with jacketing techniques:

(Dingorkar and Srivastava, 2016) the study examined the strength improvement from two retrofitting methods: reinforced concrete jacketing and FRP confinement. It assessed their effectiveness to indicate the optimal way for strengthening compromised structural elements. The findings provide guidance for engineers selecting the most suitable retrofitting technique on the base of specified strength improvement requirements.

Table 1 shows that the strength provided in columns after RC jacketing is significantly higher than that get with FRP wrapping, whether under minimum or maximum conditions.

Table 1. comparing of the strength increases between jacketing with R.C. and FRP confinement.

Methods	Minimum condition		Maximum condition	
	Original	Deteriorated	Original	Deteriorated
RC Jacketing	(0.015% steel in jacket)		(0.04% steel in jacket)	
	117.478%	239.59%	118.5%	241.19%
FRP Wrapping (with 2 layers)	(α=.67)		(α=.85)	
	38.79%	116.73%	73.45%	170.84%
FRP Wrapping (with 1 layer)	(α=.67)		(α=.85)	
	22.42%	91.17%	52.68%	138.42%

(Fukuyama et al., 2000) experiments on repaired and strengthened reinforced concrete columns demonstrated that damaged columns could regain or repair their pre-damaged levels of shear strength and ductility. The use of shrinkage-compensating mortar restored shear strength to its original level, albeit with a subsequent drop likely caused by reduced aggregate interlocking. Columns jacketed with steel plates, carbon fiber (CF) sheets, or preformed CFRP plates showed substantial improvements in ductility. Formulas for calculating maximum shear strength of columns repaired with RC, steel, or CF aligned closely with experimental results.

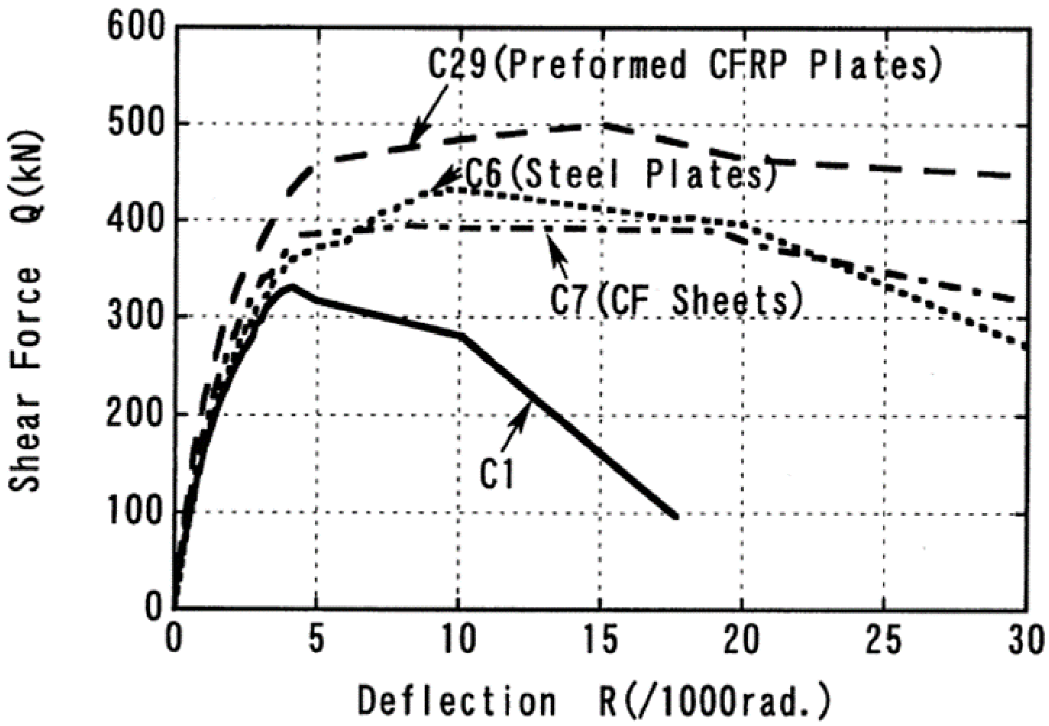
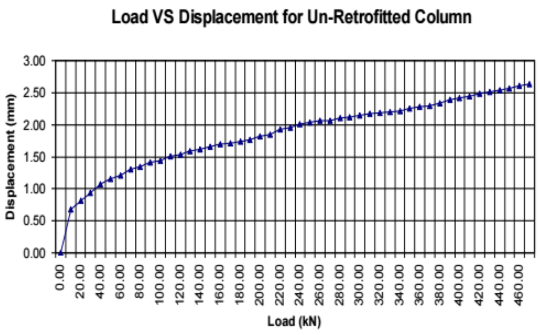
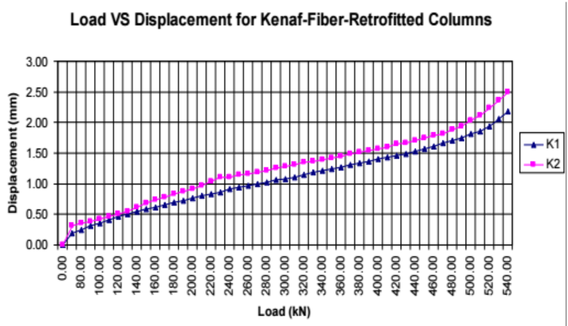


Figure 5. illustrates the envelopes of shear force-deflection hysteresis loops.

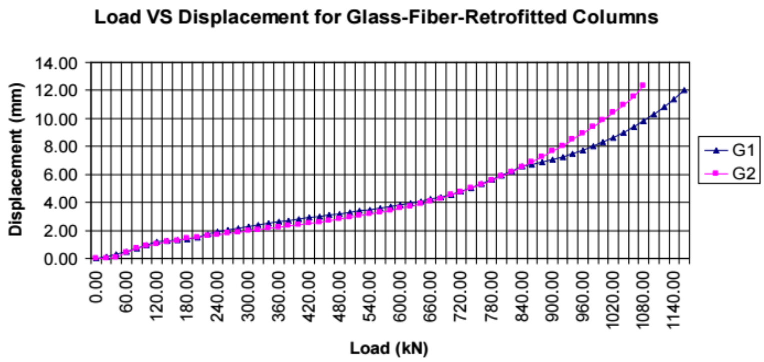
(Mahjoub et al., 2016) the study compared Kenaf fiber, a natural alternative to traditional FRP, with GFRP in retrofitting cylindrical concrete specimens. GFRP exhibited higher tensile strength compared to Kenaf, where Kenaf withstood 540 kN, GFRP held 1120 kN, and un-retrofitted concrete bore 470 kN. Increasing Kenaf's thickness could potentially enhance its strength, suggesting a need for further research on how thickness affects Kenaf and glass fiber performance in retrofitting. Graphs showing load versus displacement, derived from data loggers, are presented in subsequent figures.



Load VS displacement for un-retrofitted column



Load VS displacement for Kenaf fiber reinforced polymer retrofitted columns (for two samples)



Load VS displacement for GFRP retrofitted columns (for two samples)

Figure 6. The load versus displacement graphs, created using data from the data logger.

(Micelli and Modarelli, 2013) the study investigated factors affecting FRP-confined concrete by testing 128 specimens, including 89 wrapped in CFRP and GFRP, and others left as plain concrete. They analyzed compressive load, axial load, and hoop strain to understand the stress-strain relationship. Results indicated that as concrete strength rose, the effectiveness of confinement decreased, yet FRP still significantly increased compressive strength—by 95% to 64% for concrete strengths ranging from 28 MPa to 38 MPa. Retrofitting column corners ensured full strength. Overall, FRP confinement improved the strength, ductility, and energy absorption capacity of concrete columns. Graphs depicting the relationship between strength increase and FRP quantity in hollow-core circular and prismatic columns follow.

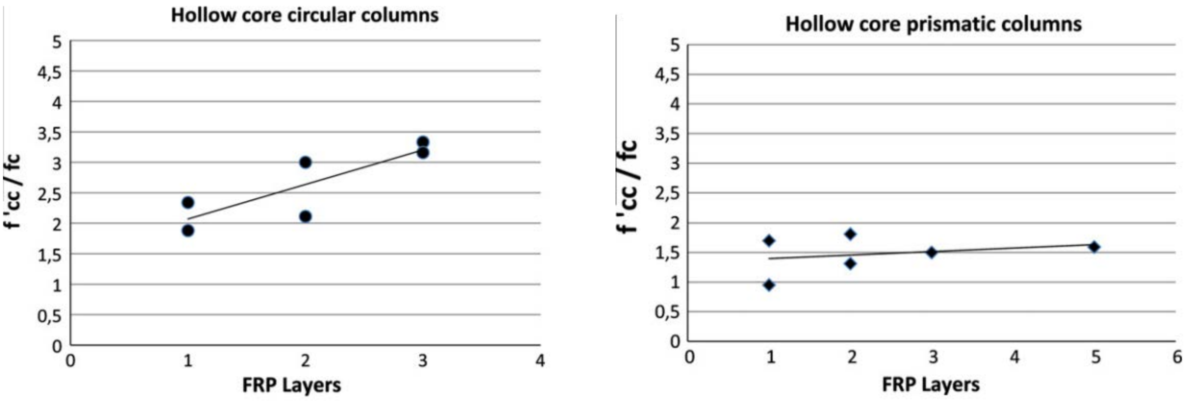


Figure 7. The correlation between the increase in strength and the amount of FRP used in hollow-core circular columns and hollow-core prismatic columns.

(Sen, 2017) in an experimental study, six reinforced concrete (RC) columns were retrofitted using steel jacketing with steel angles and strips. Results demonstrated significant performance improvement, with steel-jacketed columns achieving a 240% capacity increase compared to un-strengthened columns under concentric loads. However, the study noted that eccentricity reduced the ultimate capacity of these jacketed columns by approximately 15% as the eccentricity ratio ranged from 0 to 0.45 of the column width. Additionally, eccentricity was observed to affect the ductility of steel-jacketed RC columns.

Table 2. Axial and moment capacity of jacketed column.

Eccen-tricity	Experimental		FEM		Analytical*		P_{exp}/P_{fem}	P_{exp}/P_{ana}
	Load (KN)	Moment (KN-m)	Load (KN)	Moment (KN-m)	Load (KN)	Moment (KN-m)		
0	1235	0	1235	0	830	0	1.00	1.48
0.10	1180	18	1250	19	750	12	0.94	1.57
0.25	1185	45	1305	46	675	25	0.91	1.76
0.45	1065	72	1165	76	575	39	0.91	1.85
Mean							0.94	1.67
Standard Deviation							0.04	0.17

* Analytical values are obtained by linear interpolation

(Vandoros and Dritsos, 2008) the study assessed the use of concrete jackets to strengthen full-size concrete columns reduced to half their typical height. It compared three jacketing methods to determine their effectiveness and evaluated the practicality of various construction procedures. Seismic performance was evaluated through measures such as strength, stiffness, and hysteretic response, providing insights into how concrete jacketing enhances the structural integrity and seismic resilience of reinforced concrete columns.

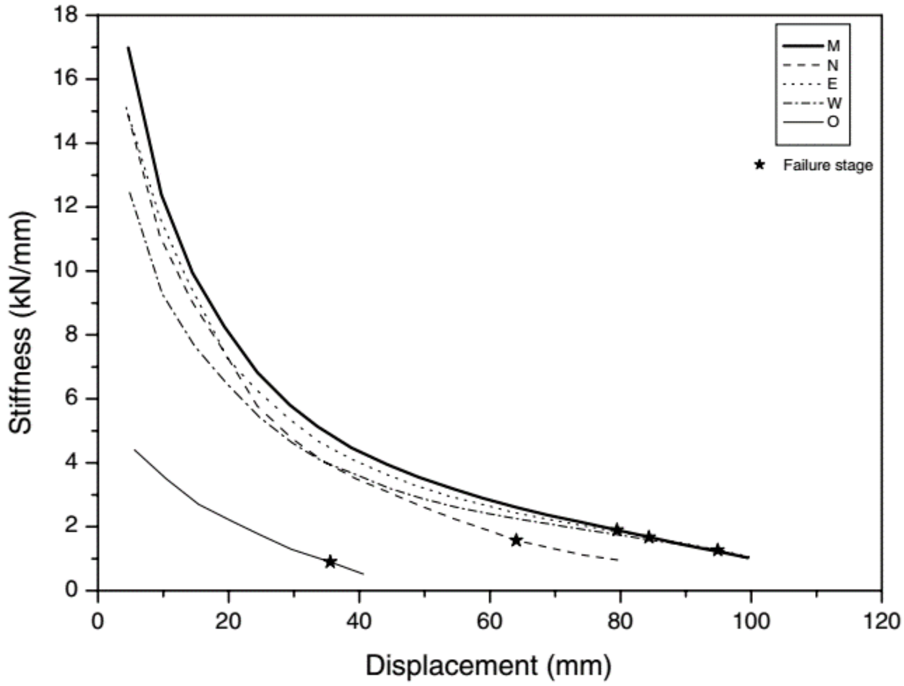


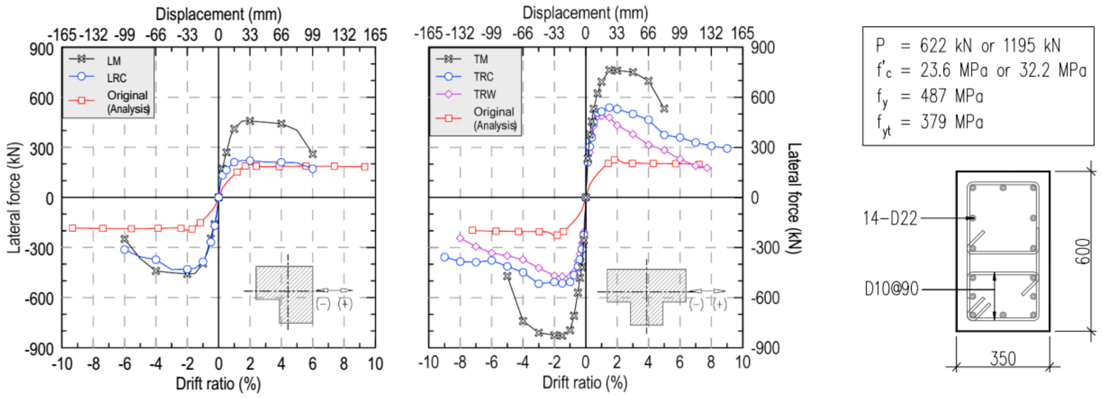
Figure 8. Stiffness against displacement envelopes for all specimens

(Ou and Truong, 2018) the study explained a seismic retrofit technique changing rectangular columns into L- and T-shaped to address weak-story vulnerabilities. Studies showed these retrofitted columns exhibited ductile behavior primarily effected by flexure under cyclic loading, without occur cracking or detachment. This retrofitting method increased average load capacity by 120%. However, due to non-continuity in longitudinal reinforcement at the base of column, retrofitted columns have lower lateral strength compared to monolithic columns but showed better ductility and less damage. Analysis model accurately predicted these behaviors, highlighting this technique as a good for addressing weak-story issues.

Table 3. Lateral force - displacement capacities.

Column	Idealized yield drift %		Peak load, kN		Peak load drift, %		Ultimate drift, %		Displacement ductility	
	(1) −	(2) +	(3) −	(4) +	(5) −	(6) +	(7) −	(8) +	(9) −	(10) +
LM [11,12]	−0.90	+0.80	−459	+465	−1.89	+1.92	−5.00	+5.25	5.56	6.56
TM [11,12]	−0.63	+0.65	−828	+762	−1.36	+1.78	−4.30	+4.55	6.83	7.00
LRC	−0.80	+0.43	−433	+222	−2.95	+1.85	−5.18	+5.84	6.48	13.58
TRC	−0.40	+0.40	−517	+540	−2.81	+1.31	−5.18	+4.50	12.95	11.25
TRW	−0.40	+0.40	−476	+490	−1.01	+1.01	−3.90	+3.00	9.75	7.50

Note: "−" and "+" indicates the loading in negative and positive direction, respectively.



(a) L-columns (b) T-columns (c) Original column

Figure 9. Force-drift envelopes of: (a) L-columns; and (b) T-columns; and (c) original columns (Ou and Truong, 2018).

4. Conclusion

In summary, recent works and ongoing research in retrofitting and reinforcing reinforced concrete columns highlight an increasing on sustainability, safety. This certainty responds to natural disasters and the shortages of aging infrastructure. Many studies investigate techniques at enhancing structural stability and seismic resistance of RC columns, providing a good solution to tackle the complexities of contemporary construction and infrastructure issues.

The review of retrofitting methods—from older ones like reinforced concrete and steel jacketing to newer options such as FRP and ferrocement—shows each method has their specialty. Jacketing by reinforced concrete effectively strength columns but can change their cross-section and requires more labor. Steel jacketing, while less affected, may face challenges with eccentric loads.

FRP jacketing is important for its excellent strength/weight ratio and straight forward installation but can be valuable to debonding and effective to temperature variations. Ferrocement jacketing provides strength improvements while improving the column's shape, but it requires meticulous application and thorough curing.

The research highlights the importance of retrofitting solutions that meet specific project needs, increasing load-bearing capacity, ductility, and seismic resistance. Insights get from experiments and analyses conducted by researchers offer valuable information about the performance and contribute of each retrofitting method, supporting those decisions by structural engineers and designers.

Finally, the case of retrofitting and strengthening RC columns is evolving as the industry to prioritize safety, longevity, and environmental impact. Advancements in construction technologies and materials development the need for ongoing research to innovate retrofitting solutions aligned with sustainable infrastructure aims. The studies explained in this review contribute valuable insights and propose work for future research to enhance retrofitting methods and ensure the long-term performance structural resistance of reinforced concrete buildings.

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