

Review the Behavior of eccentrically loaded RC Columns Strengthened using CFRP Bars and Sheet

Liqaa Salam Mahdi

*Building and Construction Department, Al-Mussaib Technical Collage, Al-Furat Al-Awsat
Technical University, Babylon, Iraq*

Ali Hadi Adheem

Polytechnic College-Karbala, Al-Furat Al-Awsat Technical University, Karbala, Iraq

Abstract: This literature review highlights the use of Fiber-Reinforced Polymer (FRP) composites to strengthen reinforced concrete (RC) columns under various loading conditions. It focuses on two main methods: near-surface mounted (NSM) FRP reinforcement and external FRP confinement, often used in combination.

Key findings indicate that NSM FRP enhances flexural capacity and seismic performance, particularly under eccentric and biaxial loads. In contrast, external FRP confinement improves axial load capacity but is less effective with increasing eccentricity.

Hybrid systems, which integrate NSM FRP and external wraps, effectively mitigate debonding and buckling, enhancing strength and deformation capacity. The review also mentions analytical models that predict the behavior of FRP-strengthened columns. Applications of these methods include corroded, fire-damaged, or seismically challenged columns, confirming FRP composites as a valuable solution for reinforcing concrete structures.

Keywords: CFRP, strengthened columns, flexural.

Introduction:

Fiber-reinforced polymer (FRP) composites are widely used to restore concrete structures, particularly by wrapping concrete columns. This wrapping strengthens the core, enhancing the column's weight-bearing capacity and flexibility (1–6). CFRP confinement supports concrete from the sides, preventing chipping and bending of steel bars, which enhances column flexibility during earthquakes. Its effectiveness is greater with even, direct loads compared to off-center ones (7-12).

To strengthen reinforced concrete (RC) members, grooves are cut in the surface to place near surface mounted (NSM) rods or laminates using a bonding agent like epoxy resin. This method protects NSM materials from external risks, such as fire. Reinforcing RC columns is vital in earthquake-prone areas to prevent collapse. Many studies have explored using fiber-reinforced polymers (FRPs) to enhance the seismic performance of these columns (13–22).

Literature Review

Tamer El-Maaddawy¹ and Amr S. El-Dieb². This article examines how NSM-GFRP reinforcement and CFRP confinement enhance the strength of reinforced concrete (RC) columns under biaxial eccentric loading with equal eccentricity. Key conclusions include:

1. NSM-GFRP with one layer of CFRP confinement is more effective at improving load capacity at higher eccentricities, while two layers are better for lower eccentricities.
2. Increasing CFRP confinement with NSM-GFRP significantly boosts load capacity at lower eccentricities, with minimal impact at higher eccentricities.
3. NSM-GFRP reinforced columns with two layers of CFRP show greater load capacity increases with lower concrete grades, whereas one layer has less impact on capacity across different grades.
4. An analytical model accurately predicts the load capacity of these RC columns under axial load and biaxial bending, aligning well with experimental results (23).

Koosha Khorramian, a,*, **Pedram Sadeghian**. The hybrid strengthening system underwent two testing phases. Phase I assessed small-scale models to ensure longitudinal laminates were adequately supported to prevent local buckling. Phase II focused on larger columns for global buckling management. Key findings include:

1. Crushing of CFRP laminates reduced the system's overall effectiveness in small-scale concrete columns under axial load, limiting the potential of GFRP wrapping.
2. Two main failure modes were identified: i) CFRP laminate debonding followed by GFRP wrap rupture, and ii) CFRP laminate crushing leading to GFRP wrap rupture. Increased GFRP wraps shifted failure from buckling to crushing and rupture.
3. The hybrid system outperformed wraps alone for eccentrically loaded thin columns, enhancing flexural stiffness and yielding improvements of 52%, 105%, and 94% in axial capacity, flexural capacity, and lateral displacement, respectively.
4. The failure progression in thin columns involved: i) CFRP laminate reaching maximum crushing capacity, followed by ii) GFRP wrap rupture leading to total failure (24).

Koosha Khorramiana, Pedram Sadeghianb.* This study investigated the behavior of short concrete columns reinforced with longitudinal NSM CFRP laminates using both analytical and experimental methods. Researchers tested fourteen samples under four load placements: 0%, 10%, 20%, and 30% of the specimen's width.

Key findings include:

1. The CFRP laminates exhibited straight stress-strain curves until failure, with an elastic modulus, ultimate strain, and a compressive-to-tensile strength ratio of 34%, 86%, and 40%, respectively. CFRP's compressive strength is still twice that of regular structural steel.
2. No buckling or peeling of NSM FRP strips occurred, but four failure types were observed: concrete spalling, concrete crushing, compressive FRP crushing, and tensile FRP rupture.
3. The average compressive strain of CFRP strips under eccentric loads was only 41% at peak load and 84% after a 15% drop, indicating that strip crushing was not a concern.
4. Reinforced specimens had load capacities 7.7% higher under pure compression and 10.9% higher at a 10% eccentricity compared to plain concrete, with a CFRP reinforcement ratio of 0.21%.
5. A parametric study showed that compressive strain in CFRP laminates increases with a higher reinforcement ratio, though it did not reach crushing values under practical ratios (less than 1%).
6. Higher concrete strength from 25 MPa to 45 MPa resulted in increased CFRP strain at peak load, but it still did not exceed 50% of the crushing strain.

7. Overall, the study concluded that crushing, buckling, or debonding of CFRP laminates did not affect the load capacity of short concrete columns reinforced with NSM CFRP laminates, demonstrating the practicality of this reinforcement approach (25).

Koosha Khorrarnian and Pedram Sadeghian. This study examines the performance of short concrete columns reinforced with Basalt Fiber-Reinforced Polymer (BFRP) wraps and Carbon Fiber-Reinforced Polymer (CFRP) laminates. Eighteen concrete column specimens, each 500 mm long with a 150 mm square cross-section, were tested under various eccentricity-to-width ratios (0.1, 0.2, and 0.3).

The research focused on small columns with transverse BFRP wraps and longitudinal CFRP strips, testing four eccentricity-to-width ratios (0, 0.1, 0.2, and 0.3). The specimens included 5 plain concrete, 9 with CFRP strips, and 4 with both reinforcements. Key findings include:

1. Five failure modes were identified: compression buckling of CFRP strips, debonding on the compression side, concrete destruction, crushing, and spalling. CFRP strips did not crush under compression, with failure first occurring through debonding leading to buckling.
2. At buckling, the average compressive strain of CFRP strips was 21% of the rupture strain, increasing to 24% at final measurement.
3. A wrapping system improved performance of longitudinally bonded specimens, yet did not prevent debonding and buckling.
4. Transverse BFRP wraps effectively limit the unbraced length of longitudinal CFRP strips in a manner similar to stirrups limiting rebars in concrete columns (26).

Koosha Khorrarnian¹ and Pedram Sadeghian². This study examines the performance of concrete columns reinforced with carbon fiber-reinforced polymer (CFRP) strips placed near the surface. We tested fourteen concrete specimens (150 x 150 x 500 mm) under concentric and eccentric compressive stress until failure, using four CFRP strips (10 x 1.2 mm) for each specimen and varying eccentricities of 0, 10, 20, and 30% of the width. The goal was to understand the CFRP behavior under compression, as the strips reached about 70% of their tensile breaking strain before failure.

We identified five failure modes: splitting of concrete, rupture of FRP, crushing of concrete, crushing of FRP, and splitting the concrete in half. The CFRP strips enhanced the columns' strength, managing large strains without buckling or separation. Our findings showed that CFRP strips significantly improved load capacity and resistance to the highest eccentric loads.

We also calculated ratios between the tensile rupture strain of the FRP coupons and the ultimate strain on the compression side for N-e10, N-e20, and N-e30 with FRP crushing, averaging 0.70, 0.53, 0.48, and 1.10, respectively. Overall, longitudinal CFRP strips can endure significant compressional strains, highlighting their important contribution (27).

Khorrarnian, Koosha¹, Sadeghian, Pedram^{1,2} This research evaluates a hybrid strengthening system using fiber-reinforced polymers (FRP) on existing bridge piers and columns, testing four types of concrete cylinders: plain, those reinforced with transverse glass FRP (GFRP) wraps, those strengthened with longitudinal carbon FRP (CFRP) strips (2.7% reinforcement ratio), and a hybrid of both.

Key observations from the twelve specimens tested include:

1. Four failure mechanisms were identified: GFRP wrap rupture, CFRP strip buckling, concrete crushing, and a combination of CFRP and GFRP failures. The maximum strength occurred with buckling and concrete crushing in specific specimens.
2. Strength increased in the longitudinal (13.99%), transverse (23.11%), and hybrid (32.64%) specimens over ordinary cylinders. The hybrid system achieved approximately 90% of the

combined gains from individual systems. The longitudinal system failed quickly without softening, while the transverse system exhibited a softening phase.

3. The hybrid system showed both a softening phase and resistance to sudden failure, benefiting from the strengths of both methods. It effectively reinforces concrete bridge columns under axial loads and bending moments, with transverse FRP providing confinement and longitudinal FRP resisting forces (28).

Koosha Khorramian. This study investigates the behavior of glass fiber-reinforced polymer (GFRP) bars under compression using experiments on short concrete columns. We tested fourteen specimens, including nine reinforced and five plain concrete columns, all measuring 500 mm long and 150 x 150 mm in cross-section. The columns underwent straight and off-center compressive loads until failure, with eccentricity ratios of 0.1, 0.2, and 0.3 applied symmetrically.

Results indicated that GFRP bars did not crush at maximum load, with strains remaining below 50% of their crushing capacity. Our analytical model, validated by experimental data, confirmed that GFRP bars can withstand significant strains without exceeding compressive limits. Additionally, we studied the impact of eccentricity, reinforcement ratio, and concrete strength on performance, concluding that GFRP bars are effective longitudinal reinforcement in concrete columns.

Coupon tests showed similar moduli of elasticity in tension and compression, with GFRP exhibiting higher strength in compression. No buckling or crushing was observed before failure. The average compressive strain at peak load was 22% and 16% of ultimate capacity, and they did not reach 50% of their capacity overall.

The analysis revealed a strong correlation between experimental results and the analytical model, with an average prediction error of less than 7%. We recommend treating GFRP bars as linear elastic materials in compression until concrete reaches a strain limit of 0.003 mm/mm, considering the parameters studied (29).

Guohua Xing¹, Osman E Ozbulut², Mohammed Ali Al-Dhabyani¹, Zhaoqun Chang¹, and Sherif M Daghsh². This study examined the performance of reinforced concrete (RC) columns during earthquakes with various reinforcement types. Seven columns were tested: one regular, two with shape memory alloy (SMA) bars without additional protection, two with SMA bars and a carbon fiber reinforced polymer (CFRP) cover, and two with only CFRP bars and covering.

Key findings include:

1. Adding SMA bars slightly improved peak load strength, but they experienced minimal stress and pull-out issues, limiting effectiveness. However, they allowed for more sideways movement before failure.
2. Columns with SMA bars showed only minor strength increases under heavy loads, with low stress on the bars leading to similar pull-out problems but greater drift capacity before failure.
3. Columns reinforced and covered with CFRP bars displayed significant strength increases when the bars remained intact.
4. Overall, using SMA or CFRP enhanced the columns' ability to endure seismic activity by reducing stiffness loss and increasing energy absorption, especially with CFRP jackets extending from base to reinforcement (30).

Haonan Wang, Guohua Xing *, Jiahua Zhao, Fayong Wen. This study examined how the NSM reinforcement ratio, CFRP wrapping, and axial compression ratio influence the seismic performance of eight reinforced concrete columns, tested under axial compression and lateral cyclic loading. We used 3D nonlinear finite element models to simulate columns strengthened with NSM AA bars.

Results indicated that with the same axial compression ratio ($n_t = 0.1$), AA-strengthened columns exhibited a peak load-bearing capacity increase of 58% to 109% and an energy dissipation capacity increase of 62% to 347% compared to the control column. The NSM method using AA bars significantly enhances the seismic performance of RC columns.

As the NSM reinforcement ratio increased, load-bearing ability, stiffness, and energy dissipation capacity improved, though higher reinforcement ratios reduced ductility and damping behavior. CFRP wrapping enhanced load-bearing capacity, ductility, stiffness, and energy dissipation by minimizing concrete spalling and providing hoop confinement to prevent AA bar buckling.

Increasing the axial compression ratio from 0.1 to 0.4 resulted in noticeable stiffness loss but a significant increase in lateral load-bearing and energy dissipation capacities. Our finite element models accurately predicted responses, with discrepancies between numerical and experimental results within $\pm 15\%$. The study concludes that combining CFRP wrapping with AA bars is an effective NSM strengthening method for RC columns (31).

Raed Abokwiek¹; Jamal A. Abdalla, F.ASCE²; Rami A. Hawileh, M.ASCE³; and Tamer El Maaddawy⁴. This research investigated the effectiveness of using NSM-CFRP strips alongside CFRP confinement to enhance the ductility and load-carrying capacity of reinforced concrete (RC) columns under straight and angled loads. Various eccentricity ratios and CFRP wrapping configurations were tested.

Key findings include:

1. More CFRP layers increased load capacity under straight loads.
2. NSM-CFRP strips did not significantly impact axial load-carrying capacity.
3. Under angled loads, NSM-CFRP strips improved ductility and sideways bending.
4. At high eccentricity, these strips shifted the failure mode from sudden brittle failure to ductile tension failure.
5. Higher eccentricity ratios reduced axial capacity but increased deflections.
6. More CFRP layers improved load capacity at low eccentricity but reduced lateral bending capacity at high eccentricity.
7. More NSM-CFRP strips enhanced ductility, while adding CFRP layers decreased it.

Overall, combining CFRP wraps with NSM-CFRP strips effectively strengthens RC columns (32).

Katarina Gajdosova, Ph.D.¹; and Juraj Bilcik². This research investigates the performance of thin, rectangular reinforced concrete columns reinforced with carbon fiber-reinforced polymers (CFRPs) using two methods: CFRP sheet jacketing and near-surface-mounted (NSM) CFRP strips.

Eight full-scale columns (210×150 mm) were tested under eccentric compressive force until failure. Key findings include:

1. CFRP reinforcement effectively strengthens both short and slender columns without significant size increase, though the impact varies with stress type.
2. For short columns under high compressive stress, transverse CFRP sheet confinement is most effective, while slender columns show limited resistance improvement.
3. In thin columns that bend, longitudinal NSM CFRP strips enhance resistance to bending better than sheet jacketing, making them more effective for improving flexural strength (33).

Koosha Khorramian¹ and Pedram Sadeghian, M.ASCE²

This study investigates a new hybrid system that enhances the performance of thin circular concrete columns by using transverse fiber-reinforced polymer (FRP) wrapping along with

longitudinally bonded carbon fiber-reinforced polymer (CFRP) laminates. The CFRP laminates boost the flexural stiffness of slender steel-reinforced concrete (RC) columns under eccentric axial compression, while the FRP wraps provide lateral support to prevent debonding and local buckling.

Researchers tested six large circular RC columns (3,048 mm long, 260 mm in diameter) under axial and flexural loads. Three columns featured the hybrid system, incorporating longitudinal CFRP strips and transverse wrapping, while two had GFRP or CFRP wraps, and one served as a control.

Key findings include:

1. Hybrid specimens with 8 and 16 CFRP strips improved GFRP-wrapped columns, increasing flexural capacity by 82.2% and 96.4%, and axial capacity by 21.8% and 50.9% compared to wrapped-only columns.
2. Hybrid specimens with eight CFRP strips enhanced CFRP-wrapped column performance by 39.5% in axial and 63% in flexural capacities.
3. No catastrophic failures were observed after peak loads; hybrid specimens continued to support loads, with gradual failure of the longitudinal strips reducing capacity but not causing complete failure.
4. The post-peak behavior indicated that axial load capacity improved with the ratio of CFRP strips, with higher reinforcement ratios leading to small cracks in the GFRP wrap.
5. The study's analytical-numerical model aligned well with experimental results, incorporating eccentric loading and nonlinearity effects.
6. The parametric analysis revealed the hybrid system's effectiveness, noting better performance with larger column diameters and as slenderness and eccentricity rise (34).

Koosha Khorramian Pedram Sadeghian. This study explored a new hybrid strengthening system for circular steel-reinforced concrete columns, combining external transverse GFRP wraps with longitudinal CFRP laminates. An analytical-numerical model accounting for second-order effects and material nonlinearity was created and validated against experimental data from thin concrete columns with fiber-reinforced polymer. Although experimental data for the hybrid system itself was lacking, the model was used in a parametric study, revealing that the hybrid system significantly enhances the load-carrying capacity compared to conventional wrapping. The GFRP wrapping is believed to confine and control the buckling of the CFRP laminates. However, further experimental data is necessary to confirm this hybrid system's effectiveness (35).

Mu sh ta q S. Ra dh i a ,Ma an S. Ha ss an b ,* , Iq ba l N. This study evaluates the effectiveness of CFRP (Carbon Fiber Reinforced Polymer) wrapping on corroded circular reinforced concrete (RC) columns, with tests conducted on columns with varying corrosion levels: none, mild, moderate, and severe. Fourteen columns were wrapped with CFRP, while ten remained unwrapped.

Key findings include:

1. Two layers of CFRP significantly enhanced the strength and axial capacity of corroded columns.
2. Corrosion level impacted the load and strain capacity, with multiple CFRP layers recommended for highly corroded columns.
3. A single CFRP layer performed similarly to unwrapped columns up to 30% corrosion, while two layers showed better confinement and five times the final axial strain of unwrapped columns.

4. More CFRP layers increased initial stiffness but overall strength decreased with higher corrosion.
5. Confined columns exhibited a three-part stress-strain curve; unconfined columns exhibited two.
6. CFRP wrapping improved stiffness, ductility, and deformation behavior of corroded columns.
7. Unconfined corroded columns failed through splitting and debonding, mainly in the upper half.
8. Confined columns with CFRP layers failed with loud tearing at peak loads, predominantly in the upper half, suggesting that reinforcing support areas could reduce excessive stress (36).

M. Chellapandiana, S. Suriya Prakasha*, Akanshu Sharmab. This study explored three methods to strengthen reinforced concrete (RC) beams under flexural loads: near-surface mounting (NSM), external bonding, and a combination of both. Researchers conducted three-dimensional nonlinear finite element analysis (FEA) and tests to identify the best edge distances for NSM and optimal carbon fiber reinforced polymer (CFRP) amounts.

Key findings include:

1. Beams strengthened with both methods exhibited a substantial increase in load capacity. Even when NSM laminates failed, these beams maintained considerable strength, akin to control beams.
2. The hybrid method absorbed more energy than either NSM or external bonding alone, though predictions from sectional analysis often did not align with experimental results for both unconfined and FRP-confined concrete.
3. A micro-plane-based finite element model effectively predicted the bending behavior of beams with various FRP strengthening techniques. (37).

Hemanth Kumar Chinthapalli, M. Chellapandian, Anil Agarwal, S. Suriya Prakash*. Under a combination of heat loads from fire and axial compression, the effectiveness of the hybrid FRP retrofitting technology is examined in order to recover the strength and axial stiffness of badly damaged columns. Several factors, including (i) concrete strength, (ii) transverse reinforcement ratio, and (iii) fire exposure length, are taken into consideration when evaluating the effectiveness of the hybrid FRP retrofitting technique. According to test results, hybrid FRP retrofitting is a viable approach that can be used in the field for urgent repairs. According to test results, columns that had suffered severe damage from a combination of fire and axial compression might have their ultimate load-carrying capability and ductility restored using the hybrid FRP approach. The axial rigidity could not be completely restored, however. The following key conclusions may be made from the findings of this investigation:

1. The heated columns' axial compressive strength considerably decreased as compared to the undamaged columns. Depending on the column dimensions and heating time, the residual compressive strengths ranged from 15% to 67%. Additionally, fire loads resulted in a considerable loss of axial stiffness, which increased as compressive strength increased.
2. It was discovered that the hybrid FRP retrofitting was highly successful in regaining the entire strength of columns that had been exposed to axial compression and fire stress for two hours. Hybrid FRP retrofitting only restored 70% of the peak strength of RC columns that had been subjected to 3-hour fire loading in addition to axial stresses. As a result, hybrid FRP retrofitting became less effective as heating time increased .
3. The column's axial rigidity could not be completely restored by the hybrid FRP retrofitting method .

4. Columns constructed with higher-grade concrete were shown to regain less of their initial strength (38).

Vui Van Cao a,b,*, **Det Van Doan a,b**, **Luan Hoai Dinh**, **Huy Ba Vo c**. This study examined the behavior of post-fire reinforced concrete (RC) joints under various loads, with a focus on the impact of CFRP (Carbon Fiber Reinforced Polymer) retrofitting. We tested nine joints in three groups: one control joint (J0), four exposed to 45 minutes of fire (J45), and four to 75 minutes (J75). The J45 group consisted of two joints tested after the fire and two retrofitted with CFRP, each tested under steady and cyclic loading conditions.

Key findings showed that fire exposure, cyclic loading, and CFRP retrofitting significantly affected failure modes and properties.

The control joint failed under steady loading as tension steel broke and concrete crushed, forming a plastic hinge of half its height ($h/2$). In contrast, fire-exposed joints had longer plastic hinges extending to the full height (h), while cyclic loading created deep cracks.

CFRP retrofitting shifted damage from the beam plastic hinge to the joint center and beam ends, with no damage seen in retrofitted areas. Fire and cyclic loading reduced the load capacity by about 11% and stiffness by up to 25.5% compared to the control, although the joints maintained ductile behavior. The combination of fire and cyclic loading further decreased yield load and ductility.

CFRP improved performance, increasing yield load by up to 9.7%, enhancing ultimate load by 15%, and restoring near-original stiffness, with ductility improving from "low or moderate" to "highly ductile." Cyclic loading led to noticeable stiffness deterioration and varying strength loss, particularly when exceeding critical loading levels. Both retrofitted and un-retrofitted joints showed significant pinching under cyclic loading, with an average pinching index of 0.75 (39).

Kabil Cetin a,*, **Taha Yasin Altiok b**, **Ali Demir b** The strength of beam-column joints is essential for a building's seismic resilience, as damage often occurs at these points when they lack adequate strength. Many buildings have collapsed due to shear failure from poorly designed joints. To improve safety, carbon fiber reinforced polymer (CFRP) sheets can be added, but debonding of these sheets poses a significant challenge.

In this study, researchers repaired weak reinforced concrete beam-column connections using CFRP sheets, employing bore-epoxy anchorage and externally bonded reinforcement on grooves (EBROG). Six $\frac{1}{2}$ scale specimens with no transverse reinforcement were tested, five of which were retrofitted. Under cyclic loads, retrofit improved performance, delaying shear failures significantly.

Results showed yield load increases of 32% to 67%, with enhancements in initial stiffness, load-carrying capacity, and energy dissipation—up to 68%, 64%, and 104%, respectively. Ductility also improved by 7% to 26%. The use of bore-epoxy anchorage and EBROG methods effectively prevented early debonding, with the debonding displacement level for these techniques being approximately four times higher than standard methods. Overall, these methods outperform traditional externally bonded reinforcement techniques (40).

Guo-Lin Wanga, **Jian-Guo Daib,***, **Yu-Lei Baic**. This research evaluates six externally reinforced concrete (RC) beam-column junctions using fiber-reinforced polymer (FRP) materials for seismic resistance. Key findings include:

1. An RC joint built to the Hong Kong Code failed in flexure, creating a plastic hinge near the column, while a joint per BS 8110 without transverse steel reinforcement failed in shear under cyclic loads.
2. Strengthening with L-shaped CFRP sheets at corners and wrapping did not prevent shear failure, showing only slight energy dissipation improvement.

3. The most effective method was near-surface mounted (NSM) CFRP strips anchored in the adjacent beam, which shifted the plastic hinge away from the column, promoting ductile failure.
4. NSM CFRP strips along the column with end anchorage performed worse than those along the beam, still resulting in shear failure.
5. Strain analysis revealed that NSM CFRP strips reduced shear deformation, contributing to a more ductile failure mode by moving the failure from the joint to the beam end (41).

Elias I. Saqana*, **Hayder A. Rasheedb**, **Tarek Alkhrdajic**. This study evaluated the performance of beam-column assemblies reinforced with bonded CFRP sheets and NSM CFRP bars per seismic codes. Key findings include:

1. Both techniques enhanced strength, energy absorption, and stiffness compared to control specimens.
2. NSM bars exhibited higher yielding and ultimate strength.
3. CFRP sheet specimens absorbed more energy during cyclic loading due to gradual debonding.
4. NSM bars are better for added strength, while CFRP sheets may be preferable for energy absorption.
5. Thickening epoxy at member corners negatively impacted frame behavior and should be avoided.
6. For both methods, load-deflection response diminished after internal steel yielding due to localized debonding, unlike monotonic loading, which retains stiffness post-yielding (42).

References

1. Nanni A, Bradford N. FRP Jacketed Concrete under Uniaxial Compression. *Constr Build Mater* 1995;9(2):115–24.
2. H. A. Toutanji, "Stress-Strain Characteristics of Concrete Columns Externally Confined with Advanced Fiber Composite Sheets," *ACI Materials Journal*, pp. 397-404, 1999.
3. Hadi MNS. Behaviour of FRP Wrapped Normal Strength Concrete Columns under Eccentric Loading. *Compos Struct* 2006;72(4):503–11.
4. Sadeghian P, Rahai AR, Ehsani MR. Experimental Study of Rectangular RC Columns Strengthened with CFRP Composites Under Eccentric Loading. *J Compos Constr* 2010;443–50.
5. Bisby L, Ranger M. Axial–flexural Interaction in circular FRP-Confined Reinforced Concrete Columns. *Constr Build Mater* 2010;24(9):1672–81. [6] Yu F, Xu G, Niu D, Cheng A, Wua P, Kong Z. Experimental Study on PVC-CFRP Confined Concrete Columns under Low Cyclic Loading. *Constr Build Mater* 2018; 177:287–302.
6. Chaallal, O., and Shahawy, M. (2000). "Performance of fiber-reinforced polymer-wrapped reinforced concrete columns under combined axial-flexural loading." *ACI Struct. J.*, 97(4), 659–669.
7. Parvin, A., and Wang, W. (2001). "Behavior of FRP jacketed concrete columns under eccentric loading." *J. Compos. Constr.*, 5(3), 146–152.
8. Mukherjee, A., Boothby, T., Bakis, C., Joshi, M., and Maitra, S. (2004). "Mechanical behavior of fiber-reinforced polymer-wrapped concrete columns: complicating effects." *J. Compos. Constr.*, 8(2), 97–103.
9. Hadi, M. (2006). "Behaviour of FRP wrapped normal strength concrete columns under eccentric loading." *Compos. Struct.*, 72(4), 503–511.

11. Parvin, A., and Schroeder, J. (2008). "Investigation of eccentrically loaded CFRP-confined elliptical concrete columns." *J. Compos. Constr.*, 12(1), 93–101.
12. El-Maaddawy, T., El-Sayed, M., and Abdel-Magid, B. (2010). "The effects of cross-sectional shape and loading condition on performance of reinforced concrete members confined with carbon fiber-reinforced polymers." *Mater. Des.*, 31(5), 2330–2341.
13. Barros JA, Ferreira DR, Fortes AS, Dias SJ. Assessing the effectiveness of embedding CFRP laminates in the near-surface for structural strengthening. *Constr Build Mater* 2006;20(7):478–91.
14. Barros JA, Varma RK, Sena-Cruz JM, Azevedo AF. Near-surface-mounted CFRP strips for the flexural strengthening of RC columns: Experimental and numerical research. *Eng Struct* 2008;30(12):3412–25.
15. Perrone, M., Barros, J. A., & Aprile, A. (2016). CFRP-based strengthening technique to increase the flexural and energy dissipation capacities of RC columns. *J. Compos. Constr.* 2009;13(5):372–83.
16. Bournas DA, Triantafillou TC. Flexural strengthening of RC columns with NSM FRP or stainless steel. *ACI Struct J* 2009;106(4):495–505.
17. Ding L, Wu G, Yang S, Wu Z. Performance advancement of RC columns by applying basalt FRP composites with NSM and confinement system. *J Earthq Tsunami* 2013; 7(2):1–20.
18. Hasan QF, Tekeli H, Demir F. NSM Rebar and CFRP laminate strengthening for RC columns subjected to cyclic loading. *Constr Build Mater* 2016;119:21–30.
19. Fahmy MF, Wu Z. An exploratory study of the seismic response of deficient lap-splice columns retrofitted with near-surface-mounted basalt FRP bars. *J. Struct. Eng.* 2016; 142(6): 1–16.
20. Seifi A, Hosseini A, Marefat MS, Khanmohammadi M. Seismic retrofitting of old-type RC columns with different lap splices by NSM GFRP and steel bars. *Structural Design Tall Spec Build* 2018; 27(2): 1–21.
21. Sarafraz ME, Danesh F. New technique for flexural strengthening of RC columns with NSM FRP bars. *Mag Concr Res* 2012; 64(2): 151–61.
22. Xing G, Ozbulut OE, Al-Dhabyani MA, Chang Z, Daghash SM. Enhancing the Flexural Capacity of RC Columns through Near-Surface-Mounted SMA and CFRP Bars. *J Compos Mater* 2020;54(29):4661–76.
23. (2011) El-Maaddawy, Tamer, and Amr S. El-Dieb. "Near-surface-mounted composite system for repair and strengthening of reinforced concrete columns subjected to axial load and biaxial bending." *Journal of composites for construction* 15.4 (2011): 602-614.
24. (2021) Khorramian, Koosha, and Pedram Sadeghian. "Hybrid system of longitudinal CFRP laminates and GFRP wraps for strengthening of existing circular concrete columns." *Engineering Structures* 235 (2021): 112028
25. (2019) Khorramian, Koosha, and Pedram Sadeghian. "Performance of high-modulus near-surface-mounted FRP laminates for strengthening of concrete columns." *Composites Part B: Engineering* 164 (2019): 90-102.
26. (2017) Khorramian, Koosha, and Pedram Sadeghian. "Strengthening short concrete columns using longitudinally bonded CFRP laminates." *The 13th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures (FRPRCS-13), Anaheim, CA, USA.* 2017.
27. (2017) Khorramian, Koosha, and Pedram Sadeghian. "Strengthening concrete columns using NSM CFRP laminates." 6th Asia-Pacific Conference on FRP in Structures, 2017.

28. (2018) Khorramian, Koosha, and Pedram Sadeghian. "Rehabilitation of Bridge Columns Using Hybrid Strengthening Method of Longitudinal CFRP and Transverse GFRP Wraps." *10th International Conference on Short- and Medium-Span Bridges*. 2018.
29. (2020) Khorramian, Koosha. *Short and slender concrete columns internally or externally reinforced with longitudinal fiber-reinforced polymer composites*. Diss. Dalhousie University, 2020.
30. Xing, Guohua, et al. "Enhancing flexural capacity of RC columns through near-surface mounted SMA and CFRP bars." *Journal of Composite Materials* 54.29 (2020): 4661-4676.
31. Wang, Haonan, et al. "Seismic behavior of RC columns strengthened with near-surface-mounted aluminum alloy bars and CFRP wraps." *Engineering Structures* 268 (2022): 114742.
32. Abokwiek, Raed, et al. "RC columns strengthened with NSM-CFRP strips and CFRP wraps under axial and uniaxial bending: experimental investigation and capacity models." *Journal of Composites for Construction* 25.2 (2021): 04021009.
33. Gajdosova, Katarina, and Juraj Bilcik. "Full-scale testing of CFRP-strengthened slender reinforced concrete columns." *Journal of Composites for Construction*, 17 (2), 2013, pp. 239-248.
34. Khorramian, Koosha, and Pedram Sadeghian. "Slender RC columns strengthened with a novel hybrid strengthening system of external longitudinal and transverse FRPs." *Journal of Structural Engineering* 147.10 (2021): 04021154.
35. Khorramian, Koosha, and Pedram Sadeghian. "Strengthening slender circular concrete columns with a novel hybrid FRP system." *CSCE Annual Conference 2018, Fredericton, NB, Canada*. 2018.
36. Radhi, Mushtaq S., Maan S. Hassan, and Iqbal N. Gorgis. "Carbon fibre-reinforced polymer confinement of corroded circular concrete columns." *Journal of Building Engineering* 43 (2021): 102611.
37. Chellapandian, M., S. Suriya Prakash, and Akanshu Sharma. "Experimental and finite element studies on the flexural behavior of reinforced concrete elements strengthened with hybrid FRP technique." *Composite Structures* 208 (2019): 466-478.
38. Chinthapalli, Hemanth Kumar, et al. "Effectiveness of hybrid fibre-reinforced polymer retrofitting on behaviour of fire-damaged RC columns under axial compression." *Engineering Structures* 211 (2020): 110458.
39. Van Cao, Vui, et al. "Monotonic/cyclic behavior of postfire RC beam-column joints without/with CFRP retrofitting: Experiments." *Journal of Building Engineering* (2025): 113371.
40. Cetin, Kabil, Taha Yasin Altiok, and Ali Demir. "Experimental investigation of EBROG and bore-epoxy anchorage methods used for interior RC beam-column joints strengthened with CFRP sheets." *Structures*. Vol. 66. Elsevier, 2024.
41. Wang, Guo-Lin, Jian-Guo Dai, and Yu-Lei Bai. "Seismic retrofit of exterior RC beam-column joints with bonded CFRP reinforcement: An experimental study." *Composite Structures* 224 (2019): 111018.
42. Saqan, Elias I., Hayder A. Rasheed, and Tarek Alkhrdaji. "Evaluation of the seismic performance of reinforced concrete frames strengthened with CFRP fabric and NSM bars." *Composite Structures* 184 (2018): 839-847.