3rd International Conference on Advances in Civil and Environmental Engineering (ICACEE-2024)

University of Engineering & Technology Taxila, Pakistan

Conference dates: 21st and 22nd February 2024; ISBN: 978-969-23675-2-3

Hybrid Strengthening of Reinforced Concrete Compressive Members Using Fiber-Reinforced Polymers

Nihal Shafiq[1,*], Saleh Muhammad[1], Muhammad Azhar Nauman[1],
Qaiser uz Zaman Khan[1], Ali Raza[1]

Department of Civil Engineering, University of Engineering and Technology Taxila, 47050 Pakistan

*Corresponding author: nihalshafiq1544@gmail.com

ABSTRACT

Reinforced Concrete (RC) Structure is showing signs of wear and tear. A way is needed to improve its strength and resilience, but traditional methods haven't been ideal. Entering into the Fiber-reinforced cementitious matrix (FCM) technology, a promising solution thanks to its ease of application and effectiveness in reviving these structures. However, simply adding more layers of FCM doesn't always guarantee better results, sometimes leading to unexpected failures. A hybrid approach that combines FCM technology with the power of Fibre-Reinforced Polymer (FRP) strengthening. Think of it as a hybrid strengthening approach, by strategically employing external FRP bonding, we can minimize the reliance on bulky FCM layers, while simultaneously achieving superior ductility, confinement, and ultimately, a higher load-bearing capacity for the reinforced concrete member. This study investigates the behaviour of circular reinforced concrete columns under uniaxial compression load when reinforced with a hybrid FCM and externally bonded fiber-reinforced polymer (EBF). Six reinforced columns and one control column made up the seven columns that were built. For strengthening, carbon or glass FRP was employed. The principal purpose or goal of research is to assess the efficacy of combining fiber slippage prevention, FCM, and EBF strengthening techniques in enhancing deformation characteristics and mitigating the need for further FCM layers. The load-carrying capacity under uniaxial loading, load against axial deformation, and failure patterns are some of the important study factors.

KEYWORDS

Fiber reinforced polymers; columns; confinement; load-deflection behaviour; axial strength

1. INTRODUCTION

Due to a variety of problems, including inadequate capacity brought on by excessive loads, structural deterioration from chemical attacks, flaws in design or construction, code violations, variations in use, and exposure to normal disasters such as seismic activity and cyclones, many civil infrastructures need to be repaired and renovated [1]. As a result of their inherent benefits—such as corrosion resistance, high tensile strength, a favorable strength-to-weight ratio, and ease of use—Fibre Reinforced Polymer (FRP) systems have garnered increasing attention in comparison to traditional methods for strengthening these structures over time. As a result, the use of FRP strengthening has gained acceptance and popularity [2-4]. These include being exposed to fire or severe temperatures, being inappropriate for damp surfaces, and offering limited compatibility with some substrates.[5].

In the realm of FRP strengthening, numerous techniques have been employed to improve or alter the behavior of structures. These methods include FRP wrapping and the near-surface installation of FRP bars or laminates [6, 7]. Within the FRP realm, external bonded FRP (EBF) wrapping and Fiber Reinforced Cementitious Matrix (FCM) methods have gained popularity due to their ease of application [8]. Past study has indicated that the application of the EBF approach to strengthen columns improves their load-bearing ability and buckling properties when subjected to vertical and lateral loads [9, 10]. Moreover, these investigations have demonstrated that circular columns behave better than square columns. Although this can be mitigated by increasing the corner radii of the column edges, square or rectangular columns often collapse at their edges. [11, 12].

FCM addresses issues like FRP's limitations in high-temperature or fire environments, its incompatibility with concrete substances, and its application on damp surfaces by combining fiber networks or interconnects with inert mediums (cementitious matrices) [9, 13, 14]. The preference for inorganic cementitious mortar over epoxy is gaining popularity [15, 16]. In order to assess the performance of the FCM system in the strengthening of beams and columns, a number of experiments have been carried out, signifying its ability to improve strength and other structural properties. Prior experiments have shown that the FCM system significantly contributes to the beams flexural and shear capacities, the axial capacity of columns, and the ductility of beam-column joints. Rather than debonding, fiber slippage within the matrix is the most common cause of failure in the FCM system. [17, 18].

To address both the advantages and disadvantages of individual techniques, combinations of multiple methods are employed to increase the performance of column behaviour, a practice recognised as hybridization. Hybridization serves to improve the capacity, toughness, detention, flexibility, and buckling ability of reinforced concrete columns, while also modifying their failure patterns [19, 20]. Ispir et al. [21] enhanced ductility and confinement were achieved by employing a hybrid technique combining carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) sheets to study the behavior and efficacy of confined columns. Shear capacity, maximum load/flexural carrying capacity, and deformation capacity are all improved by combining various ways. The externally bonded FCM layer may separate from the concrete substrate, though, as the quantity of coats also increases the element's width [22].

Previous experimental studies have demonstrated that the implementation of the FCM system significantly enhances the flexural and shear capacities of beams, columns, and beam-column joints. (Faleschini et al., 2019; Kyaure, 2021) investigated the primary mode of failure observed in the FRCM system is the slippage of fibers within the matrices, limiting its widespread application. Notably, carbon-based FCM exhibits superior strength when compared to glass-based FCM. Investigating square and circular columns confined with 1, 2, or 4 layers of PBO-FCM [23].

Noor Tello et al. (2021) found increased load-carrying capacity and ductility ranging from 5 to 36% compared to unconfined columns. The impact of confinement was more evident in circular columns than in square ones. Square columns mainly failed due to PBO ruptures at the edges, while circular columns with 1 or 2 layers of PBO FRCM failed due to fiber rupture, and those with four layers failed due to steel yielding. Feras Abu Obaida et al. (2021) investigated the substitution of FRCM cementitious matrices with Geopolymer matrices, revealing that Geopolymer matrices reduced the bonding length and increased the load capacity by 71% compared to cement-based matrices [24].

The current work fills a research gap in hybrid strengthening strategies, which has been demonstrated in previous studies. Spagnuolo (2019), Feng et al. (2021), Zhu et al. (2021) have all contributed to the understanding of FCM systems. It is essential to emphasize that, with an increase in the number of FCM layers, there is a concurrent rise in layer thickness, resulting in a reduction in both capacity and ductility [25, 26, 27]. Few studies shows the primary failure mechanism in FCM layers primarily revolves around slippage within the FCM matrices rather than rupture, especially when reinforcing specimens with more than two layers [28, 29]. In terms of flexural, shear, and compressive behavior, hybrid systems such as an external bonded fibre-reinforced polymer (FRP) and FCM have demonstrated promising performance. However, RC element ductility has reduced and fiber slippage has resulted in early failure as FCM layers have risen. Comparing the effectiveness and behavior of using FCM/EBF in conjunction with FCM alone is the aim of this study. Columns are reinforced with glass and carbon fibers to enhance their failure modes, ductility, and compressive behavior. It is observed that the new hybrid FCM/EBF technology uses EBF to minimize FCM layers, improving strength and ductility.

2. MATERIALS AND METHODS

2.1. Materials

With a maximum coarse aggregate size of 10 mm, three distinct batches of grade 42 ordinary Portland cement were used to cast the RC columns. For the creation of concrete, a mix ratio of 1:1.5:3 was utilized. Three 150 x 300 mm cylinders were cast for each batch of concrete to guarantee its compressive strength, resulting in an average compressive strength of 20.5 MPa. The columns were reinforced longitudinally and transversely using Grade 60 deformed ribbed steel reinforcing bars. Each column was reinforced with six 8 mm vertical reinforcing bars as well as three 6mm transverse reinforcement bars. All six longitudinal bars featured with 90° hooks on both ends. There were stirrups every 350 mm. Figure 1 shows the details of the reinforcement. The columns were cast, left in their formworks for two days, then de-molded and cured for a total of twenty-eight days in a curing tank. FRP made of glass and carbon, as well as FCM composites, were used to reinforce the columns. According to the manufacturer, Tables 1 and 2 provide a full overview of the characteristics of the CFRP/GFRP fibers, fiber mesh, and fabric utilized

.

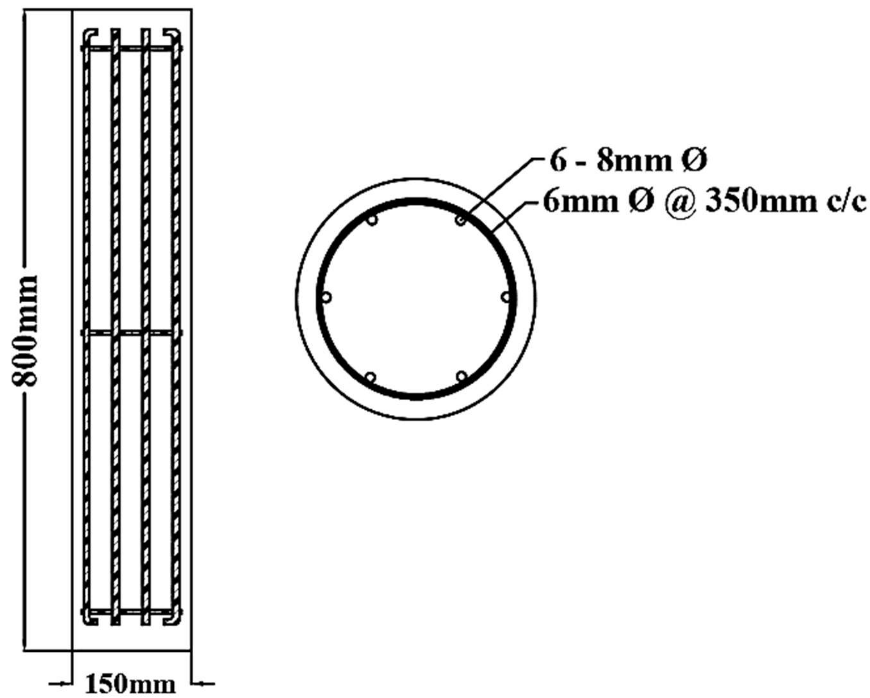


Figure 1: Reinforcement detailing of RC circular column.

The labelling of samples was done in this way: CONT (samples), SLGFCM (spherical column strengthened with single layer glass FCM), DLGFCM (circular column strengthened with double layer glass FCM), SLGFCM_EBF (circular column strengthened with single layer glass FCM and external epoxy bonded glass FRP sheets), SLCFCM (circular column strengthened with single layer carbon FCM), DLCFCM (circular column strengthened with double layer carbon FCM), and SLCFCM_EBF (circular column strengthened with single layer carbon FCM and external epoxy bonded carbon FRP sheets).

Table 1: Fiber properties

Type of fiber	Tensile strength (MPa)	Compressive strength (MPa)	Young's modulus (GPa)	Density (g/cm^3)	Elongation (%)
Glass fiber	3576	1075	73	2.59	4.47
Carbon fibre	3900	786	235	1.79	1.46

Table 2: Fabric properties

Type of fiber	Type Woven	Elongation	Area weight	Tensile strength	Sheet Thickness
Glass	Bi-directional (0^0-90^0)	4.67%	200 g / Sqm	3500 MPa	0.25 mm
Carbon	Uni-directional 0^0	1.59%	225 g / Sqm	3980 MPa	0.25 mm

2.2. Strengthening and Testing Method:

In the experimental setup, seven of these columns were used to assess how RC circular columns with hybrid strengthening behaved. These 800 mm tall and 150 mm diameter columns were subjected to an axial compression force. Both FCM and FRP wrapping techniques were used to strengthen the RC columns. Both single-layer and double-layer configurations were used in the FCM process, and epoxy bonding was used for the FRP wrapping. To achieve consistent application, the concrete surface surrounding the columns was mechanically ground before the FCM/FRP composites were applied. In addition, the columns' corners were smooth-edged to the 10mm span. Particles of moveable grit were removed from a surface. The RC columns were painted with white lime to improve the visibility of any fracture patterns after the strengthening treatments were finished. Figure 2 shows the steps involved in the strengthening process employing carbon and glass fiber-reinforced polymers.

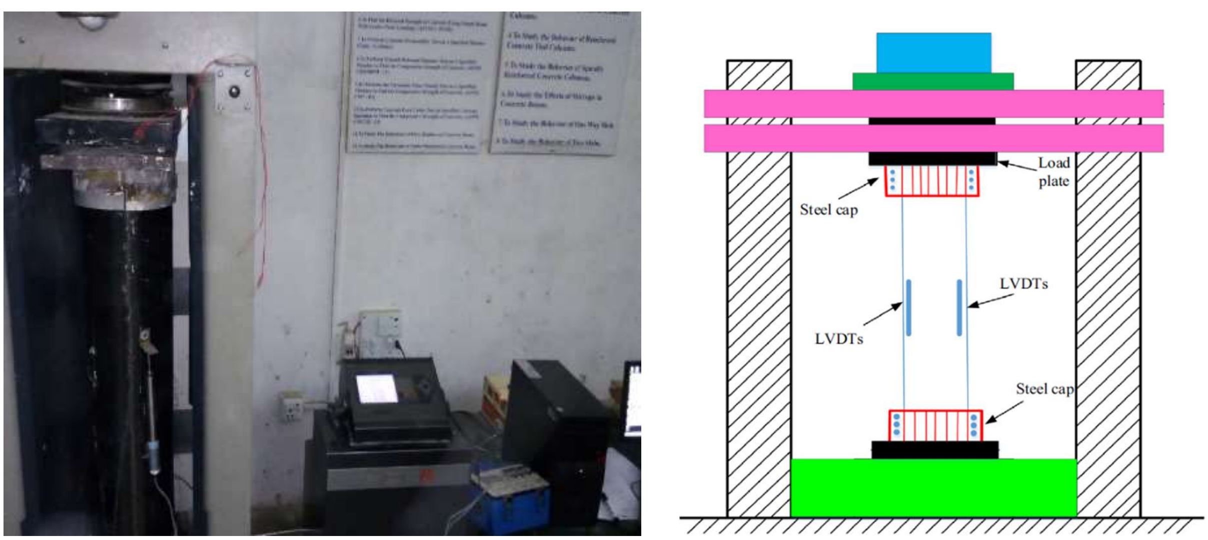
The concrete surface was first ground and then wet with water for the FCM strengthening procedure. Then a first, approximately five millimetres thick layer of the cementic matrix was added. Then a second layer of cementitious matrix was added, and the GFRP mesh had been gently placed on that surface. A second layer of GFRP mesh was added to the newly created matrix after the addition of other cementitious matrices to the surface. The CFRP was installed on the specimen using a similar process.

Using the FRP wrapping process, the column's length was wrapped, beginning with the FCM composite system that was already installed. First, the surface of the dried concrete was covered with a coating of epoxy resin. Subsequently, a 5 mm wide GFRP cloth was gently placed over the epoxy resin to guarantee enough resin impregnation and strong adherence. The cloth was then covered in still another coat of resin. Likewise, a similar process was used to place the CFRP composite on the specimen.

Column Mortar repair GFRP mesh CFRP mesh CFRP wrapping

Figure 2: Strengthening of RC columns

Using a compression testing machine, the RC column was subjected to axial loading along its longitudinal axis at an average loading rate of 0.003 mm/s. During testing, loading was periodically stopped at different load points so that pictures could be taken. To measure axial deflections, three linear variable differential transducers were also installed at the column's mid-height, arranged in three distinct directions. Figure 3 shows a testing and schematic diagram of the instrumental setup.



(a) (b)

Figure 3: Testing of samples (a) experimental setup (b) schematic test setup

3. RESULTS AND DISCUSSION:

3.1. Peak strength and load-deflection behaviour

Figure 4 also shows a comparison of all specimens' ultimate capacities and percentage increments. All the FRP-enhanced specimens showed greater strength than the RC column used as a control (CONT). The specimens that were enhanced through hybridization showed the greatest capacity, suggesting better bonding and confinement at the interfaces. Increased capacities of 264 kN, 275 kN, 334 kN, and 362 kN were shown by the single-layer (SLGFCM) and double-layer (DLGFCM) FCM-strengthened columns, as well as the single-layer (SLCFCM) and double-layer (DLCFCM) FCM-strengthened columns. Notably, the double-layer FCM column had less ductility than the single layer despite having a larger capacity.

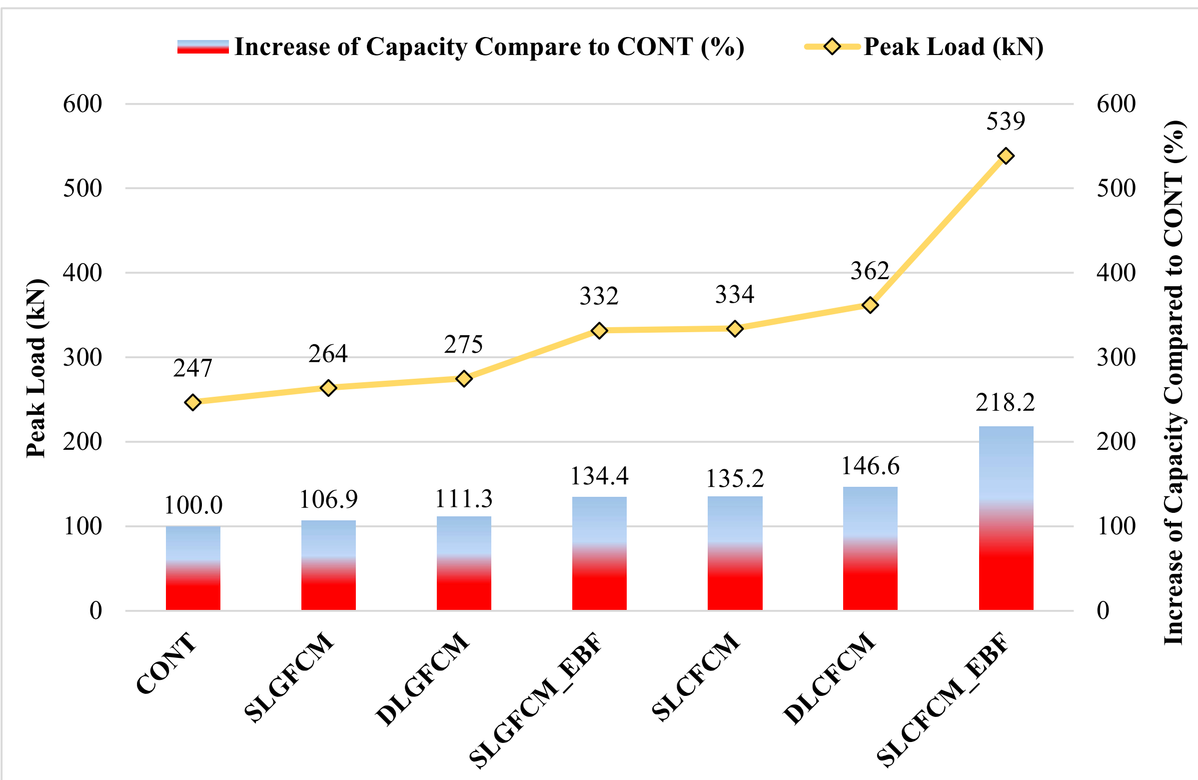
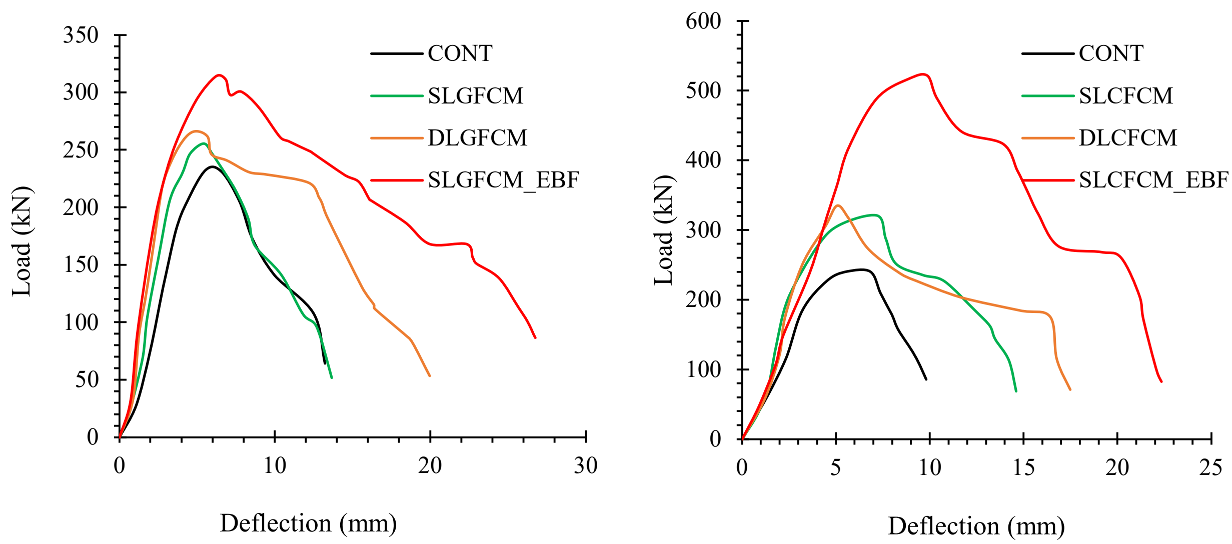


Figure 4: Comparison between Peak Load (kN) and Percentage Increase (%).

The FCM-strengthened columns started to yield until the concrete failed, reaching their maximum capacity with minimal distortion. The hybrid FCM/FRP-strengthened columns, SLGFCM_EBF and SLCFCM_EBF, both showed enhanced capacities of 332 kN and 539 kN, respectively. The ultimate capacity of the hybrid-strengthened columns (SLGFCM_EBF and SLCFCM_EBF) ranged from 27.5% to 83% higher than that of the columns strengthened only with the FCM approach. This highlights the importance of confinement in hybrid strengthening and validates the hybrid method's improved efficiency compared to the FCM technique alone. The final capacity and deformation capabilities are improved by the external wrapping. Because of their higher tensile capacity, carbon fiber-reinforced polymer (FRP) columns demonstrated capacities greater than those of glass FRP-enhanced columns. Moreover, offering FRP that is externally bonded might improve confinement and lessen the quantity of FCM layers needed for strengthening. Figure 5 displays the entire load-deflection response of the samples.



(a) (b)

Figure 5: Comparison of load versus deformation of samples (a) GFRP-wrapped samples (b) CFRP-wrapped samples

3.2. Failure Load

A crack that started in the middle of the control column and moved towards its conclusion was the first sign of the column's failure. Abrupt failure was caused by a concentration of stress at the end of the column. Figure 6 shows the failure modes of the reinforced and control specimens. Notably, larger maximum loads were found in the columns strengthened by FCM in both single and double layers, suggesting enhanced confinement effects. The failures of the FCM-strengthened columns were characterized by fiber slippage, delamination of the external mortar layer, and finally, concrete crushing. The carbon FCM system outperformed the glass FCM system inspite of having comparable failure modes. A cementitious matrices first developed cracks, which later grew and caused fiber slippage in the DLGFCM and DLCFCM specimens as well as the SLGFCM and SLCFCM specimens. Before the final failure brought on by concrete crushing in the double-layer FCM-strengthened column, the single-layer FCM demonstrated effective confinement. When compared to the other strengthened specimens, the hybrid FCM/FRP specimens SLGFCM_EBF and SLCFCM_EBF showed a greater enhancement in ultimate capacity. These hybrid specimens failed due to fabric debonding followed by fiber rupture, ultimately culminating in concrete smashing just at tip, largely a consequence of immersed stress.

Figure 6: Failure modes of the specimens

4. CONCLUSION:

This research basically investigated the axial compression behavior of reinforced concrete circular columns reinforced with hybrid fiber-reinforced cementitious matrix (FRCM) and externally bonded (EB)-FRP sheets. Utilizing both experimental and analytical methods, the study comprehensively evaluated the performance of these columns. The key findings emerging from this investigation are summarized below:

- The results showed that hybrid strengthening significantly increased the capacity of the columns as compared to traditional methods using fiber-reinforced cementitious matrix (FCM).
- The capacity of the single and double-layer FCM-strengthened samples were less than that of the hybrid-strengthened columns, SLGFCM_EBF and SLCFCM_EBF. Additionally, it suggests that hybrid strengthening with external FRP wrapping over the FCM layer can reduce the number of FCM layers and achieve higher strength with fewer FCM layers.
- The confinement of the RC circular column was more pronounced in CFRP-wrapped specimens than in GFRP-wrapped specimens.
- The maximum capacity of hybrid-reinforced columns ranged from 27.5% to 83% higher than that of columns strengthened only with the FCM approach.
- The control column failed due to crushed concrete. Both single and double layers failed as a result of mortar layer delamination and subsequent fiber rupture. Debonding of the FRP covering and fiber yielding, followed by concrete crushing, caused the hybrid FCM/EBF column to fail.

The study also found that hybrid-strengthened columns exhibited a more ductile failure process compared to FCM-strengthened columns. This is due to the confinement provided by the FRP wrapping, which helps to prevent the concrete from crushing. To conclude, we can say that basically this study provides strong evidence that hybrid strengthening with FRP is a promising method for improving the capacity and performance of reinforced concrete columns.

ACKNOWLEDGMENTS

None.

REFERENCES

1. Fossetti, M., et al., *Simplified analytical models for compressed concrete columns confined by FRP and FRCM system. Materials and Structures*, 2017. **50**: p. 1-20.
2. Raafat El-Hacha, M.A.M., *Effect of SFRP confinement on circular and square concrete columns.*

3. Tavakkolizadeh, A.A.M., P*redictive model for slenderness limit of circular RC columns confined with FRP wraps.*
4. Flora Faleschini, J.G.-L., Mariano Angelo Zanini , Lorenzo Hofer , Lesley Sneed , Carlo Pellegrino, *REPAIR OF SEVERELY-DAMAGED RC EXTERIOR BEAM-COLUMN JOINTS WITH 2 FRP AND FRCM COMPOSITES*
5. Gonzalez-Libreros, J.H., et al., *Behavior of RC beams strengthened in shear with FRP and FRCM composites. Engineering Structures*, 2017. **150**: p. 830-842.
6. Ahmad, A. and A. Raza, *Reliability analysis of strength models for CFRP-confined concrete cylinders. Composite Structures*, 2020. **244**: p. 112312.
7. Aslam, H.M.U., A. Sami, and A. Raza, *Axial compressive behavior of damaged steel and GFRP bars reinforced concrete columns retrofitted with CFRP laminates. Composite Structures*, 2021. **258**: p. 113206.
8. Klajdi Toska a, F.F., *FRCM-confined concrete: Monotonic vs. Cyclic axial loading.*
9. *Gonzalez-Libreros J., Z.M.A., Faleschini F., Pellegrino C., Confinement of low-strength concrete with fiber reinforced cementitious matrix (FRCM) composites.*
10. Jacopo Donninia, S.S.a.V.C., *A comparison between the use of FRP, FRCM and HPM for concrete confinement.*
11. Toutanji, H., et al., *Behavior of Large-Scale Rectangular Columns Confined with FRP Composites.*
12. Sushil S. Sharmaa, U.V.D., Himat Solanki, *FRP Wrapping for RC Columns with Varying Corner Radii.*
13. H Hasan1, R.P.a.D.P.G., *Experimental and numerical investigation of plain concrete columns strengthening by FRCM composite material.*
14. Flora Faleschini, M.A.Z., Lorenzo Hofer, Carlo Pellegrino, *Experimental behavior of reinforced concrete columns confined with carbon-FRCM composites.*
15. Muhammad Kyaure, F.A., *Finite element parametric analysis of RC columns strengthened with FRCM.*
16. Feras Abu Obaida, T.E.-M.a.H.E.-H., *Bond Behavior of Carbon Fabric-Reinforced Matrix Composites: Geopolymeric Matrix versus Cementitious Mortar.*
17. Wakjira, U.E.a.T.G., *Behaviour of RC beams strengthened in shear using near surface embedded FRCM.*
18. Liangliang Wei, T.U., Koji Matsumoto, Ji-Hua Zhu, *Experimental and analytical study on the behavior of RC beams with externally bonded carbon-FRCM composites.*
19. Ispir, M., K.D. Dalgic, and A. Ilki, *Hybrid confinement of concrete through use of low and high rupture strain FRP. Composites Part B: Engineering*, 2018. **153**: p. 243-255.

20. Noroozieh, E. and A. Mansouri, *Lateral strength and ductility of reinforced concrete columns strengthened with NSM FRP rebars and FRP jacket. International Journal of Advanced Structural Engineering,* 2019. **11**(2): p. 195-209.
21. Medine Ispir∗, K.D.D., Alper Ilki, *Hybrid confinement of concrete through use of low and high rupture strain FRP.*
22. El-Sherif, H., T.G. Wakjira, and U. Ebead, *Flexural strengthening of reinforced concrete beams using hybrid near-surface embedded/externally bonded fabric-reinforced cementitious matrix. Construction and Building Materials*, 2020. **238**: p. 117748.
23 F. Faleschini, J. Gonzalez-Libreros, M. A. Zanini, L. Hofer, L. Sneed, and C. Pellegrino, *'Repair of severely-damaged RC exterior beam-column joints with FRP and FRCM composites'*, *Compos Struct*, vol. 207, pp. 352–363.
24 F. Abu Obaida, T. El-Maaddawy, and H. El-Hassan, *'Bond behavior of carbon fabric-reinforced matrix composites: Geopolymeric matrix versus cementitious mortar', Buildings*, vol. 11, no. 5.
25 J. Donnini, S. Spagnuolo, and V. Corinaldesi, 'A comparison between the use of FRP, FRCM and HPM for concrete confinement', *Compos B Eng*, vol. 160, pp. 586–594, Mar. 2019.
26 R. Feng, J. Zhang, Y. Li, and J. H. Zhu, *'Experimental study on hysteretic behavior for corroded circular RC columns retrofitted by ICCP-SS', Structures,* vol. 35, pp. 421–435.
27 J. H. Zhu, J. Chen, Y. Feng, and C. Bin Liu, *'Compression tests of C-FRCM jacket confined hollow section RC columns', Structures,* vol. 31, pp. 961–969.
28 M. Chellapandian, S. S. Prakash, and A. Sharma, *'Experimental and finite element studies on the flexural behavior of reinforced concrete elements strengthened with hybrid FRP technique', Compos Struct,* vol. 208, pp. 466–478.
29 H. E. El-Sherif, T. G. Wakjira, and U. Ebead, *'Flexural strengthening of reinforced concrete beams using hybrid near-surface embedded/externally bonded fabric-reinforced cementitious matrix', Constr Build Mater*, vol. 238, p. 117748.