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ORIGINAL

Failure behavior of Strengthen reinforced concrete columns under effect of static load

Comportamiento de falla de columnas de hormigón armado reforzadas bajo el efecto de carga estática

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ABSTRACT

Introduction: this study aimed to present a rapid and effective repair method using Cempatch and carbon fiber-reinforced polymer (CFRP) for reinforced concrete (RC) columns affected by seismic events.
Method: the study included both experimental and theoretical components. The experiment involved casting and testing thirteen 900 mm long reinforced concrete columns with identical longitudinal steel reinforcement and a cross-section of 200 x 200 mm. An axial compressive load (N) was applied to all specimens, starting from zero and increasing until failure. The columns were divided into four groups, each containing a control column. Three damaged columns in each group were repaired with Cempatch and different levels of CFRP. The theoretical analysis utilized ANSYS software (version 14) for simulation.
Results: the experimental results showed that the failure pattern shifted from the repaired areas to the unrepaired ones as the number of CFRP layers increased. This indicates that the restoration materials efficiently deflected stress and enhanced the load-bearing capacity of the columns. Finite element analysis results showed strong agreement with the experimental findings, with final load differences of 17,3 % and 0,9 %, respectively. The tests demonstrated a 148,7 % increase in ultimate load with additional CFRP layers, and a 30,3 % rise in the number of repaired faces. However, repairs near the center of the columns yielded less favorable outcomes than those at the top.
Conclusions: the study confirms that using Cempatch and CFRP significantly improves the seismic resistance of RC columns, with optimal repair outcomes achieved with CFRP layers applied near the top of the columns.

Keywords: Reinforced Concrete Column; CFRP Strips; Repaired Column.

RESUMEN

Introducción: este estudio tiene como objetivo presentar un método de reparación rápido y efectivo utilizando Cempatch y polímero reforzado con fibra de carbono (CFRP) para columnas de concreto armado (RC) afectadas por eventos sísmicos.
Método: el estudio incluyó componentes experimentales y teóricos. El experimento consistió en la fabricación y prueba de trece columnas de concreto armado de 900 mm de longitud con refuerzo longitudinal de acero idéntico y una sección transversal de 200 x 200 mm. Se aplicó una carga axial de compresión (N) a todas las muestras, comenzando desde cero e incrementando hasta el fallo. Las columnas se dividieron en cuatro grupos, cada uno con una columna de control. Tres columnas dañadas en cada grupo fueron reparadas con Cempatch y diferentes niveles de CFRP. El análisis teórico utilizó el software ANSYS (versión 14) para la simulación.

Resultados: los resultados experimentales mostraron que el patrón de fallo se desplazó desde las áreas reparadas hacia las no reparadas a medida que aumentaba el número de capas de CFRP. Esto indica que los materiales de restauración desviaron eficientemente el estrés y aumentaron la capacidad de carga de las columnas. Los resultados del análisis de elementos finitos mostraron una fuerte concordancia con los hallazgos experimentales, con diferencias finales de carga de 17,3 % y 0,9 %, respectivamente. Las pruebas demostraron un aumento del 148,7 % en la carga máxima con capas adicionales de CFRP y un aumento del 30,3 % en el número de caras reparadas. Sin embargo, las reparaciones cerca del centro de las columnas produjeron resultados menos favorables en comparación con las realizadas en la parte superior.
Conclusiones: el estudio confirma que el uso de Cempatch y CFRP mejora significativamente la resistencia sísmica de las columnas RC, logrando los mejores resultados de reparación con capas de CFRP aplicadas cerca de la parte superior de las columnas.

Palabras clave: Columna de Concreto Reforzado; Tiras de CFRP; Columna Reparada.

INTRODUCTION

Infrastructures can be subject to sever damages during earthquake attacks leading to devastating consequences on several sectors of the affected areas. Among these structures, bridges hold particular significance, especially those situated on critical roads vital for rapid emergency response. Repair activities for such “critical” bridges should typically be completed within three days ATC-18.[1] A variety of techniques has been utilized to restore the functionality of damaged reinforced concrete columns. These techniques were effective but require considerable time (not rapid), specialized equipment, and expert workers to do the repairing.[2,3,4,5,6,7]

One of the sufficient techniques that reduces the repairing time is using externally bonded strengthening systems.[8,9,10,11,12,13,14,15,16] FPR composites can be used for this purpose because they can be installed easily and the ratio of their strength / stiffness to weight is too high.[17,18] Many studies over the last decades have shown the effectiveness of using FPR in repairing the RC columns.[19,20,21,22] The performance of a bridge structure with columns can be modified by repairing an individual RC column especially under the seismic loading condition.

In the context of repairing RC columns damaged by seismic events, He et al.[23] introduced a novel method to rehabilitate the structural integrity of bridge columns following substantial earthquake-induced damage. The efficacy of this technique was assessed using experimental and analytical examinations. The study investigated half-scale reinforced concrete square columns exposed to concurrent constant axial and incrementally increasing cyclic lateral loads, simulating circumstances that induce flexure, shear, and torsion with varying moment ratios. CFRP sheets, externally adhered, were employed to rehabilitate the columns over a three-day duration, after which the restored columns underwent retesting under the same combined loading conditions. No efforts were undertaken to rectify the deformed longitudinal reinforcing bars. Notwithstanding this constraint, the findings indicated the effective rehabilitation of the impaired columns.

Prachasaree et al.[24] performed a study to examine the behavior of concrete columns reinforced with fiberglass under compressive loading. The results indicated that the strengthening substantially improved the load-bearing capability of the columns. Furthermore, it was noted that lateral reinforcement significantly influenced the performance of the columns more than vertical reinforcement.

Fakharifar et al.[25] designed to be lightweight PSJs, or prestressed steel jackets, for the purpose of repairing badly damaged circular-sectioned reinforced concrete columns. A thin steel sheet with several prestressed strands reinforcing it makes up the bulk of the PSJ system. After using the repair approach, the columns’ ultimate strength was 115 % and their ductility was 140 % of what it had been before. However, due to the PSJ’s lack of fundamental engineering for stiffness recovery, the initial stiffness was only restored to 84 %. By affixing the broken columns to their bases using dowel rods, the ultimate strength, stiffness, and ductility levels of the repair were enhanced by 20 %.

Bermejo et al.[26] focused on accurately simulating the phenomenon of structural collapse and identifying cost-effective treatment methods to mitigate it. The research demonstrated that the finite element method accurately captures the reaction of concrete under applied stresses by simulating the behavior of concrete buildings.

Deng et al.[27] examined the impact of high-ductility fiber (HDF) RC on the endurance of short concrete columns under seismic loading. The study involved testing six short columns reinforced with HDF and one conventional RC column under cyclic loading. The RC column exhibited brittle shear failure with low energy dissipation. In contrast, the HDF-RC columns demonstrated improved performance, with shear strength increased by 12,6 % to 30,2 % and energy dissipation enhanced by 56,9 % to 88,5 %.

As a result, theoretical and practical investigations into the behavior of repaired reinforced concrete columns subjected to static loads are crucial. Regardless of the ongoing study, it is crucial to evaluate how well

Cempatch and CFRP enhance the structural performance of damaged columns. This study's overarching goal is to analyze the impact on reinforced concrete columns' performance when subjected to axial and seismic stresses of various CFRP layer configurations and repair methods (partial and full repairs at various column positions). This requires looking at the repair method's overall effectiveness, as well as its failure modes, load capabilities, and stiffness increases. In order to assess the effectiveness and performance enhancement of various repair methods, the results of the repaired columns are contrasted with control specimens.

METHOD

Experimental Program

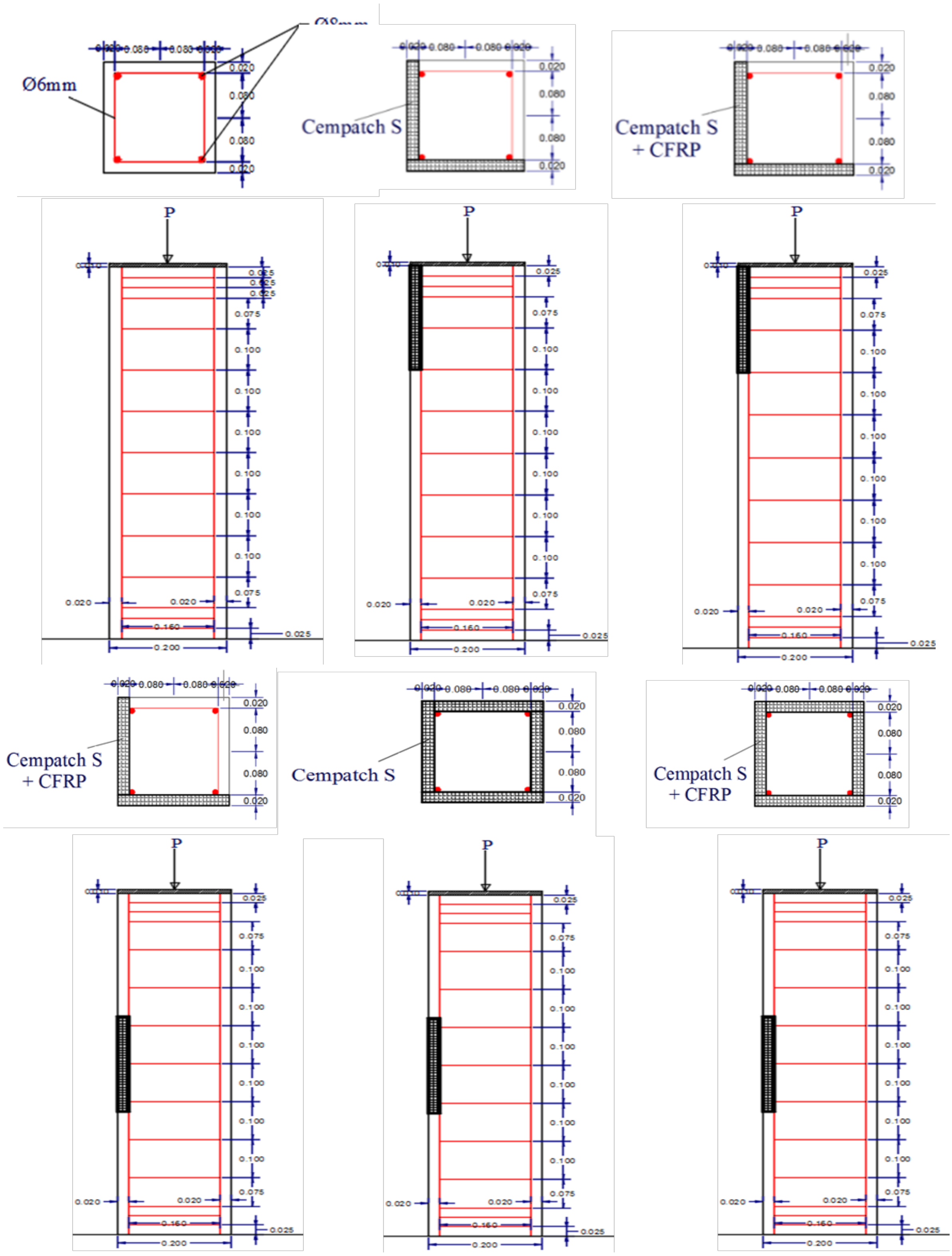

Figure 1. Distribution repaired of Columns

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The selection of Cempatch and CFRP as repair materials was driven by their rapid curing time and high-strength properties, making them particularly suitable for efficient repair methods in seismic-prone regions. An experimental program was implemented to assess the effectiveness of strengthening on twelve reinforced concrete columns, with one additional column acting as a control without any enhancements. The columns, uniformly measuring 900 mm in height with a square cross-section of 200 × 200 mm and similar reinforcing, underwent multiple restoration scenarios. Three columns were repaired with Cempatch material, the other three were repaired with Cempatch material and one CFRP layer, and the last three were repaired with Cempatch material with two CFRP layers. Figure 1 illustrates the damaged areas at the upper and mid-height positions of the columns, which were repaired using these techniques. The study focused on assessing the performance improvements in stiffness and load capacity, highlighting the practicality and scalability of these repair methods for field implementation.

Materials Properties

The materials employed in this study include cement, fine aggregate, and coarse aggregate, steel wire mesh reinforcement for concrete, water, Cempatch, and CFRP products.

The testing samples were categorized into two groups, each containing three samples: three standard cylinders (150×300 mm) and three standard cubes (150×150×150 mm). All samples were evaluated to ascertain the compressive strength (f'c) at 28 days. Two dimensions of reinforcing deformed steel bars were employed to fortify all the concrete columns. Longitudinal reinforcement utilized steel bars of diameter Φ8 mm, whilst radial reinforcement employed steel bars of diameter Φ6 mm. The characteristics for both dimensions are presented in table 1. Yield stress and ultimate strength values are derived in accordance with ASTM standard A615 specifications for each bar size, as presented in table 1, along with the technical information for Cempatch quick repair mortar in table 2.

Figure 2 illustrates the casting and preparing procedure of the RC columns before testing. This encompasses the procedures employed to manufacture the columns, guaranteeing consistency in their size and reinforcing configuration, along with the preparation of the compromised areas for future repair and fortification interventions.

Figure 2. Casting and preparation of the columns and control specimens for test

Table 1. Steel bars properties

Nominal diameter, mm	Actual Diameter, mm	Yield Stress (f_y), MPa	Ultimate Strength (f_u), MPa
8	7,83	537	567
6	6,06	554	632

Table 2. Technical information of Cempatch rapid repair mortar

BS EN 13813 Designation	CT-C30-F4
Working time @ 20°C	10 – 15 minutes
Walk on hardness time @ 20°C	20 - 30 minutes
Ready for over coating after	1½ hours @ 2mm

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Compressive Strength (N/mm2) BS EN 13892-2 1 Day 7 Days 28 Days	 > 15,0 > 25,0 > 30,0
Flexural Strength (N/mm2) BS EN 13892-2 1 Day 7 Days 28 Days	 > 2,0 > 3,0 > 4,0
Yield per 22 kg Sack	13,5 liters
Consumption per mm thickness	1,63 kg/m²
Application thickness Unfilled Filled	 2-20mm 20-50mm

For theoretical

Structures examined in this research made use of materials such as concrete, steel reinforcing bars, Cempatch S, and CFRP. As seen in table 3, the parameters used by the finite-element models are numerous.

Table 3. The F.E. Model's parameters for the column

Representation	Element Type	Characteristics
Concrete	Solid65	Compressive strength (f'c)=30 MPa Poisson's ratio= 0,17 Modulus of elasticity=25740 MPa Ultimate strain=0,003
Steel Reinforcement	Link8	Ø8, Ø6, Yield strength= 537, 554 MPa
CFRP	Shell41	Thickness = 0,131, Tensile strength (MPa)= 4300, E-modulus (GPa)= 234, Elongation at break (%) = 1,8
Cempatch S	Solid65	Compressive strength (f'c) =85 MPa Poisson's ratio=0,2 Modulus of elasticity=43332 MPa Ultimate strain=0,0045
Steel plate	Solid45	Modulus of elasticity = 200000 MPa Poisson's ratio=0,3

Finite Element Modeling

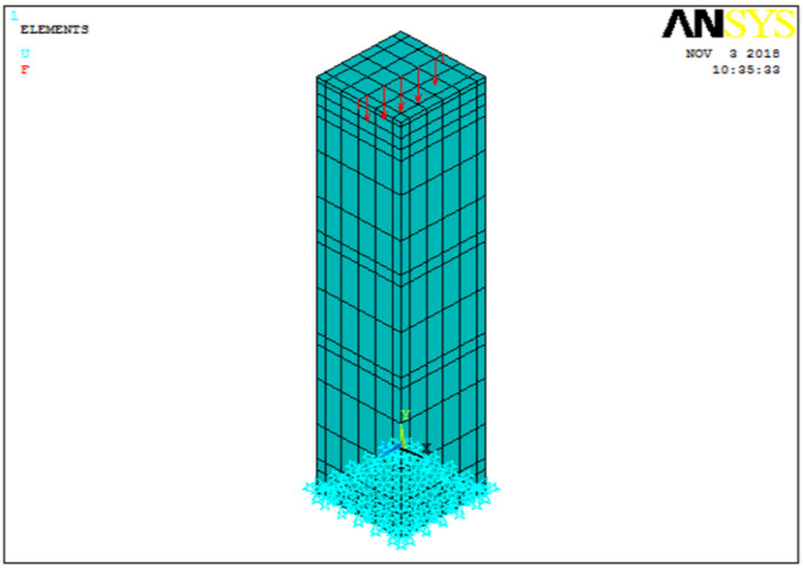

Figure 3. Geometry of the numerical model of column

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The process of finite element analysis involves partitioning the model into smaller elements, a procedure referred to as meshing. This facilitates the simulation of diverse physical behaviors under varying settings. Figure 3 illustrates the meshing, applied load, and boundary conditions for the columns.

RESULTS AND DISCUSSIONS

This section presents the results derived from experimental and theoretical analyses are displayed for 13 columns divided to four group and one control column, every group consisted of three columns one of these was repaired by cempatch and other columns were repaired by cempatch and CFRP with one layer and two layers. This groups were divided according the number of faces (two and four) and the area of repair (25 % and 50 %) in the top and mid of columns.

Figure 4 depicts the load-deflection curves for each repair scenario, demonstrating the correlation between load and deformation. It emphasizes that augmenting the quantity of CFRP layers improves both rigidity and maximum load capacity. The columns reinforced with Cempatch material and two CFRP layers consistently exhibit superior performance relative to other configurations, demonstrating a 30,3 % enhancement in capacity for load compared to the control columns. This illustrates the considerable effect of reinforcing the columns on all four sides with Cempatch and two layers of CFRP.

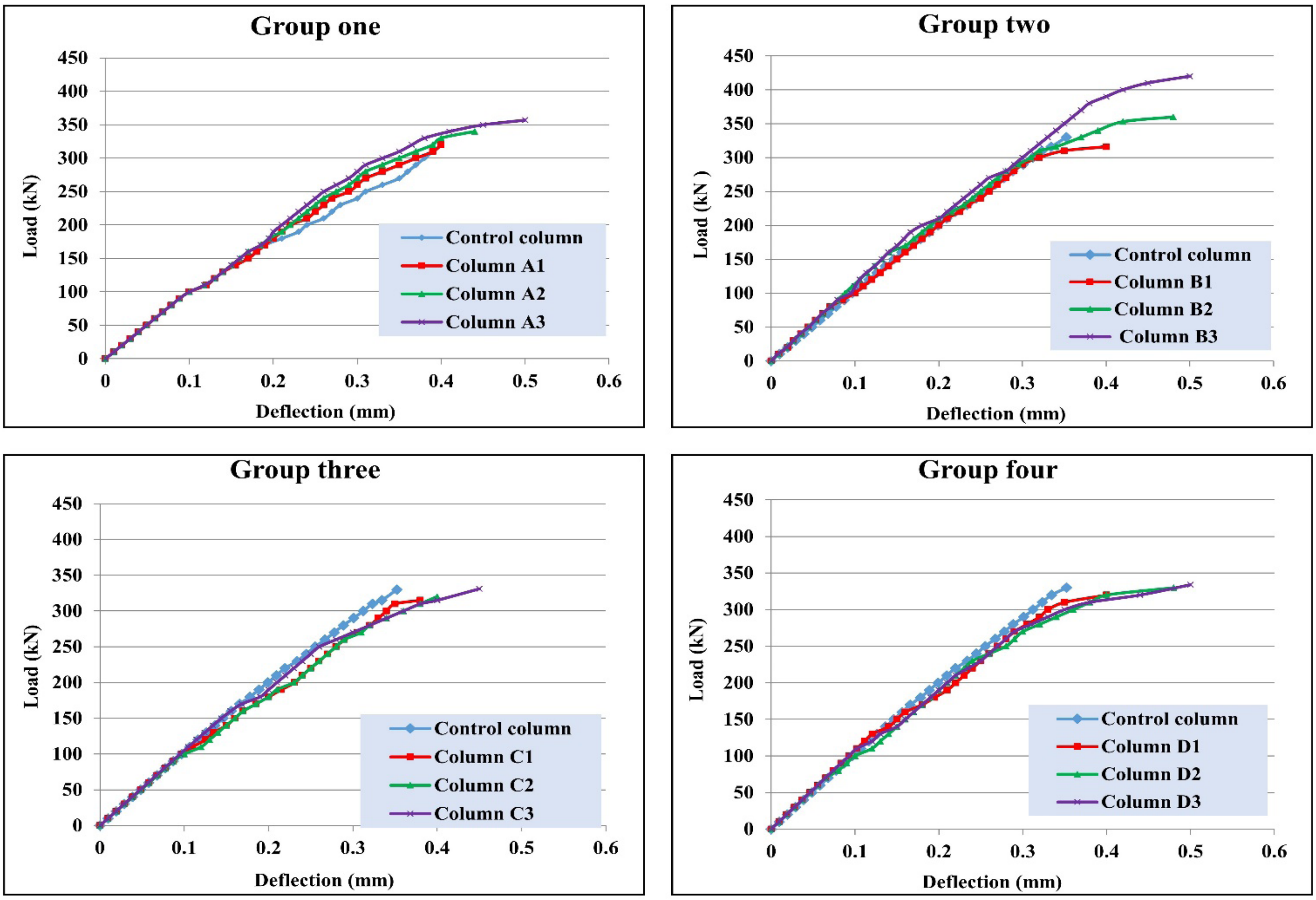

Figure 4. Load-deflection curve for each group.

The experimental study revealed that the failure pattern transitioned from the repaired areas to the unrepaired areas with an increase in the number of CFRP layers. This signifies that the repair materials successfully deflected stress, hence augmenting the load capacity of the columns. The results derived by ANSYS 14 are shown for 13 columns and are compared with experimental data. Table 4 show the result for all columns (first crack, ultimate load and deflection) for experimental and numerical. Table 5 and figures 5-8 shows the compare load-deflection curve between experimental and numerical models. Figure 9 shows the cracks pattern for the tested columns.

The experimental results revealed a slight deviation from numerical predictions, which can be attributed to material imperfections and bond conditions in experimental setups. However, the overall trends remain consistent, verifying the reliability of the finite element model.

Table 4. Result for all columns (first crack, ultimate load and deflection)

Group name			Numerical			Experimental		
			Failure Load (kN)	1st crack load (kN)	Deflection (mm)	Failure Load (kN)	1st crack load (kN)	Deflection (mm)
Control column			325	105	0,3522	320	110	0,4
Group one	Cempatch only	A1	329	105	0,361336	320	112	0,4
	Cempatch + 1 CFRP	A2	351	104	0,379716	346	115	0,44
	Cempatch + 2 CFRP	A3	395	103	0,463167	357	115	0,5
Group two	Cempatch only	B1	344	130	0,32156	316	140	0,4
	Cempatch + 1 CFRP	B2	421	130	0,400805	359	139	0,48
	Cempatch + 2 CFRP	B3	433	130	0,408169	417	142	0,5
Group three	Cempatch only	C1	319	105	0,333477	315	112	0,38
	Cempatch + 1 CFRP	C2	323	105	0,340053	320	112	0,4
	Cempatch + 2 CFRP	C3	353	105	0,392129	331	115	0,45
Group four	Cempatch only	D1	334	105	0,33778	322	110	0,4
	Cempatch + 1 CFRP	D2	372	104	0,383714	330	112	0,48
	Cempatch + 2 CFRP	D3	374	105	0,380965	334	113	0,5

Table 5. Comparison of numerical and experimental data

		Numerical Pu (kN)	Experimental Pu (kN)	Percentage Difference (%)	Increase in ultimate experimental load (%)
Control column		325	320	1,56	----------
Group one	A1	329	320	2,8	0
	A2	351	346	1,44	8,1
	A3	395	357	10,6	11,56
Group two	B1	344	316	8,86	-1,25
	B2	421	359	17,3	12,18
	B3	433	417	3,8	30,3
Group three	C1	319	315	1,2	-1,56
	C2	323	320	0,9	0
	C3	353	331	6,6	3,44
Group four	D1	334	322	3,7	0,6
	D2	372	330	12,7	3,125
	D3	374	334	11,98	4,375

Reviewing the curves of the load-deflection graph presented in figures 4 to 8 and the crack patterns for the columns shown in figures 9 to 10 for both experimental and numerical results, the general behavior of the load-deflection curves for all columns was similar. As the number of layers of CFRP increased, the columns became stiffer. Additionally, the columns that were repaired at the top from all four sides exhibited greater stiffness. The columns were repaired from two side (25 %) three of these columns were repaired from top and three were repaired from mid the increase of ultimate load of these columns by (8,1, 11,56 and 3,44 %) for (A2, A3 and C3) respectively, two of these columns not affected (A1 and C2) and the last column there was a decrease by (1,56 %) for (C1) was repaired by cempatch only, the best columns of these repaired was A3 by (11,56 %) was repaired by cempatch and two layers of CFRP. The columns were repaired from four side (50 %) three of these columns were repaired from top and three were repaired from mid the increase of ultimate load of these columns by (12,18, 30,3, 0,6, 3,13 and 4,38 %) for (B2, B3, D1, D2 and D3) respectively and the last column there was a decrease by (1,25 %) for (B1) was repaired by cempatch only, the best columns of these repaired was B3 by (30,3 %) was repaired by cempatch and two layers of CFRP. The columns were repaired from top and mid with cempatch only these columns where cracks and failures occurred at the top near the shed point of loading that means repaired only cempatch was not enough to carry high compression loads while the columns that repaired with cempatch and CFRP where cracks and failures occurred at the bottom of column thus the repaired in this way is better. The preceding tables and figures provide a comparison of experimental

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and numerical results for load, deflection, and all columns in the current study. This comparison indicates that the numerical models exhibit stronger stiffness, resulting in lower deflection values and higher ultimate load estimates in the numerical analysis. These discrepancies may be attributed to the following factors:

- The concrete of the experimental samples is not entirely homogeneous, contrary to the assumptions made in the computer models.
- The compressive strength of the evaluated concrete cubes may not accurately reflect the true compressive strength.
- Microcracks that may occur in concrete owing to shrinkage diminish stiffness to some extent.
- The finite element studies assume an ideal link between concrete and steel or CFRP reinforcements; however, in the experimental samples, this bond is imperfect, resulting in slippage that diminishes composite action.

The overall behavior of finite element models depicted in the load-deflection plots exhibited strong correlation with the data from experimentally tested columns. The largest and minimum differences in ultimate loads for columns were 17,3 % and 0,9 %, respectively. The cracks that appeared in experimental similar that cracks in numerical.

The results highlight the significance of material characteristics, including compressive strength and stiffness, in assessing repair efficacy. The utilization of modern materials such as CFRP not only reinstates structural integrity but also extends the service life of compromised columns subjected to cyclic loading conditions.

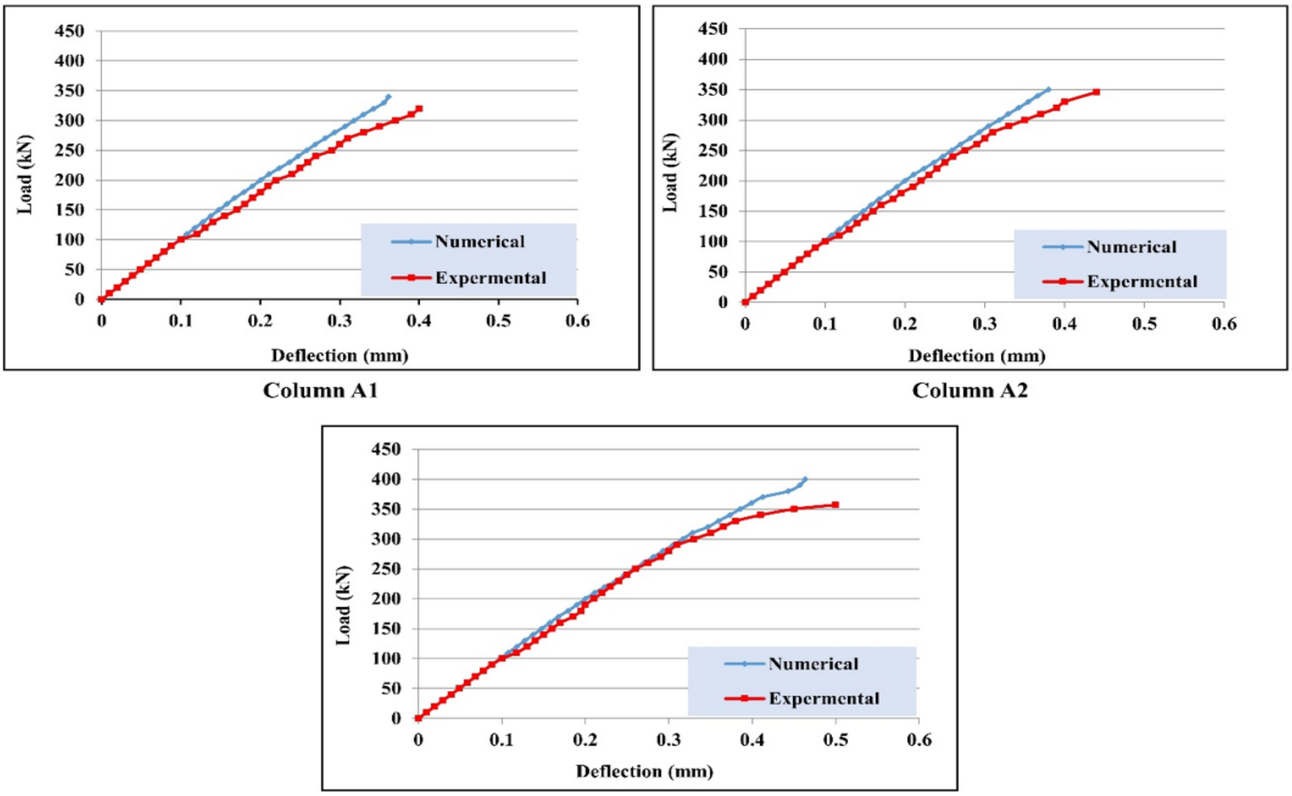
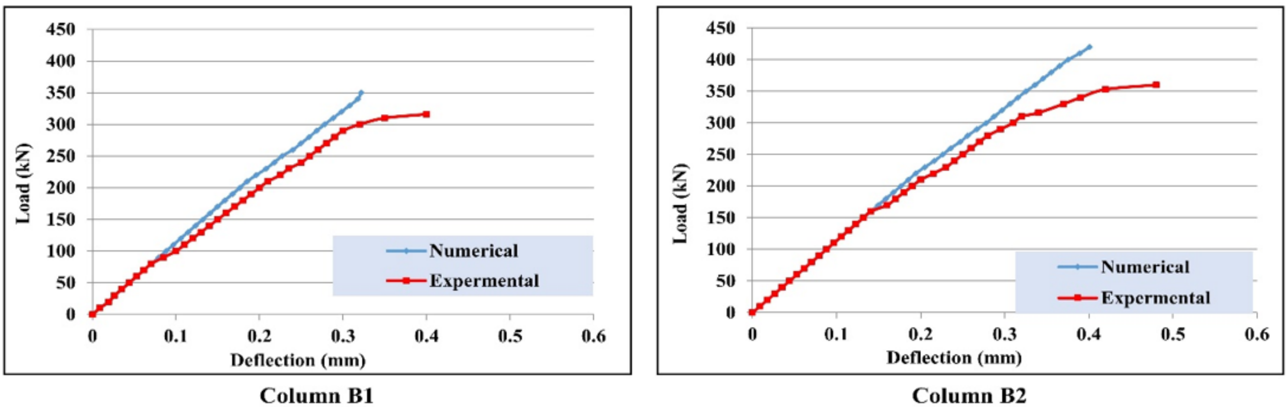
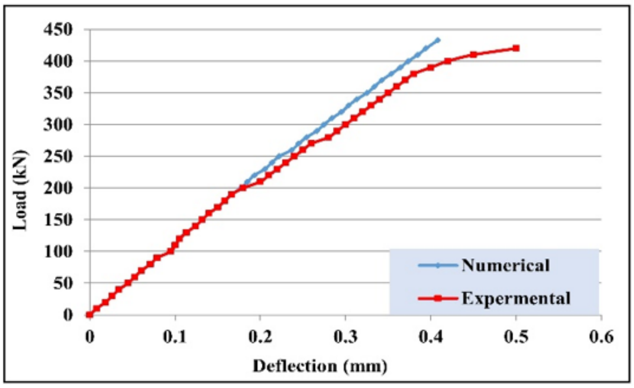


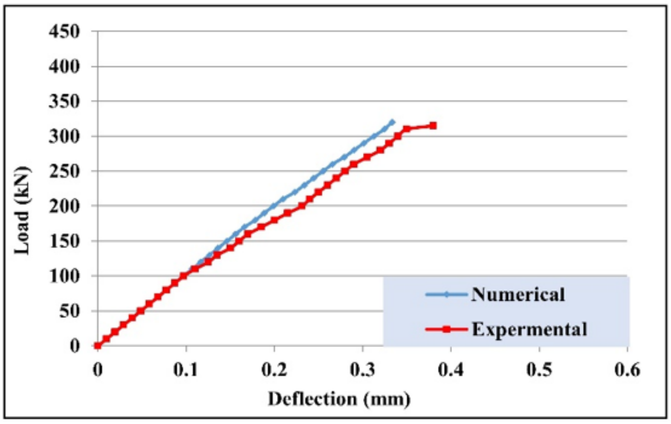
Figure 5. Load-deflection relationship for group one



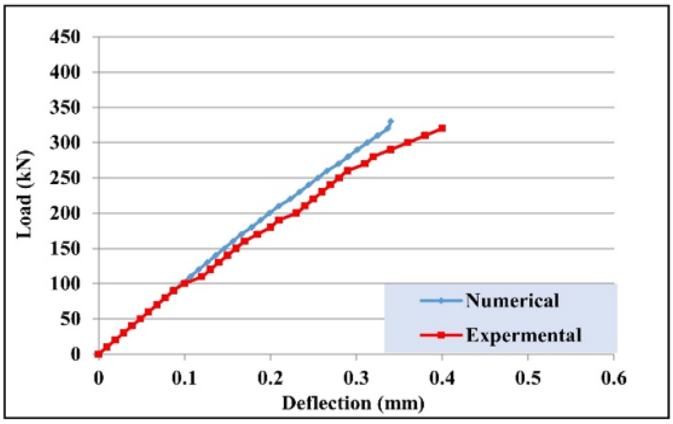


Column B3

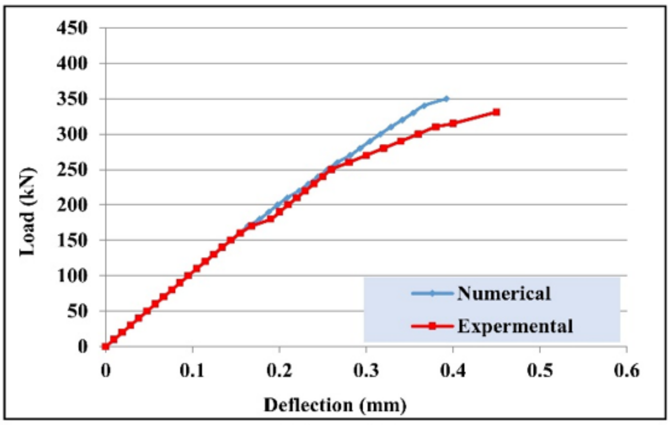
Figure 6. Load-deflection relationship for group two



Column C1

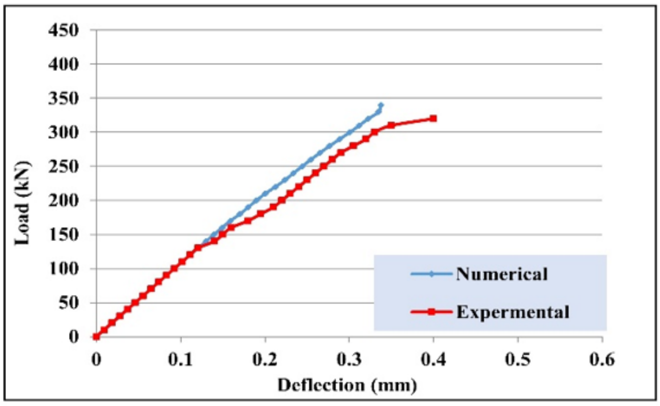


Column C2

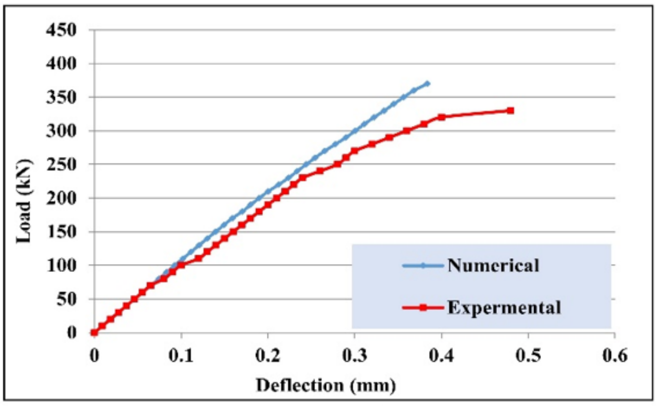


Column C3

Figure 7. Load-deflection relationship for group three



Column D1



Column D2

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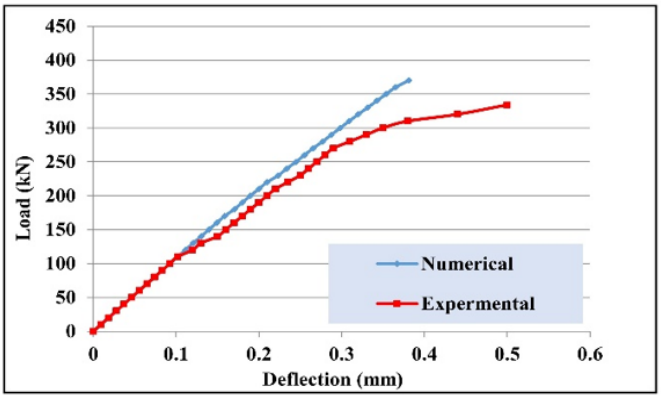

Column D3

Figure 8. Load-deflection relationship for group four

At each applied load increase, the propagation of fractures is tracked using the ANSYS 14 program. Figure 10 shows the results of a finite element study that included the Crack/Crushing plot option, which revealed crack patterns. At each integration point, the ANSYS program uses a different color circle to indicate a different type of crack. A red circle indicates a minor fissure, a green circle indicates a moderate fissure, and a blue circle illustrates a catastrophic failure.

Figure 9. Cracks pattern for columns

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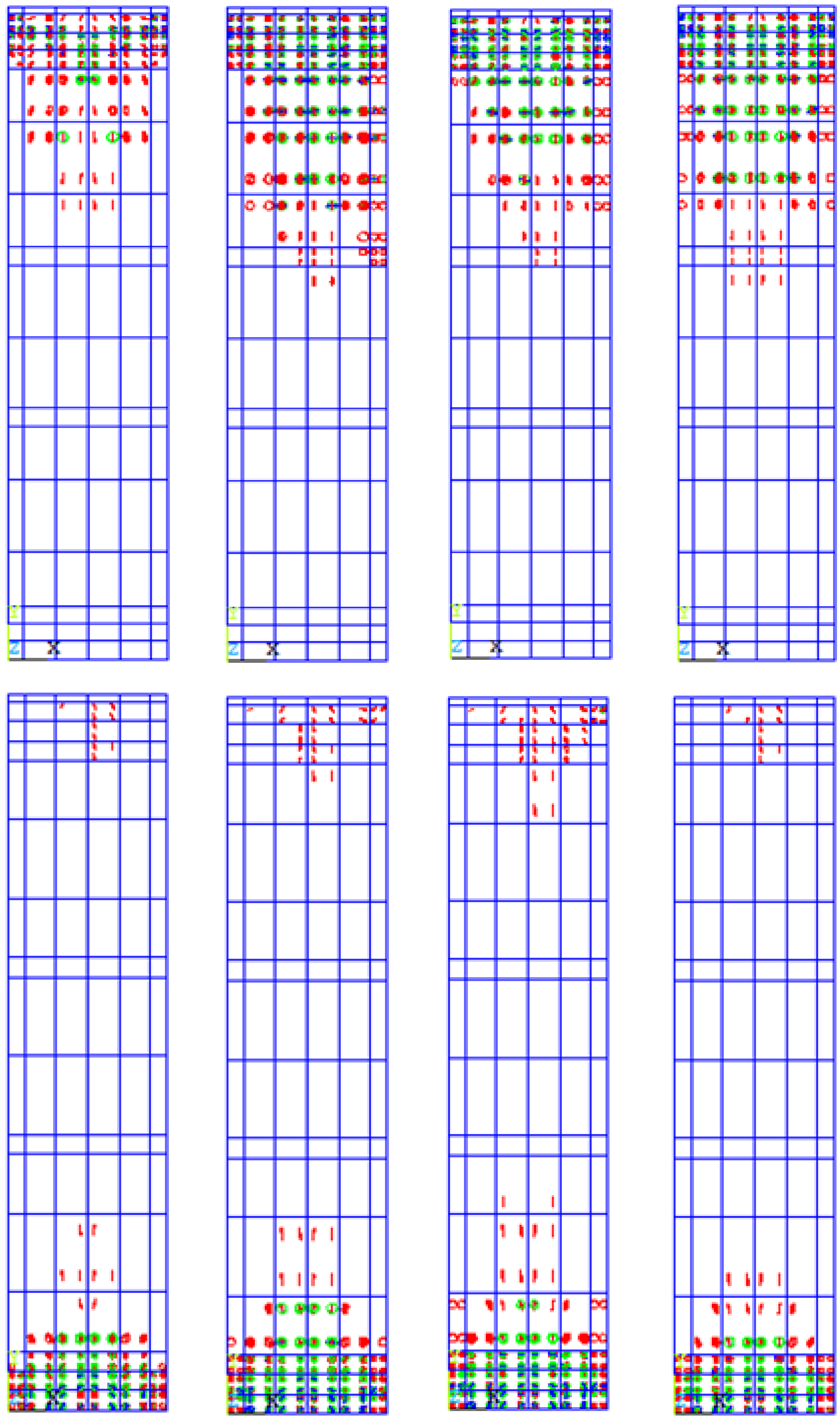

Figure 10. Crack propagation at ultimate load for columns

CONCLUSIONS

The combination of Cempatch and CFRP repair materials showed a significant improvement in load-bearing capacity and stiffness, with the best results achieved when multiple layers of CFRP were used. Repairs on all sides of the columns using two layers of CFRP proved highly effective in enhancing load-bearing capacity compared to the reference column, highlighting the importance of this arrangement in improving column performance under seismic loads. In contrast, repairs using Cempatch alone showed less significant improvements, indicating the importance of material integration to achieve maximum benefit. The combination of Cempatch and CFRP resulted in a notable increase in ultimate load capacity, particularly when multiple layers of CFRP were applied, enhancing the columns' flexibility. Numerical models provided good simulations of experimental results, despite some differences due to ideal bonding assumptions, which emphasized the effects of slip and micro-cracks on column stiffness. The repaired columns effectively redistributed stresses, shifting the failure pattern away from the repaired regions and enhancing structural stability. Additionally, the results showed that the repair location played a significant role, with repairs focused on the upper sections of the columns proving more effective.

Finally, the rapid curing time of Cempatch stands out as a key advantage for emergency repairs in seismic-prone areas, helping to minimize downtime while ensuring structural safety.

BIBLIOGRAPHIC REFERENCES

1. (ATC). ATC. Seismic design criteria for bridges and other highway structures: Current and future. 1997;

2. Raza S, Khan MKI, Menegon SJ, Tsang HH, Wilson JL. Strengthening and repair of reinforced concrete columns by jacketing: State-of-the-art review. Sustainability. 2019;11(11):3208. https://doi.org/10.3390/su11113208.

3. Pendhari SS, Kant T, Desai YM. Application of polymer composites in civil construction: A general review. Composite structures. 2008;84(2):114–124. http://dx.doi.org/10.1016/j.compstruct.2007.06.007.

4. Cui C, Sheikh SA. Experimental study of normal-and high-strength concrete confined with fiber-reinforced polymers. Journal of Composites for Construction. 2010;14(5):553–561. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000116.

5. Micelli F, Modarelli R. Experimental and analytical study on properties affecting the behaviour of FRP-confined concrete. Composites Part B: Engineering. 2013;45(1):1420–1431. https://doi.org/10.1016/j.compositesb.2012.09.055.

6. Sim J, Park C. Characteristics of basalt fiber as a strengthening material for concrete structures. Composites Part B: Engineering. 2005;36(6–7):504–512. https://doi.org/10.1016/j.compositesb.2005.02.002.

7. Yao Y, Zhu D, Zhang H, Li G, Mobasher B. Tensile behaviors of basalt, carbon, glass, and aramid fabrics under various strain rates. Journal of Materials in Civil Engineering. 2016;28(9):4016081. https://doi.org/10.1061/(asce)mt.1943-5533.0001587.

8. Campione G, La Mendola L, Monaco A, Valenza A, Fiore V. Behavior in compression of concrete cylinders externally wrapped with basalt fibers. Composites Part B: Engineering. 2015;69:576–586. http://dx.doi.org/10.1016/j.compositesb.2014.10.008.

9. Fiore V, Di Bella G, Valenza A. Glass–basalt/epoxy hybrid composites for marine applications. Materials & Design. 2011;32(4):2091–2099. https://doi.org/10.1016/j.compositesb.2014.10.008.

10. Di Ludovico M, Prota A, Manfredi G. Structural upgrade using basalt fibers for concrete confinement. Journal of composites for construction. 2010;14(5):541–552. https://doi.org/10.1061/(asce)cc.1943-5614.0000114.

11. Fiore V, Scalici T, Di Bella G, Valenza A. A review on basalt fibre and its composites. Composites Part B: Engineering. 2015;74:74–94. http://dx.doi.org/10.1016/j.compositesb.2014.12.034.

12. Ouyang LJ, Gao WY, Zhen B, Lu ZD. Seismic retrofit of square reinforced concrete columns using basalt and carbon fiber-reinforced polymer sheets: A comparative study. Composite Structures. 2017;162:294–307. https://doi.org/10.1016/j.compstruct.2016.12.016.

13. Liu HX, Liu GJ, Wang XZ, Kong XQ. Effect of cross-sectional aspect ratio and basalt fiber-reinforced polymer-confined number on axial compression behavior of short columns. Journal of Reinforced Plastics and Composites. 2015;34(10):782–794. https://doi.org/10.1177/0731684415580330.

14. De Luca A, Nardone F, Matta F, Nanni A, Lignola GP, Prota A. Structural evaluation of full-scale FRP-confined reinforced concrete columns. Journal of Composites for Construction. 2011;15(1):112–123. http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000152.

15. Sadeghian P, Fillmore B. Strain distribution of basalt FRP-wrapped concrete cylinders. Case Studies in Construction Materials. 2018;9:e00171. https://doi.org/10.1016/j.cscm.2018.e00171.

16. Suon S, Saleem S, Pimanmas A. Compressive behavior of basalt FRP-confined circular and non-circular concrete specimens. Construction and Building Materials. 2019;195:85–103. https://doi.org/10.1016/j.conbuildmat.2018.11.039.

17. Farghal YAKOA, Fahmy MFM. Behavior of rectangular RC columns confined with BFRP sheets subjected to axial loading. International Journal of Engineering Development and Research IJEDR. 2018;6:215–230.

18. Patel T, Salla S, Vasanwala S, Modhera C. Strengthened of a square RC columns using BFRP and GFRP: the experimental investigations. Trends in Sciences. 2022;19(15):5602. https://doi.org/10.48048/tis.2022.5602.

19. Sadeghian P, Fam A. Improved design-oriented confinement models for FRP-wrapped concrete cylinders based on statistical analyses. Engineering Structures. 2015;87:162–182. http://dx.doi.org/10.1016/j.engstruct.2015.01.024.

20. Keshtegar B, Sadeghian P, Gholampour A, Ozbakkaloglu T. Nonlinear modeling of ultimate strength and strain of FRP-confined concrete using chaos control method. Composite Structures. 2017;163:423–431. http://dx.doi.org/10.1016/j.compstruct.2016.12.023.

21. Xie T, Ozbakkaloglu T. Behavior of recycled aggregate concrete-filled basalt and carbon FRP tubes. Construction and Building Materials. 2016;105:132–143. http://dx.doi.org/10.1016/j.conbuildmat.2015.12.068.

22. Shen H, Chen L, Zheng H, Zhang F. Experimental study on axial compression performance of new-type BFRP-confined square concrete columns. In: Journal of Physics: Conference Series. IOP Publishing; 2023. p. 12008.

23. He R. Rapid repair of severely damaged RC columns under combined loading of flexure, shear, and torsion with externally bonded CFRP. Missouri University of Science and Technology; 2014.

24. Prachasaree W, Piriyakootorn S, Sangsrijun A, Limkatanyu S. Behavior and performance of GFRP reinforced concrete columns with various types of stirrups. International Journal of Polymer Science. 2015;2015(1):237231. https://doi.org/10.1155/2015/237231.

25. Fakharifar M, Chen G, Wu C, Shamsabadi A, Elgawady MA, Dalvand A. Rapid repair of earthquake-damaged RC columns with prestressed steel jackets. Journal of Bridge Engineering. 2016;21(4):4015075. https://doi.org/10.1061/(asce)be.1943-5592.0000840.

26. Bermejo M, Santos AP, Goicolea JM. Development of practical finite element models for collapse of reinforced concrete structures and experimental validation. Shock and Vibration. 2017;2017(1):4636381. https://doi.org/10.1155/2017/4636381.

27. Deng M, Zhang Y. Seismic Performance of High-Ductile Fiber-Reinforced Concrete Short Columns. Advances in Civil Engineering. 2018;2018(1):3542496. https://doi.org/10.1155/2018/3542496.

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