Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

Investigation of Astral CFRP Strengthening Effect on the Punching Shear Response of Self-Compacting RC Two-Way Slabs with Openings

Noor Mokhaif Kareem and Ali Al-Balhawi

Civil Engineering Department, Mustansiriyah University, Baghdad, Iraq

ARTICLE INFO

Article history:

Received 23 December 2025
Revised 23 December 2025
Accepted 07 January 2026
Available online 07 January 2026

Keywords:

Punching shear
Self compact
CFRP
RC two-way slabs
Strengthening

ABSTRACT

Fiber Reinforced Polymers (FRP) are widely employed for the strengthening and rehabilitation of reinforced concrete (RC) structures. Openings are frequently incorporated into structural members, such as slabs, to accommodate essential building services (e.g., pipes, electrical conduits). However, these openings inevitably comproise structural integrity, often leading to a significant reduction in performance metrics such as punching shear capacity. This degradation can be mitigated through the application of Carbon Fiber Reinforced Polymer (CFRP) sheets. This experimental study investigates the punching shear behavior of self-compacting concrete (SCC) two-way slabs with inherent square openings, strengthened with CFRP sheets configured in a square pattern around the openings. The experimental program comprised five 1000 mm x 1000 mm x 75 mm slabs, identically reinforced, including one solid control specimen and one unstrengthened slab with an opening as reference specimens. The remaining three slabs, each featuring an opening, were strengthened with one, two, and three layers of CFRP, respectively. The results indicate that while the CFRP strengthening technique did not fully restore the ultimate load capacity to that of the solid slab, it significantly enhanced the performance compared to the unstrengthened slab with an opening. Improvements were observed in the first-crack load, ultimate load, and stiffness. Specifically, the first-crack load for the strengthened specimens (AW1, AW2, AW3) exceeded that of the unstrengthened specimen by 25.3%, 41.8%, and 40.5%, respectively. Correspondingly, the ultimate load capacity was enhanced by 19.2%, 21.0%, and 22.9%.

1. Introduction

The inclusion of openings in reinforced concrete (RC) slabs is an important architectural necessity, to allow air flow, lighting and the passage of services like lifts, ductwork and staircases [1-3]. However, openings are known to be structurally detrimental because of their inherent flaws such as strength reduction and deflection deterioration. A common approach to address the limitations consists of Fibre Reinforced Polymers (FRP) that are attractive for their high strength-to-weight ratio, corrosion resistance and simplicity of application; therefore, they have been extensively used for flexural rehabilitation of RC beams [4-7]. Carbon FRP (CFRP) is one of the most widely used types among different kinds of FRPs applied for the repair and rehabilitation of RC members [8–11].

Numerous studies have investigated the general performance of strengthened RC slabs. For instance, Anil et al. [12] experimentally demonstrated that CFRP strips significantly enhance the load capacity and stiffness of slabs with openings, with performance varying based on opening geometry and position. Similarly, Mahlis et al. [13] reported that central openings

Corresponding author E-mail address: noor.m@uomustansiriyah.edu.iq
https://doi.org/10.61268/h75dz694

can reduce the load capacity of two-way slabs by approximately 20%, a deficit recoverable through CFRP strengthening, though premature failure due to bond degradation was noted. Other researchers, such as Aman et al. [14], observed brittle failure modes in slabs strengthened with multiple CFRP layers, while El-Mandouh et al. [15] found that CFRP strengthening may not fully restore the original load capacity of perforated slabs.

The effectiveness of FRP systems has also been examined in the context of Self-Compacting Concrete (SCC). Turanli et al. [16], Bencardino and Condello [17], and Elsanadedy et al. [18] have all documented improvements in flexural performance, ductility, and punching shear strength in SCC slabs retrofitted with CFRP, with the latter emphasizing the critical role of FRP-to-concrete bond strength.

A synthesis of the existing literature reveals a significant research gap: the strengthening behavior of Self-Compacting Concrete (SCC) slabs with openings remains inadequately characterized, particularly under specific boundary conditions. Therefore, this research program is designed to systematically investigate the punching shear behavior of SCC two-way slabs containing square openings and strengthened with CFRP sheets configured in a square arrangement around these openings.

2. Importance of the Study

The integration of service openings within the shear zones of self-compacting concrete (SCC) two-way slabs is a common yet crucial design challenge, which is why this research is significant. Despite being crucial to the architecture, these apertures significantly reduce punching shear resistance. In order to restore structural capacity, this study methodically assesses a strengthening technique using multi-layer Carbon Fiber Reinforced Polymer (CFRP) sheets arranged in a square pattern. This work's main contribution is the solid experimental evidence it provides to guide safer and more effective design procedures for such elements.

3. Experimental Details

This experimental study's main goal is to assess how CFRP strengthening can reduce punching shear deficiencies caused by square openings in self-compacting reinforced concrete (RC) two-way slabs. The high-shear region, which is the perimeter at half the effective depth (d/2) from the column face, was where these apertures were placed. One, two, and three layers of CFRP were applied as study variables. The following sections give a thorough description of the material properties, specimen specifics, and strengthening methods used.

3.1 The Used Materials

The materials used in this experimental program conformed to relevant standards. Below is a list of such materials.

3.1.1 Cement: Ordinary Portland cement (TASLUJA) was utilized, the physical properties of which observe the requirements of Iraqi Specification No. 5/1984 [19].

3.1.2 Aggregates: Natural sand with a maximum grain size of 4.75 mm was used as the fine aggregate. Gravel with a maximum size of 14 mm served as the coarse aggregate. Both aggregates' gradations met the restrictions outlined in Iraqi Specification No. 45/1984 [20].

3.1.3 Reinforcing Steel: The reinforcement mesh was made of deformed steel bars with a 6 mm diameter. The applicable ASTM standards were followed in determining the steel's mechanical characteristics [21].

3.1.4 CFRP Strengthening System: Unidirectional carbon fiber sheets made up the externally bonded reinforcement. According to the manufacturer's specifications, the CFRP has a nominal thickness of 0.167 mm per ply, an ultimate tensile strength of 4000 MPa, and a Young's modulus of 230 GPa.

3.1.5 Adhesives and Admixtures: The CFRP was bonded to the concrete substrate using a two-part epoxy resin (Sikadur-330). A high-range water-reducing admixture (ViscoCrete®-180 GS) was added to the mixes to provide the necessary workability for self-compacting concrete (SCC). The manufacturer's technical data sheets provided all of the epoxy and superplasticizer's characteristics.

3.2 Mix Proportions

The mix proportions that considered during this research to cast the specimens in all the RC slabs are listed in Table 1.

Table 1: Mix design

Material	*Cement*	*Sand*	*Gravel*	*Limestone*	*Water*
Quantity (kg/m^3)	430	800	700	200	172

3.3 Specimen detailing

A number of flat slab specimens made of reinforced concrete were used in this study. The slabs had a constant thickness of 75 mm and a square plan measuring 1000 mm by 1000 mm. The design followed the guidelines established by ACI [22] and included a reinforcing mesh of 6 mm diameter bars spaced 75 mm from center to center. A monolithic column stub measuring 150 mm by 150 mm in cross-section and 200 mm in height was used to introduce load. Figures 1 and 2 show schematic diagrams showing the formwork assembly, the reinforcement layout, and the specimen cross-section.

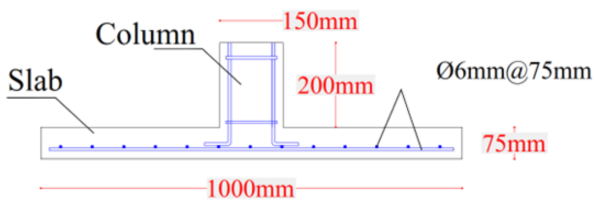

Figure 1. Cross section

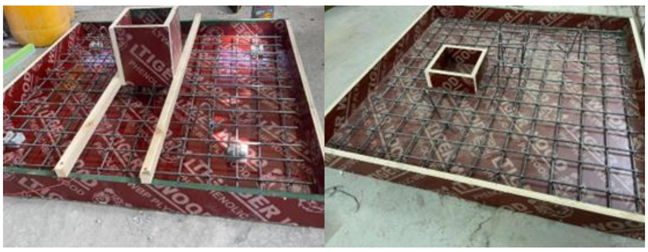

Figure 2. Molds and rebar

3.4 Designation of specimens

A three-character code that contains the main test variables is used to identify specimens. The specimen is categorized by the first character as either a Reference (R) or one strengthened with astral CFRP sheets (A). The second character, either None (N) or Within the shear zone (W), indicates whether an opening is present and where. The number of CFRP layers is indicated by the third character, which is an integer (1, 2, 3). Table 2 provides an overview of this labeling system.

Table 2: Designation

Designation	Technique	Opening Location	Number of Layers
RN0	Reference	Nell	Nell
RW0	Reference	Within shear zone	Nell
AW1	Astral sheeting	Within shear zone	1
AW2	Astral sheeting	Within shear zone	2
AW3	Astral sheeting	Within shear zone	3

3.5 Strengthening technique

The CFRP sheets were also installed around the openings borders in the tension face of slab but in a way that CFRP sheets are inclined to the square opening borders (Astral shaped). This was done inside the shear zone (near columns) and out of shear zone in one, two and three layers. Figure 3. shows the configuration of the technique.

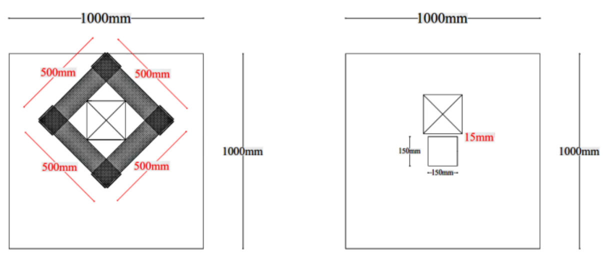

Figure 3. The strengthening technique

3.6 Preliminary properties results of the mix design

The fresh and hardened properties of the concrete mix created for this study were described. The mechanical characteristics of the hardened concrete are shown in Table 3, and the results of the slump flow test, which confirmed the fresh mixture's capacity for self-compaction, are shown in Table 4.

Table 3. Preliminary properties

28-day Compressive strength in MPa	Modulus of Elasticity in MPa	Modulus of rapture MPa	Splitting Tensile Strength in MPa
39.24	29.192	3.89	4.26

Table 4. Preliminary properties

Test type	Unit	Measured	Typical range value (EFNARC, 2002)	Typical range value European guidelines, 2005)
Slump flow	mm	740	650-800	550-850
T500 slump flow	Sec	3	2-5	≥ 2

3.7 Preparing and testing of specimens

An EPP300MFL hydraulic testing machine with a 3000 kN capacity was used in the Structural Laboratory at Mustansiriyah University to test each specimen under a monotonic load. Each slab's tensile face was painted white to increase the visibility of tiny cracks. To precisely determine the cracking and ultimate loads, the load was applied in controlled 5 kN increments. A variety of instruments were used to measure the structural response, as shown in Figure 4. Linear Variable Differential Transformers (LVDTs) were positioned at crucial points, directly beneath the column and next to any openings, in order to record deflections. In order to quantify local deformations, strain gauges were also installed.

Figure 4. The testing machine and its system

4. Results and discussion

4.1 First cracking load, the ultimate load carrying capacity and the fracture load.

The results of this experimental program are discussed based on the observation of load – deflection response. the cracking patterns were also recorded and investigated.

The flexural behavior of RC slabs of is illustrated in this section. Also, the impact of number layers to flexural performance of slabs that have squared opening within its shear zone and strengthened by astral CFRP sheets around openings is shown within Table 5., Table 6. and Table 7 This behavior is indicated by the first cracking load, P_{cr}, the ultimate load carrying capacity, P_u and the fracture load, P_f.

Table 5. The impact of layers number to the flexural behavior of RC slabs to first cracking load

Specimen	First cracking load (kN)	Change in first cracking load %	
		Change with RN0	Change with RW0
RN0	45.623	/	/
RW0	25.458	-44.199	/
AW1	41.520	-8.993	63.092
AW2	39.431	-13.572	54.886
AW3	36.361	-20.301	42.827

Table 6. The impact of layers number to the flexural behavior of RC slabs to ultimate load carrying capacity

Specimen	Ultimate load (kN)	Change in ultimate load %	
		Change with RN0	Change with RW0
RN0	111.956	/	/
RW0	74.265	-33.666	/
AW1	87.240	-22.077	17.471
AW2	91.842	-17.966	23.668
AW3	95.453	-14.741	28.530

Table 7. The impact of layers number to the flexural behavior of RC slabs to fracture load

Specimen	Fracture load (kN)	Change in fracture load %	
		Change with RN0	Change with RW0
RN0	77.138	/	/
RW0	58.959	-23.567	/
AW1	59.140	-23.332	0.307
AW2	59.605	-22.729	1.096
AW3	61.472	-20.309	4.262

Table 5. outlined that the presence of opening in RC slab of RW0 significantly decreases the first cracking load, P_{cr} by 44.199% in comparing with RN0. Also,

implementation of astral CFRP sheets around the square openings within the shear zone of RC slabs can further decrease the P_{cr} by 8.993%, 13.572% and 20.301% for the AW1, AW2 and AW3, respectively in comparing with RN0. However, the first cracking load, Pcr generally increases by 63.092%, 54.886% and 42.827% for the same slabs in comparing with RW0.

Likely, as shown in Table 6. as well the presence of opening in RC slab of RW0 decreases the ultimate load, Pu by 33.666% in comparing with RN0. However, the use of astral CFRP sheets around the square openings within the shear zone of RC slabs can gradually increase the ultimate load carrying capacity, P_u by -22.077%, -17.966% and -14.741% for the AW1, AW2 and AW3, respectively in comparing with RN0. Similarly, the ultimate load carrying capacity, Pu notably increases by 17.471%, 23.668% and 28.530% for the same slabs in comparing with RW0.

Table7. outlined that the presence of opening in RC slab of RW0 remarkably decreases the fracture load, Pf by 23.567% in comparing with RN0. In addition, the use of astral CFRP sheets around the square openings within the shear zone of RC slabs results a notably enhance in P_f value by -23.332%, -22.729% and -20.309% for the AW1, AW2 and AW3, respectively in comparing with RN0. Similarly, the Pf slightly increases by 0.307%, 1.096% and 4.262% for the same slabs in comparing with RW0.

The interaction between the number of layers with respect to P_{cr}, P_u and P_f, the strengthened specimens of the current group have a better behavior in comparison with the corresponding readings of the first group. This can be attributed to the strength components i.e. horizontal and vertical of the CFRP layers. In addition, the extensions of the CFRP configuration are more which covers more area than that area in the first group. However, the differences still in a moderate range.

4.2 Service deflection and maximum deflection.

The impact of opening and layers number to the service deflection, $\Delta_s$and maximum deflection, Δ_m of slabs that have squared opening within its shear zone and strengthened by astral CFRP sheets around openings is shown within Table 8.

Table 8. outlined that the presence of opening in RC slab of RW0 remarkably increases the Δ_s, by 28.369% in comparing with RN0. Also, this opening could lead to an increase in $\Delta_m$by 20.206% in comparing RW0 with RN0. However, the use of astral CFRP sheets around the square openings within the shear zone of RC slabs can slightly improve the service deflection $\Delta_s$by 25.921%, 21.407% and 21.333% for the AW1, AW2 and AW3, respectively in comparing with RN0. While, the Δ_s is varied by -1.907%, -5.423% and -5.481% for the same slabs in comparing with RW0.

Turning into $\Delta_m$it can be noted that using astral CFRP sheets around the square openings within the shear zone of RC slabs significantly increase value by 5.423%, 23.812% and 33.960% for the AW1, AW2 and AW3, respectively in comparing with RN0. While, Δ_m could vary by -12.298%, 3.000% and 11.442% for the same slabs in comparing with RW0. Figure 5. illustrates the load-deflection curves to the tested specimens RN0, RW0, AW1, AW2 and AW3. In addition, the same phases that recognized within the previous groups were observed within this group.

Table 8. The impact of layers number to the service and maximum deflections of RC slabs

Specimen	Δ_s (mm)	Change in Δ_s %		Δ_m (mm)	Change in Δ_m %	
		Change with RN0	Change with RW0		Change with RN0	Change with RW0
RN0	9.394	/	/	14.476	/	/
RW0	12.059	28.369	/	17.401	20.206	/
AW1	11.829	25.921	-1.907	15.261	5.423	-12.298
AW2	11.405	21.407	-5.423	17.923	23.812	3.000
AW3	11.398	21.333	-5.481	19.392	33.960	11.442

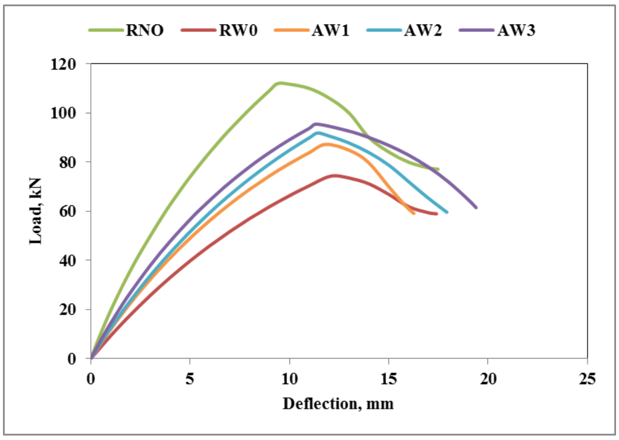

Figure 5. Load deflection response

It is also observed that the increase of the CFRP layers number in the RC slabs include opening within the shear zone can decrease the relevant Δ_s and Δ_m as in the previous two groups. In terms of Δ_s, the levels are approximately the same as those of the first group. In terms of Δ_m , the levels of this group are lower than those of the first group. This can be attributed to the low ability of inclined CFRP to confine concrete fragments at phase three of load deflection behavior.

4.3 The stiffness ratio

Table 9. outlines that the presence of opening in RC slab of RW0 significantly decreases the stiffness ratio, k by 48.330% in comparing with RN0. Also, Table 9. views the effect of layers number to the k of slabs that have squared opening within its shear zone and strengthened by astral CFRP sheets around openings. It can be seen that inclusion of astral CFRP sheets around the square openings within the shear zone of RC slabs could enhance the k by -38.119%, -32.430% and -29.728% for the AW1, AW2 and AW3, respectively in comparing with RN0. However, k value significantly increases by 19.763%, 30.773% and 36.002% for the same slabs in comparing with RW0.

Table 9. The impact of layers number to the stiffness ratio of RC slabs

Specimen	P_u (kN)	Δ_s (mm)	*k* (kN/mm)	Change in *k*%	
				Change with RN0	Change with RW0
RN0	111.956	9.394	11.918	/	/
RW0	74.265	12.059	6.158	-48.330	/
AW1	87.2395	11.829	7.375	-38.119	19.763
AW2	91.842	11.405	8.053	-32.430	30.773
AW3	95.453	11.398	8.375	-29.728	36.002

4.4 The ductility ratio

Table 10. outlines that the presence of opening in RC slab of RW0 slightly decreases the ductility ratio, d by 6.360% in comparing with RN0. Table 10. views the effect of layers number to the d of slabs that have squared opening within its shear zone and strengthened by astral CFRP sheets around openings. It can be recognized that the strengthening using astral CFRP sheets around the square openings within the shear zone of RC slabs notably increases the d value by -16.288%, 1.947% and 10.383% for the AW1, AW2 and AW3, respectively in comparing with RN0. While, the d value remarkably increases by -10.603%, 8.870% and 17.879% for the same slabs in comparing with RW0.

Table 10. The impact of layers number to the ductility ratio of RC slabs

Specimen	Δ_s (mm)	Δ_m (mm)	*d*	Change in *d*%	
				Change with RN0	Change with RW0
RN0	9.394	14.476	1.541	/	/
RW0	12.059	17.401	1.443	-6.360	/
AW1	11.829	15.261	1.290	-16.288	-10.603
AW2	11.405	17.923	1.571	1.947	8.870
AW3	11.398	19.392	1.701	10.383	17.879

4.5 Cracking propagation and mode of failure

The failure mode is highly recognized as punching shear failure for strengthened and unstrengthened specimens. The RN0 first crack was emerged and extended from the bottom side of column to the edge's centers parallel to shear center of square opening (the punching parameter is perpendicular to such sides). For the strengthened specimens, the propagation of cracks is similar to RW0 and the parameter of punching is still perpendicular to edges of square openings. such propagated cracks were starting from the center of the adjacent CFRP sheets and the number of cracks beyond the center line of opening (the area between this line to the specimen edge out of column) is less than square sheets technique. Figure 6. shows the cracking pattern.

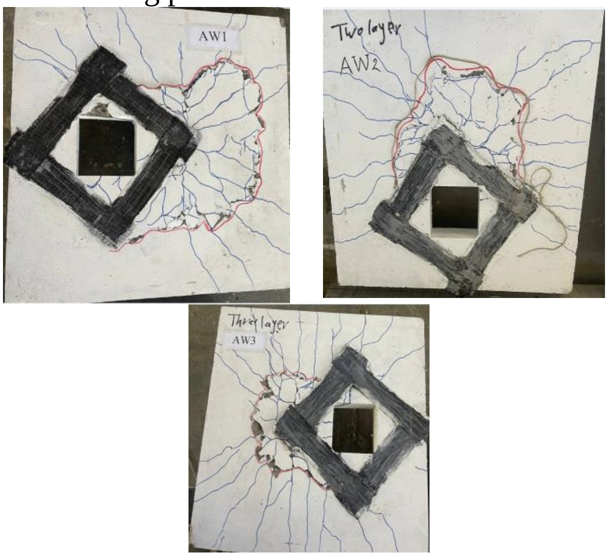

Figure 6. Cracks patterns of RC slabs

5. Conclusions

The following conclusions can be made in light of the experimental program's results and observations:

- Using CFRP sheets around the openings further enhances the stiffness and strength of the slabs and the load bearing capacity. Strengthening the slabs with additional CFRP layers improves their stiffness. Strengthened slabs with 3 layers of CFRP achieved 20–25% increase in ultimate loads compared to unstrengthen slabs with openings.
- Square openings in RC slabs lead to significant reduction on ultimate loads and first cracking loads (30–40%) in comparison with solid slabs (referenced) with openings in the punching shear zone.
- The presence of openings in RC slabs significantly reduced the first cracking, ultimate, and fracture loads compared with the solid (reference) slabs. The reduction in first cracking load is approximately 30.6%, 30.3% for ultimate load and 37.4% for fracture load.
- Further research is needed to build detailed finite element models, incorporating load-deflection curves and crack propagation patterns, to capture the model behavior and confirm the results of the experiments.
- Next studies should be extended to assess the durability of CFRP tightened slabs in different environmental conditions (humidity, temperature, chemical attacks) for Evaluating Long Term Exposure.
- Future research should explore the potential for synergistic effects by combining CFRP with other strengthening mechanisms such as external steel anchors or near-surface mounted bars.

References

[1] Z. M. Saad and A. S. Al Amli, “Shear punching behavior for flat slabs with CFRP and openings,” Eng. Technol. Appl. Sci. Res., vol. 15, no. 2, pp. 22239–22245, 2025. doi: 10.48084/etasr.9880.

[2] N. M. J. Al-Quraishy, T. M. S. Alrudaini, and Y. J. Lafta, “Effect of openings on the performance of continuous RC one-way slabs,” Eng. Technol. Appl. Sci. Res., vol. 15, no. 2, pp. 20959–20965, 2025. doi: 10.48084/etasr.9743.

[3] H. R. Ali and A. S. Al Amli, “CFRP strengthening of circular geo-polymer concrete slab with and without openings,” Eng. Technol. Appl. Sci. Res., vol. 15, no. 2, pp. 21171–21176, 2025. doi: 10.48084/etasr.10072.

[4] M. Fahim, F. Alam, H. Khan, I. U. Haq, S. Ullah, and S. Zaman, “The behavior of RC beams retrofitted with carbon fiber reinforced polymers (CFRP),” Eng. Technol. Appl. Sci. Res., vol. 12, no. 3, pp. 8701–8706, 2022. doi: 10.48084/etasr.4926.

[5] A. Yahya Turki and M. H. Al-Farttoosi, “Investigation of the stiffness and ductility of pre-cracked RC beams after repairing with CFRP using different strengthening methods,” Eng. Technol. Appl. Sci. Res., vol. 13, no. 6, pp. 12423–12426, 2023. doi: 10.48084/etasr.6555.

[6] H. Q. Abbas and A. H. Al-Zuhairi, “Flexural strengthening of prestressed girders with partially

damaged strands using enhancement of carbon fiber laminates by end sheet anchorages," Eng. Technol. Appl. Sci. Res., vol. 12, no. 4, pp. 8884–8890, 2022. doi: 10.48084/etasr.5007.

[7] N. Askarizadeh and M. R. Mohammadizadeh, "Numerical analysis of carbon fiber reinforced plastic (CFRP) shear walls and steel strips under cyclic loads using finite element method," Eng. Technol. Appl. Sci. Res., vol. 7, no. 6, pp. 2147–2155, 2017. doi: 10.48084/etasr.1279.

[8] H. Hasan and M. H. Al-Farttoosi, "Investigation of the experimental shear resistance of RC T-beams after strengthening with carbon fiber-reinforced polymer (CFRP) bars," Eng. Technol. Appl. Sci. Res., vol. 14, no. 1, pp. 12608–12614, 2024. doi: 10.48084/etasr.6578.

[9] M. Zahid and S. Al-Zaidee, "Validated finite element modeling of lightweight concrete floors stiffened and strengthened with FRP," Eng. Technol. Appl. Sci. Res., vol. 13, no. 4, pp. 11387–11392, 2023. doi: 10.48084/etasr.6055.

[10] Z. H. Abdulghafoor and H. A. Al-Baghdadi, "Static and dynamic behavior of circularized reinforced concrete columns strengthened with hybrid CFRP," Eng. Technol. Appl. Sci. Res., vol. 12, no. 5, pp. 9336–9341, 2022. doi: 10.48084/etasr.5162.

[11] O. Anil, N. Kaya, and O. Arslan, "Strengthening of one-way RC slab with opening using CFRP strips," Constr. Build. Mater., vol. 48, pp. 883–893, 2013.

[12] M. Mahlis, A. E. Shoeib, S. Abd Elnaby, and A. Sherif, "The effect of cutting openings on the behavior of two-way solid loaded slabs," Structures, vol. 16, pp. 137–149, 2018.

[13] S. Aman, B. S. Mohammed, M. A. Wahab, and A. Anwar, "Performance of reinforced concrete slab with opening strengthened using CFRP," Fibers, vol. 8, no. 4, p. 25, 2020.

[14] M. A. El-Mandouh, M. S. Omar, and A. S. Abd El-Maula, "Behaviour of RC flat slabs with openings strengthened with CFRP," Case Stud. Constr. Mater., vol. 15, 2021. doi: 10.1016/j.cscm.2021.e00587.

[15] L. Turanli, T. Ozturan, and U. Ersoy, "Strengthening of reinforced concrete slabs with FRP laminates using self-compacting concrete," Constr. Build. Mater., vol. 22, no. 5, pp. 961–971, 2008.

[16] F. Bencardino and A. Condello, "Behavior of CFRP strengthened self-compacting concrete slabs," Compos. Struct., vol. 152, pp. 529–539, 2016.

[17] H. M. Elsanadedy, T. H. Almusallam, S. H. Alsayed, and Y. A. Al-Salloum, "Punching shear performance of CFRP-strengthened SCC slabs," Eng. Struct., vol. 205, p. 110084, 2020.

[18] Central Organization for Standardization and Quality Control, Iraqi Specification No. 5/1984: Portland Cement. Baghdad, Iraq, 1984.

[19] Central Organization for Standardization and Quality Control, Iraqi Specification No. 45/1984: Portland Cement. Baghdad, Iraq, 1984.

[20] ASTM International, ASTM A615/A615M-23: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement. West Conshohocken, PA, USA, 2023.

[21] ACI (American Concrete Institute), Building Code Requirements for Structural Concrete and Commentary, ACI 318. Farmington Hills, MI, 2019.