The Punching Shear Behavior of Self-Compacted Reinforced Concrete Two-Way Slabs with Openings and Strengthened by CFRP Sheets

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Received: 22 July 2025 | Revised: 5 September 2025 | Accepted: 15 September 2025

 DOI: https://doi.org/10.48084/etasr.13003

ABSTRACT

The use of Fiber Reinforced Polymers (FRP) is a common technique for strengthening and rehabilitating a wide range of Reinforced Concrete (RC) structures. The structural members often include openings to accommodate passages for services, such as pipes and electrical wiring. The openings in structural members, such as two-way slabs, reduce their structural performance. This reduction can be overcome through the use of Carbon Fiber Reinforced Polymer (CFRP) sheets. This experimental study investigates the punching shear behavior of Self-Compacted Reinforced Concrete (SCRC) two-way slabs with square openings and strengthened with CFRP sheets in a square configuration. The experimental program consisted of five RC slabs, each measuring 1000 mm × 1000 mm × 75 mm, reinforced with the same steel ratio. Three numbers of CFRP layers were considered in this study (one, two, and three). Two reference specimens were used: one with a square opening, while the other was a solid slab. The results indicate that the proposed technique is unable to recover the full load capacity compared to the solid slab, but it improves the performance of the unstrengthened slab with a square opening. This improvement was evident in terms of the first crack load, ultimate load, and stiffness. The use of one, two, and three layers of CFRP sheets increased the first cracking load of slabs with openings by 25.304%, 41.783%, and 40.498%, respectively, compared to the unstrengthened slabs. The enhancement ratios for the ultimate loading were 19.164%, 21.033%, and 22.930%, respectively, for the same slabs.

Keywords-two-way slabs; CFRP sheets; deflection; strengthening; CFRP layers; FRP; concrete

I. INTRODUCTION

The presence of openings within RC slabs provides many essential architectural functions, such as improving air circulation, lighting, elevator shafts, ducts for cooling and heating, and stairs. Although such openings serve important functional needs, they may reduce the load-carrying capacity and overall structural performance [1-3]. In spite of being useful in providing piping and other services, the presence of openings in the walls and slabs results in a reduction of the structural performance. This drawback is represented by a loss in the load-carrying capacity and inadequate deflection limits. One of the common techniques deployed to overcome this weakness is the utilization of FRP materials for strengthening. These materials offer better mechanical properties, including a low weight-to-strength ratio, resistance to corrosion, and ease of installation; therefore, they are often used in the strengthening and rehabilitation of the RC beams [4-7]. There are several types of FRP sheets available, but CFRP sheets are extensively used to strengthen the RC structures [8-10]. The strengthening performance of CFRP for RC slabs has been investigated. An experimental program conducted in [11] examined the behavior of CFRP strips for strengthening RC slabs with and without openings, with the position and shape of the openings being additional variables. The results demonstrated that the addition of CFRP strips can increase the load-carrying capacity and stiffness to a significant level. In addition, the slabs showed a good structural integrity despite the observed tearing. Authors in [12] investigated the strengthening behavior of two-way slabs that have central openings. It was found that the presence of openings in the slabs reduced the load-carrying capacity by about 20%, while CFRP strengthening was able to compensate for this reduction.

It was also demonstrated that the inadequate bond between the CFRP and the concrete surface leads to distinctive premature failure. Authors in [13] examined RC slabs with openings strengthened using multiple layers of CFRP sheets and observed that while the strengthening enhanced the load capacity and stiffness, the failure mode remained brittle.

Similarly, Authors in [14] reported that externally bonded CFRP laminates significantly enhance the punching shear strength of RC slab-column connections, with the analytical predictions closely matching the experimental results. Authors in [15] stated that strengthening SCRC slabs with CFRP strips significantly enhanced the punching shear capacity by 23%-65% and improved the deflection performance. Authors in [16] observed that the strengthening of RC two-way slabs with CFRP laminates significantly enhanced the load capacity by up to 134%, reduced the deflection and cracking, and offered sustainable performance with a small increase in the CO_2 emissions. Authors in [17] found that strengthening RC two-way slabs with CFRP laminates significantly improved the cracking load, ultimate strength, and deformation control. Despite a slight increase in the CO_2 emissions.

Ductility is a key property of RC slabs, as it enables slabs to undergo large deformations beyond yielding without sudden failure. This capacity for energy dissipation under overload or seismic action enhances the structural resilience and overall safety of the RC systems. It has been identified that many boundary conditions affecting the strengthening behavior of SCRC slabs with openings have not yet been investigated. This study addresses these conditions, focusing on the punching shear behavior of SCRC two-way slabs with square openings strengthened by CFRP.

The importance of this research lies in understanding and enhancing the structural behavior of SCRC two-way slabs with the presence of openings within the shear zone. Such openings are often essential for practical design, but they can severely affect the punching shear resistance of the slabs. The study proposes a strengthening technique with Multilayer square carbon CFRP sheets for recovering the load-carrying capacity of two-way slabs with openings.

II. EXPERIMENTAL WORK

The experimental program is designed to investigate the effect of the CFRP strengthening in compensating for the lack of punching shear capacity in SCRC two-way slabs with square openings. The openings were located within the shear zone ($d/2$ from the column face) and strengthened with one, two, and three layers of CFRP sheets.

A. *Material Properties*

- Ordinary Portland cement with properties in accordance with Iraqi specification No. 5/1984 [18] was used for the casting of the slabs.
- The sand used during the concrete mixes is of 4.75 mm maximum size, with a grain size distribution in accordance with Iraqi specification No. 45/1984 [19].
- Gravel with a maximum size of 14 mm was used as a coarse aggregate. The grain size distribution of that gravel was performed in accordance with Iraqi specification No. 45/1984 [19].
- The reinforcing steel consists of 6 mm diameter bars conforming to ASTM standard [20].
- The CFRP utilized in this study has a Young's modulus of 230,000 MPa, an ultimate tensile strength of 4,000 MPa, and a thickness of 0.167 mm. These properties were provided by the manufacturer.
- Epoxy-based resin was used for bonding during the strengthening process.
- High-range water reducer of the Sika brand was utilized to produce the self-compacted concrete. The properties of the admixture were provided by the manufacturer.

B. *Mix Proportions*

The mix proportions considered during this study to cast the specimens of all RC slabs are presented in Table I.

TABLE I. MIX PROPORTIONS PER CUBIC METER OF CONCRETE

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

C. *Details of Specimens*

The specimens in this study are flat slabs with dimensions of 1000 mm × 1000 mm × 75 mm (length × width × thickness). Each slab was reinforced with 6 mm bars at 75 mm center-to-center spacing, in accordance with ACI [21]. The column was 150 mm × 150 mm in section with a height of 200 mm. The cross-section, mold, and reinforcement details for a typical slab specimen are shown in Figures 1 and 2, respectively.

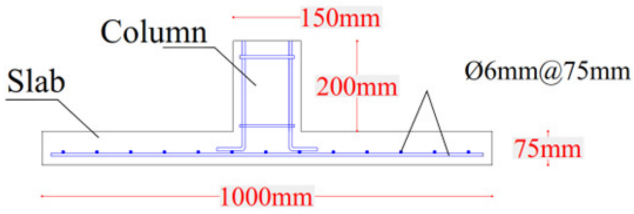

Fig. 1. Typical slab cross-section.

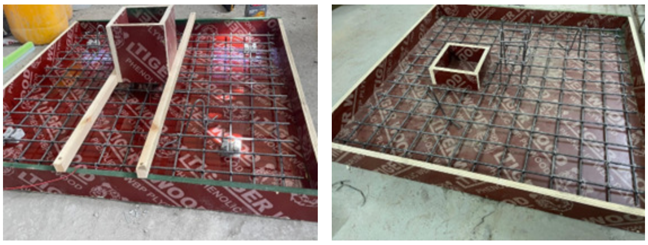

Fig. 2. Mold and reinforcement details for a typical slab specimen.

D. Designation of Specimens

The specimen designation includes three characters. The first character is either (S), referring to square CFRP sheeting, or (R), referring to a reference specimen. The second character is (W), indicating a location within the shear zone, or (N), indicating no opening. The third character is a number representing the number of CFRP layers. The specimen designations are listed in Table II.

TABLE II. DESIGNATION OF SPECIMENS

Designation	Technique	Opening location	Number of layers
RN0	Reference	No opening	–
RW0	Reference	Within shear zone	–
SW1	Square sheeting	Within shear zone	1
SW2	Square sheeting	Within shear zone	2
SW3	Square sheeting	Within shear zone	3

E. Strengthening Technique

The CFRP sheets were installed around the borders of the openings on the tension face of the slab, with the CFRP sheets being parallel to the square opening. This was done inside the shear zone (near the columns) and out of the shear zone in one, two, and three layers. The epoxy was prepared by mixing its components and was applied to install the CFRP on the concrete surface after thorough cleaning. For multilayer sheets, the process was repeated after the epoxy of the previous layer had dried. Figure 3 shows the configuration of the technique.

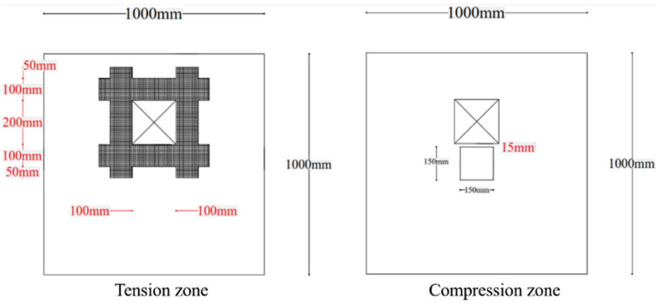

Fig. 3. Mold and reinforcement details for a typical slab specimen.

F. Preliminary Results of the Mix Design

Table III displays the mechanical properties of concrete, whereas Table IV portrays the slump test results of the mix design made for the study.

G. Preparing and Testing of Specimens

The slabs were cast and coated with white paint before testing to facilitate the crack observation. A hydraulic testing machine was set up along with strain and dial gauges. All tests were conducted in the Structural Laboratory, Civil Engineering Department, Mustansiriyah University, using an Electro-Hydraulic Pressure Plate testing machine system (EPP300MFL) with a maximum load of 3000 kN. For the identification of the initial cracks as well as the ultimate load, tests were conducted under an incremental load of 5kN. The deflection and strain were recorded utilizing the arrangement depicted in Figure 4. The deflection behavior was monitored with Linear Variable Differential Transformers (LVDTs) positioned under the column (at the point of maximum moment) and beside the openings in the slab.

TABLE III. MECHANICAL PROPERTIES OF CONCRETE

28-day Compressive strength (MPa)	Modulus of elasticity (MPa)	Modulus of rupture (MPa)	Splitting tensile strength (MPa)
39.24	29.192	3.89	4.26

TABLE IV. RESULTS OF SLUMP FLOW TEST

Test type	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

Fig. 4. The testing machine and its system.

III. RESULTS AND DISCUSSION

The results of this experimental program are discussed based on the observation of the load–deflection response. The cracking patterns were also recorded and investigated. The maximum load-carrying capacity was recorded, and the failure mode was observed. In addition, the deflection readings were recorded under the center of the specimen, which coincides with the center of the column.

A. Cracking Patterns and Ultimate Loading

It can be observed from the load-deflection response as well as the ocular reorganization of the tested slabs that there are three distinctive phases: Phase 1, which begins with the start of testing till the first cracking load. This phase represents the elastic behavior of the response. Phase 2: begins from the first cracking load to the maximum load, and includes the yielding of reinforcement. Phase 3: starts after the maximum load carrying capacity till the end of the withstanding load.

As illustrated in Table V, the percentages of the first crack to the ultimate load are 40.750%, 34.280%, 36.046%, 40.157%, and 39.179% for RN0, RW0, SW1, SW2, and SW3, respectively. The first cracking load of RW0 is less than that of RN0, which represents performance differences between the slabs with and without opening. For RN0, the first crack emerged from the bottom side of the column and extended toward the centers of the slab edges, parallel to the main shear planes, with the punching parameter being perpendicular to these directions. For the strengthened specimens, the propagation of cracks is similar to RW0, and the punching parameter remains perpendicular to the edges of the square openings, but the CFRP–epoxy interaction diverts the cracks out of the openings due to the good adhesive strength, resulting in a smaller punching parameter compared to RW0. This behavior results in higher punching stress. However, the strengthening technique used did not recover the inherent cracking load. As a consequence, the cracking load decreased by 30.078%, 20.883%, and 21.600% for SW1, SW2, and SW3, respectively, compared to RN0.

TABLE V. CRACKING LOAD, ULTIMATE LOAD, RATIO OF CHANGE, AND EFFECT OF NUMBER OF LAYERS

Specimen	RN0	RW0	SW1	SW2	SW3
First cracking load kN	45.62	25.458	31.900	36.095	35.768
Change in RN0 %	–	–	-30.078	-20.883	-21.600
Change in RW0 %	–	–	25.304	41.783	40.498
Ultimate load kN	111.95	74.265	88.497	89.885	91.294
Change in RN0 %	–	–	-20.954	-19.714	-18.455
Change in RW0 %	–	–	19.164	21.033	22.930
$\frac{First\ Crack}{Ultimate\ Load}$	40.75	34.280	36.046	40.157	39.179

In addition, the strengthening technique is able to enhance the RW0 values by 25.304%, 41.783%, and 40.498% for SW1, SW2, and SW3, respectively. This improvement was attributed to the additional stiffness. The ultimate load of SW1, SW2, and SW3, as shown in Table V, decreased by 20.954%, 19.714%, and 18.455%, respectively, compared to RN0, which confirms the inability of the proposed technique to recover the full punching capacity of the solid slabs. In contrast, the ultimate load of SW1, SW2, and SW3 increased by 19.164%, 21.033%, and 22.930%, respectively, compared to RW0, which again confirms the degree of improvement gained in the first cracking load. The ratio of the first crack load to the ultimate load provides insight into the ductile behavior of slabs. For RN0, the ratio was about 40.75%, indicating a relatively brittle failure mode. For RW0, the ratio decreased to 34.28%, indicating that the presence of openings allowed a longer nonlinear phase after cracking. The strengthened slabs, SW1, SW2, and SW3, exhibited intermediate ratios (36%–39.2%), suggesting that the CFRP sheets improved the strength and stiffness but did not significantly increase the ductility. This means that while CFRP effectively enhances capacity, its influence on the post-cracking ductility is limited. Figure 5 displays the distribution of cracks at failure for the specimens.

B. Load-Deflection Behavior

Figure 6 and Table VI present the load deflection behavior and the ultimate deflection values. The deflection under the center of the specimens and the inherent load were measured by the LVDT system. The maximum deflection corresponds to the maximum load-carrying capacity. As shown in Figure 6, RN0 clearly outperforms the slabs with openings in terms of the ultimate load, stiffness, and ductility. The effect of the CFRP layers is also evident in the better ultimate load and stiffness. However, the ductility values of the strengthened slabs are relatively unchanged. Future research should further investigate ductility, as multiple evaluation methods exist, and a more comprehensive characterization is needed.

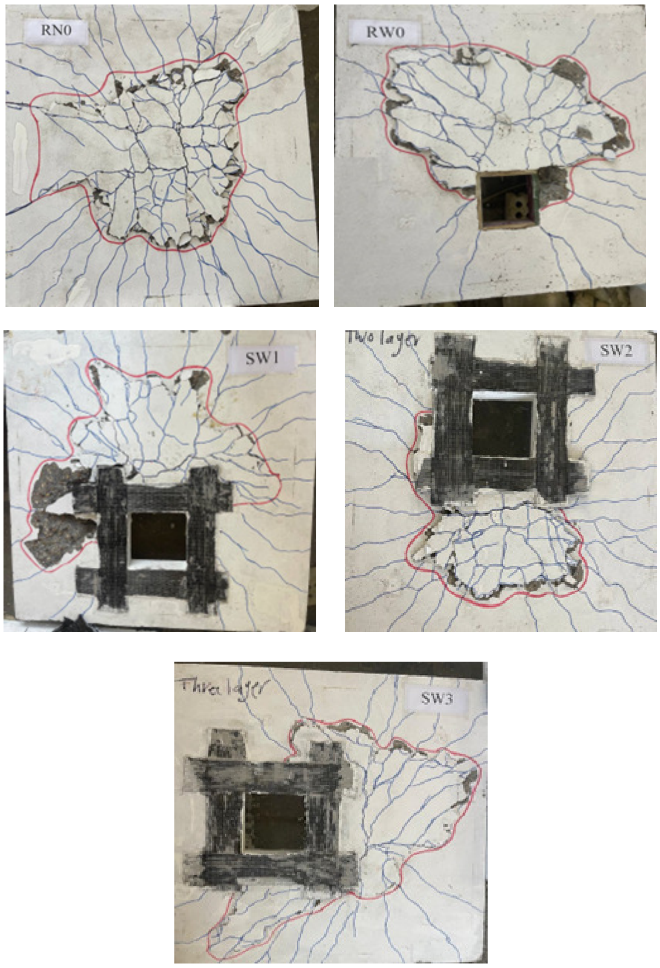

Fig. 5. Mode of failure of the tested specimens.

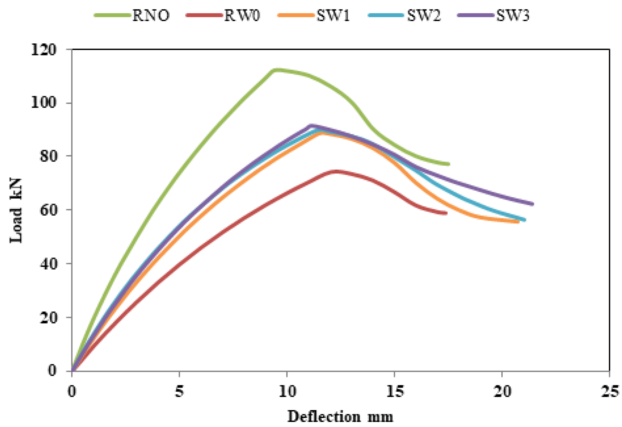

Fig. 6. Load-deflection response.

As depicted in Table VI, the ultimate deflection increased to 22.717%, 21.684%, and 18.682% for SW1, SW2, and SW3, respectively, compared to RN0, reasonably reflecting the superior ultimate load performance. The ultimate deflection decreased by 4.403%, 5.208%, and 7.546% for SW1, SW2, and SW3, respectively, compared to RW0. This can be attributed to the fact that the ultimate deflection may not be enough to characterize the stiffness, as shown in the visual observation of load deflection response. Further research is needed to characterize the stiffness and toughness of the two-way slab specimens.

TABLE VI. ULTIMATE DEFLECTIONS OF THE SPECIMENS

Specimen	Ultimate deflection (mm)	Change in ultimate deflection (%)	
		Change in RN0	Change in RW0
RN0	9.3940	–	–
RW0	12.059	–	–
SW1	11.528	22.717	-4.403
SW2	11.431	21.684	-5.208
SW3	11.149	18.682	-7.546

IV. CONCLUSIONS

This study experimentally investigated the punching shear behavior of Self-Compacted Reinforced Concrete (SCRC) two-way slabs with square openings, strengthened with one, two, and three layers of Carbon Fiber Reinforced Polymer (CFRP) sheets arranged in a square configuration. Openings in Reinforced Concrete (RC) slabs are often essential for architectural and service purposes; however, they typically lead to a significant reduction in the structural performance, such as in the punching shear capacity. Previous research on this subject has been limited, especially regarding SCRC and multilayer CFRP strengthening, which motivated the present work. Thus, the novelty of this work lies in the systematic evaluation of multilayer CFRP strengthening applied to SCRC slabs with openings under punching shear loading. The findings contribute experimental evidence according to which such a strengthening method can effectively mitigate the reduction in the performance caused by the slab openings, although it may not fully restore the original capacity of solid slabs.

The results demonstrated that CFRP strengthening does not fully recover the capacity of the solid slabs. However, it provides significant improvements compared to the unstrengthened slabs with openings. The CFRP layers enhanced the first cracking load for SW1, SW2, and SW3 by 25.304%, 41.783%, and 40.498%, respectively, compared to the unstrengthened slab with an opening. Similarly, these layers can enhance the ultimate load capacity for the same strengthened slabs by 19.164%, 21.033%, and 22.930%, respectively, compared to the unstrengthened slab with an opening. In terms of ductility, the strengthened slabs, SW1, SW2, and SW3, exhibited intermediate ratios (36%–39.2%), suggesting that the CFRP sheets improved the strength and stiffness but did not significantly increase the ductility. Also, this strengthening can decrease the deflection for the strengthened slabs by 4.403%, 5.208%, and 7.546%, respectively, compared to the unstrengthened slab with an opening. The response of strengthened slabs showed three distinct phases similar to the solid slabs, and the multilayer strengthening produced consistent improvements.

The CFRP sheets arranged around openings represent a practical and efficient strengthening technique for the RC slabs, especially where openings are unavoidable. The results of this study provide a useful reference for designers and researchers, while also highlighting the need for further investigations on long-term durability, ductility characterization, and optimization of the strengthening configurations.

ACKNOWLEDGMENT

The authors would like to thank the College of Engineering, University of Mustansiriyah, Baghdad, Iraq, for their support.

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