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EXPERIMENTAL STUDY ON THE EFFECTIVENESS OF STRENGTHENING OPENINGS IN TWO-WAY REINFORCED CONCRETE SLABS WITH CFRP SHEETS

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Abstract

This study presents an experiment on the impact of externally bonded carbon fiber-reinforced polymer (CFRP) sheets in strengthening large openings in two-way reinforced concrete (RC) slabs. Five identical square RC slabs with dimensions of 1200 mm × 1200 mm × 60 mm were fabricated. All the test slabs had a large, centrally located opening with dimensions of 400 mm × 400 mm. One slab was an unstrengthened control specimen, while four were strengthened at the opening using CFRP sheets. Two strengthening schemes were studied: CRFP sheets bonded along four sides of the opening and diagonal at the four corners of the opening at 45-degree angles. All test RC slabs were supported on all four sides and subjected to a vertical load applied to the perimeter of the opening. The main experimental results obtained include the load-displacement relationship at the edge of the opening, the cracking pattern and the failure mode of all test specimens. Based on these results, it can be seen that (1) using CFRP sheets to strengthen openings in two-way RC slabs increases the stiffness and load-bearing capacity of the slabs; (2) CFRP sheets bonded perpendicular to the principal stress direction in two-way slabs are more effective than those bonded along the edges of the openings. Additionally, an analytical calculation for the load-bearing capacity of RC slabs with openings strengthened with CFRP sheets was performed. The calculation results closely matched the experimental findings and provided a better understanding of the effect of CFRP sheets in strengthening.

Keywords: two-way slab; opening; strengthening; CFPR sheets; load-bearing capacity.

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1. Introduction

In existing reinforced concrete (RC) slabs, it is sometimes necessary to create openings, for example, to install elevators, stairs, or technical piping systems... Unlike openings in new RC slabs, which are often planned with proper detailing by adding reinforcing steel bars or thickening the slab portions around the openings, openings in existing RC slabs are typically not strengthened, making the situation more complex [1, 2]. Depending on the opening size, they can be divided into large and small openings. For large openings, a significant amount of steel reinforcement and concrete will be removed, which may affect the continuity, stiffness and bearing capacity of RC slabs [1]. In this case, the opening is usually strengthened. The selection of a suitable strengthening solution will be based on some factors, such as the location of the opening, the characteristics of the RC slab structures and the architectural requirements. Fig. 1 illustrates a large opening in existing RC slabs.

In the literature, several strengthening methods were used to strengthen openings in existing RC slabs, such as adding steel plates to the surface of a slab, adding new steel or RC beam supporting

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Figure 1. Illustration of opening in existing RC slab

elements, externally post-tensioning, application of carbon fiber-reinforced polymer (CFRP) sheets externally bonded to the tension face of the slab [3–9]. Using CFRP sheets in strengthening is an advanced method, taking advantage of this material, such as high tensile strength and elastic modulus, ease of installation and the ability to not affect the architectural space. However, this method also raises many issues that need to be resolved, such as the bonding schemes of CFRP sheets at the openings, calculating the necessary area of CFRP sheets, the problem of durability of CFRP sheets...

Research on the structural behavior of RC slabs with openings strengthened using CFRP sheets still needs to be completed. In 2007, Enochsson et al. [10] studied the behavior of strengthened two-way RC slabs with large openings. In this study, six specimens, either strengthened or unstrengthened using CFRP sheets, were tested. The experimental results showed that using CFRP sheets to strengthen two-way RC slabs with openings is an effective solution. Casadei et al. [11] conducted an experimental study on strengthening two-way RC slabs with openings using CFRP sheets. They found that anchoring the CFRP sheets led to higher load capacity than un-anchored. Anil et al. [12] and Afefy et al. [13] investigated the effects of strengthening one-way RC slabs with openings using CFRP sheets. Their study focused on the influence of the position and size of the openings on the effectiveness of the strengthening.

This study investigates the effect of externally bonded CFRP sheets on the behavior of two-way RC slabs with large openings. The findings indicate that this strengthening method is highly efficient in significantly improving the stiffness and flexural strength of these RC slabs. Experimental research has been carried out in the Laboratory of Construction Testing and Inspection at Hanoi University of Civil Engineering (HUCE).

2. Experimental research

2.1. Specimen and material properties

This experimental study investigates five RC slabs with identical geometric dimensions, steel reinforcement and concrete compressive strength. All slabs were square, measuring 1200 mm × 1200 mm with a thickness of 60 mm. The tension zone was reinforced with a single layer of ∅6 deformed bars, protected by a 15 mm concrete cover. The steel bars were arranged in two directions with a center-to-center spacing of 160 mm. Fig. 2 illustrates the details of the geometric and steel reinforcement of the test specimens. Each slab had a centrally located opening of 400 mm × 400 mm, selected to exceed the limit for a small opening [14–16]. One specimen, S-0, served as the unstrengthened control, while the other four were externally strengthened with CFRP sheets bonded to the tension face. Two specimens, S-P-1 and S-P-2 ("P" indicating perpendicular), were strengthened by applying CFRP sheets along the four edges of the opening. The remaining two, S-D-1 and S-D-2 ("D" indicating diagonal), were strengthened with CFRP sheets placed diagonally at the four corners of the opening at 45-degree angles. The CFRP sheets were cut into strips measuring 800 mm in length and 80 mm in width. Fig. 3 presents the strengthening details using CFRP materials.

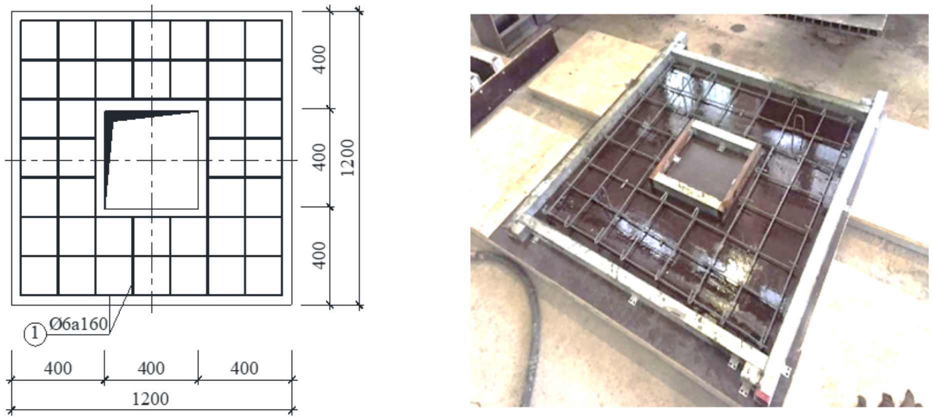
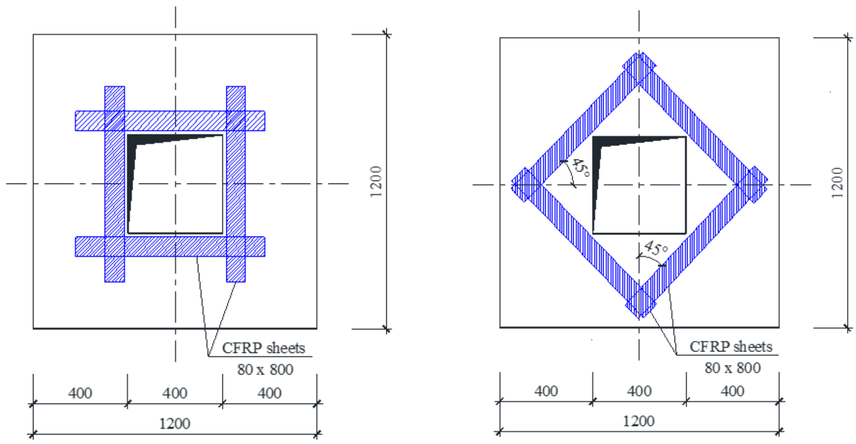


Figure 2. Details of steel reinforcement of test specimen



(a) S-P-1 and S-P-2 specimens

(b) S-D-1 and S-D-2 specimens

Figure 3. Details of strengthened test specimens

Table 1 presents the concrete mix proportions and the 28-day compressive strength. The compressive strength was determined by conducting compression tests on three standard cylindrical specimens, each measuring 150 mm × 300 mm. Fig. 4 shows a compressive test in progress.

Table 1. Concrete mix proportions (kg/m^3)

Cement (kg)	Sand (kg)	Crushed stone (10-20 mm) (kg)	Water (kg)	Water/Cement (W/C) ratio	The 28-day compressive strength (MPa)
350	680	1240	175	0.5	23.5

A uniaxial tensile test was conducted to determine the mechanical properties of the 6 mm diameter steel bars, with average yield and ultimate strengths measured at 290 and 380 MPa, respectively. The CFRP sheets used in this study were unidirectional and their mechanical properties, as provided by the manufacturer, are shown in Table 2.

Figure 4. Illustration of a concrete compressive test

Table 2. Mechanical properties for CFRP sheets

Thickness (mm)	Modulus of elasticity (GPa)	Ultimate tensile strength (MPa)	Ultimate deformation (%)
0.167	245	3400	1.6

Fig. 5 shows the unstrengthened specimen (S-0) and the two strengthened specimens (S-P-1 and S-D-1). Regarding the strengthening procedure, the surface of each test specimen was first cleaned of dust and contaminants using a high-pressure air jet. Next, a thin layer of epoxy resin coating was evenly applied onto the prepared surface of test specimens with a special broom. Then, the pre-cut CFRP sheets were placed onto the epoxy coating according to the schematic design. Finally, a sealing coat of resin was applied to the exposed surface of CFRP sheets. The strengthened specimens were left to dry under natural environmental conditions for four days before undergoing the loading test.

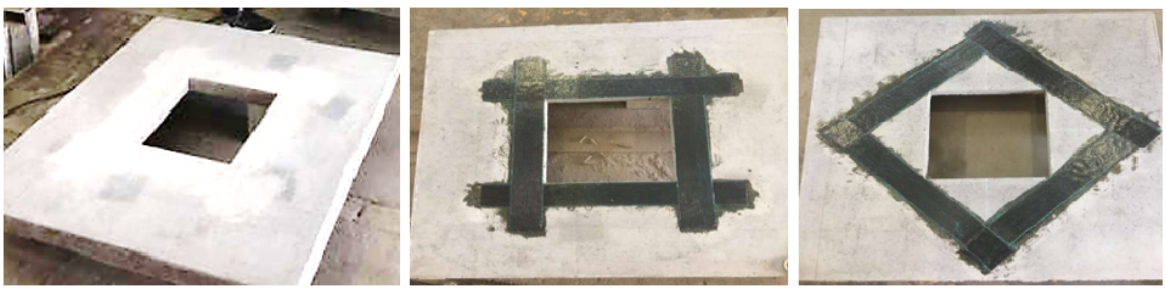


Figure 5. Images of test specimens S-0, S-P-1 and S-D-1

2.2. *Test setup and instrumentations*

Fig. 6 shows the test setup used for the experimental study, while Fig. 7 depicts a loading test in progress. All test specimens were subjected to a steadily increasing load, applied from the bottom upward through the spreader beams and a square rim formed by L-shaped steel (80 mm × 50 mm × 5 mm) positioned around the opening. The test specimens were simply supported along all four edges using a rigid steel frame, which was placed on the top (tensile) face of each specimen and anchored to the bearing floor using four 32 mm diameter bolts.

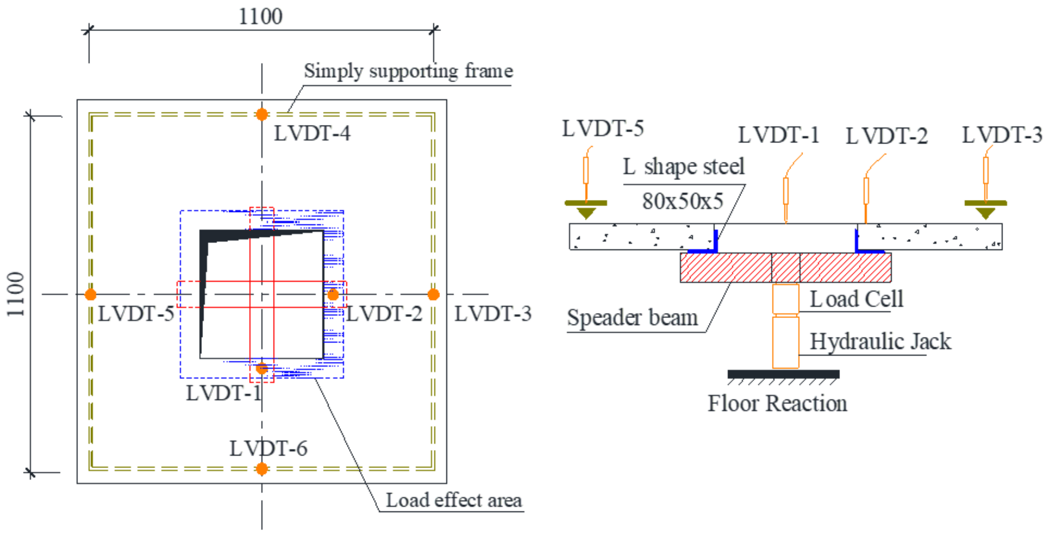


Figure 6. Test setup

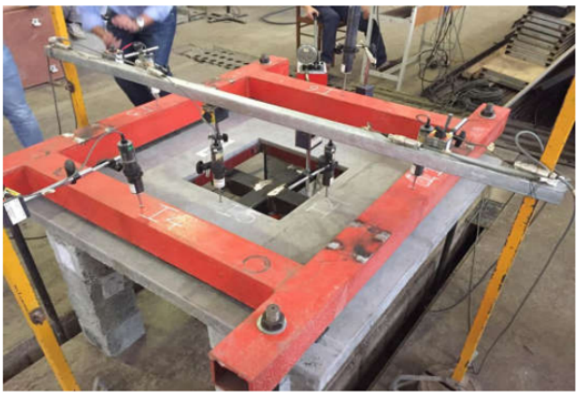


Figure 7. Illustration of a test in progress

Concerning the load test, a hydraulic jack was used to apply an axial load to the columns. An electronic force-measuring instrument (load cell) was employed to measure the magnitude of the test load. The displacements of the test specimens were recorded using six Linear Variable Differential Transducers (LVDTs). These LVDTs were positioned at specific locations on the test specimen: two at the two edges of the opening (LVDT-1 and LVDT-2) and four at the midpoint of each edge of the supporting frame (LVDT-3, LVDT-4, LVDT-5 and LVDT-6). The vertical displacements measured by these LVDTs were denoted as f_1, f_2, f_3, f_4, f_5 and f_6, respectively. The formula for determining the deflection of the test specimen, f, at the edge of the opening is as follows:

$$f = \frac{f_1 + f_2}{2} - \frac{f_3 + f_4 + f_5 + f_6}{4} \tag{1}$$

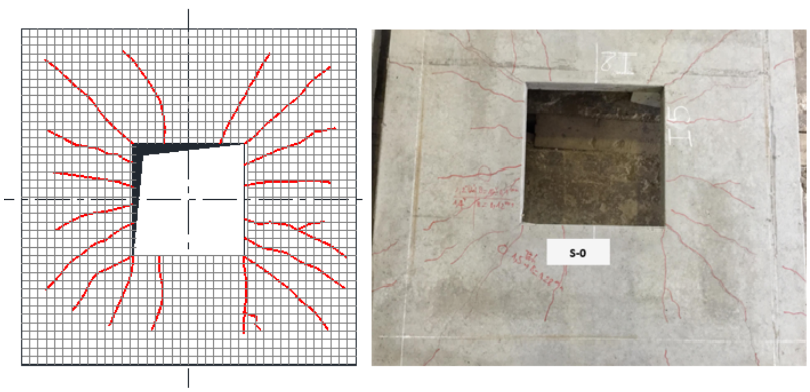
The load cell and LVDTs were connected to a TDS 530 data logger, which facilitated the continuous and automatic recording of experimental data at one-second intervals. The tests were conducted until the specimens failed.

3. Results and discussions

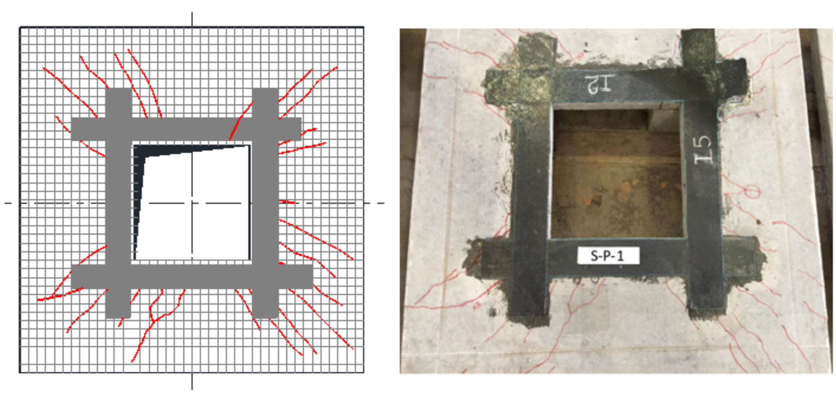
3.1. Crack map and failure mode

The cracking patterns observed in the control specimen (S-0) and the strengthened specimens (S-P-1, S-P-2, S-D-1 and S-D-2) are shown in Fig. 8. In each test slab, cracking initially appeared in the central region of the test slab, oriented perpendicular to the direction of the tensile steel reinforcement. With increasing load, additional orthogonal cracks developed and spread toward the slab edges. Next, a series of diagonal cracks appeared, originating near the corners of the opening and extending toward the slab edges and corners. Comparing all strengthened specimens (S-P-1, S-P-2, S-D-1 and S-D-2) with the control specimen (S-0) reveals significant differences in crack behavior. The strengthened specimens show a higher number of cracks, which are generally narrower than those in the control specimen. This difference can be attributed to the presence of CFRP sheets, which effectively arrest crack propagation and limit crack width.

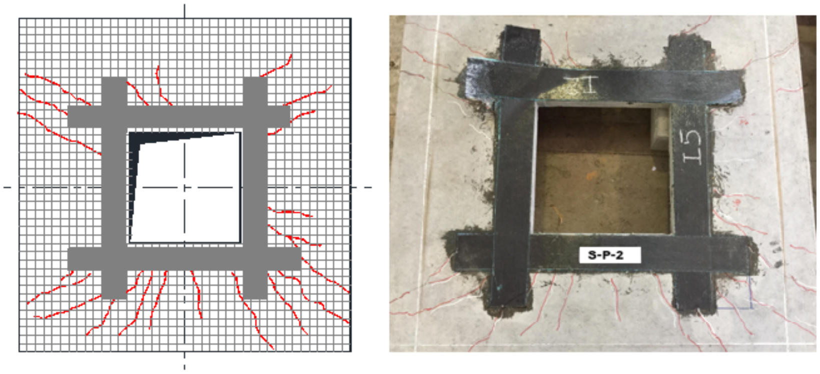
Regarding the two strengthening schemes, a comparison of the crack patterns in the S-P-1 and S-P-2 specimens with those in the S-D-1 and S-D-2 specimens reveals that when CFRP sheets were bonded diagonally, more cracks appeared compared to when the CFRP sheets were applied along the four edges of the opening. In the diagonal configuration, the CFRP sheets were installed perpendicular to the principal tensile stress direction in the test specimens. This finding is consistent with comparing stiffness and ultimate load between the S-P-1,2 and S-D-1,2 specimens.



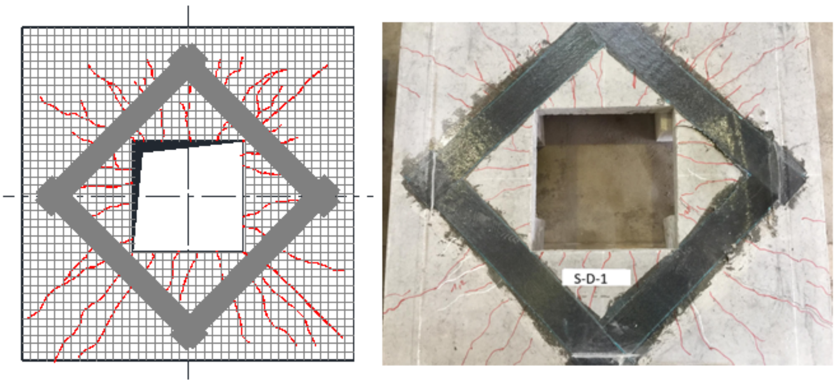
(a) Cracking pattern for S-0 specimen



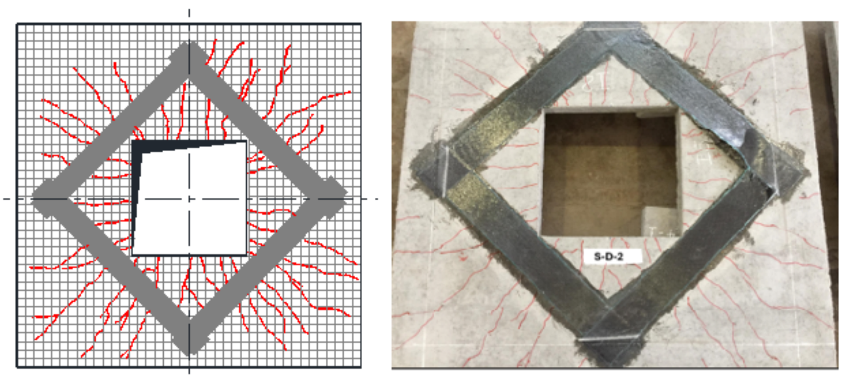
(b) S-P-1 specimen



(c) S-P-2 specimen



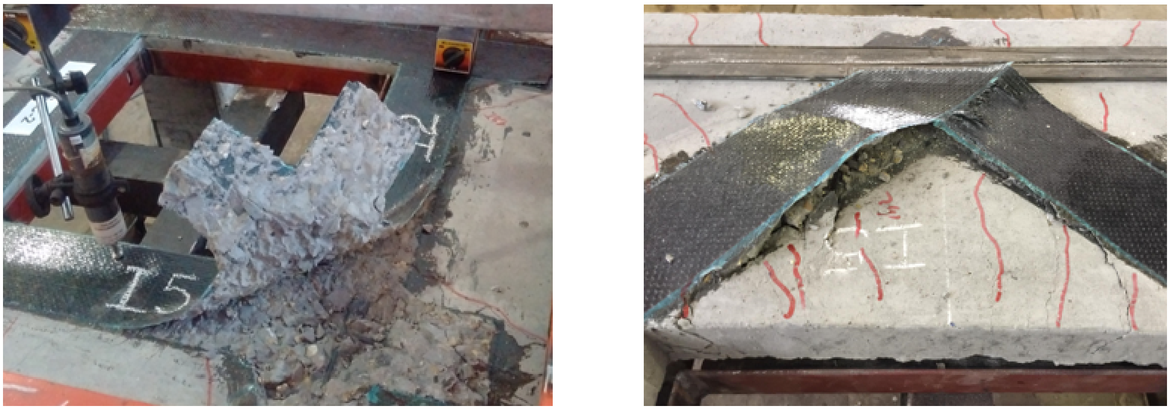
(d) S-D-1 specimen



(e) S-D-2 specimen

Figure 8. Crack patterns for all test specimens

Fig. 9 illustrates the typical failure modes of the strengthened specimens. All strengthened test specimens failed due to the debonding of the CFRP sheets, resulting in delamination along with a thin layer of concrete cover. It is important to note that the CFRP sheets did not debond due to failures in the epoxy or concrete-epoxy bond. The failure mode included removing the concrete cover and debonding the CFRP sheets from the test slabs.



(a) S-P-1 specimen (b) S-D-1 specimen

Figure 9. Photographs of failure of strengthened specimens

3.2. *Load-deflection relationship*

Fig. 10 illustrates the load-deflection (P-f) curves at the edge of the opening for all test specimens. The load-deflection response can be divided into two stages: the uncracked stage, which represents the elastic behavior before cracking occurs and the post-cracking stage. All test specimens demonstrated similar behavior during the uncracked stage, indicated by the P-f curve's O-A segment. At point A, a change in the slope of the P-f curve is observed, indicating the beginning of cracking due to bending moments in the slab. At this stage, the strengthening with CFRP sheets had not yet noticeably impacted the overall response of the test slabs.

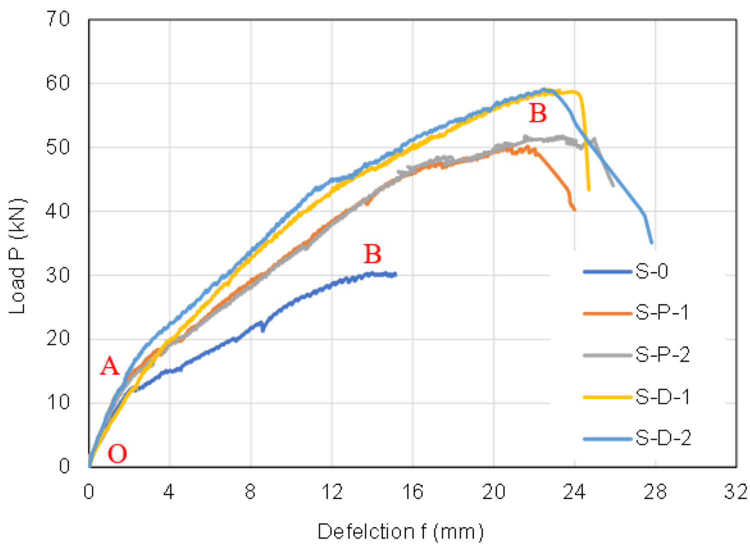


Figure 10. Load - deflection at the edge of the opening of test specimens

The AB segment in the P-f curves represents the post-cracking stage for all test slabs, with point B indicating the ultimate load of the test specimens. Based on the slope calculations of the P-f curves, it is clear that the overall post-cracking stiffness of all strengthened slabs is greater than that of the unstrengthened control slab.

The post-cracking stage of the load-deflection curve is represented by the AB portion, with point

B corresponding to the failure of the test specimens. At this point, the ultimate load can be determined. Based on the slope calculations of the *P*-*f* curves, it is evident that the overall post-cracking stiffness of all strengthened slabs is greater than that of the unstrengthened control slab. This indicates that the CFRP sheets enhance stiffness, thereby improving the structural performance of the specimens.

3.3. Cracking and ultimate load

Table 3 summarizes the characteristic loads and failure modes of all test specimens. The S-0 specimen demonstrated the lowest load-carrying capacity of all the test specimens. The results presented in Table 3 indicate that strengthening the slabs with CFRP sheets significantly enhanced their ultimate strength.

The cracking loads, ultimate loads, deflections at ultimate loads and failure modes of the test specimens are reported in Table 3. The unstrengthened control specimen (S-0) exhibited the lowest load-carrying capacity among all the test specimens. Strengthening the slabs with CFRP sheets significantly enhanced their ultimate strength. The slabs S-P-1 and S-P-2, with CFRP sheets bonded along the four edges of the opening, showed a 70.0% increase in ultimate strength compared to the unstrengthened specimen S-0. Meanwhile, slabs S-D-1 and S-D-2, with diagonally bonded CFRP sheets, exhibited a remarkable 128.3% increase in ultimate strength.

Table 3. Test results

Specimen	P_{cr} (kN)	P_{ul} (kN)	Δ_{ul} (mm)	Failure mode
S-0	12	30	14	Flexural
S-P-1	15	50	21.5	CFRP debonding-Flexural
S-P-2	16	52	22	CFRP deponding-Flexural
S-D-1	13	68	24	CFRP deponding-Flexural
S-D-2	15	69	24.5	CFRP debonding-Flexural

3.4. Simplified analytical calculation of load bearing-capacity of strengthened opening RC slabs

The research results indicate that strengthening existing RC slabs with CFRP sheets is an effective solution for large openings. To evaluate the contribution of CFRP sheets and provide a foundation for strengthening work, a simplified analytical calculation will be presented to assess the performance of RC slabs with openings.

According to [17], the load-bearing capacity of a two-way slab with a single layer of steel bar and subjected to a concentrated load, denoted P_{flex}, can be determined as the following formula:

$$P_u = \frac{0.8\left(1 + \dfrac{d}{r}\right) bd\sqrt{f_c'}}{1 + 0.433bd\dfrac{\sqrt{f_c'}}{P_{flex}}} \tag{2}$$

where m is the flexural moment capacity per unit width and w is the slab width; r is the side length of a square loaded area.

Fig. 11 presents the strain diagram and stress blocks utilized to calculate the flexural moment capacity of the strengthened test slab. The calculation is based on the assumptions: plane-section assumption; damage to the slab in flexion occurs due to the yielding of the tensile steel reinforcement, while the concrete in the compression zone is fractured; (3) the ultimate compressive deformation of concrete, ε_{cu}, is equal to 0.0035 [16].

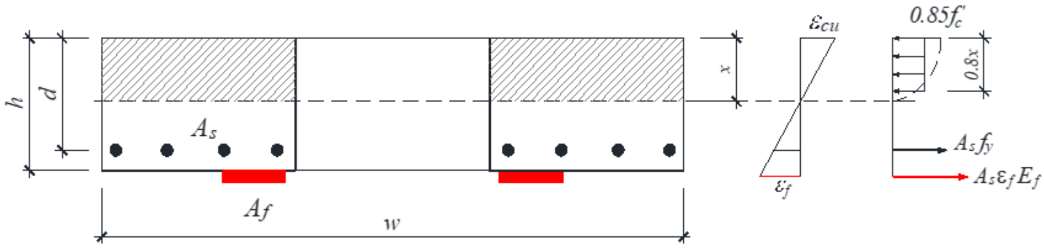


Figure 11. Section of test slabs with strain diagram and stress blocks

The depth of the neutral axis can be determined by Eq. (3):

$$0.85 f'_c (0.8x) = A_s f_y + A_f \varepsilon_f E_f \tag{3}$$

where A_s and f_y are the cross-sectional area and yield stress of the tensile steel reinforcement, respectively; A_f and ε_f are the cross-sectional area and the strain of CFRP sheets, respectively and f'_c is the concrete compressive strength.

The strain of CFRP sheets is:

$$\varepsilon_f = \varepsilon_{cu} \frac{h - x}{x} \leq \varepsilon_{fu} \tag{4}$$

where ε_{fu} is the ultimate strain of CFRP sheets.

The flexural moment capacity of section per unit width m is:

$$m = \frac{1}{w} \left[A_s f_y \left(d - \frac{0.8x}{2} \right) + A_f \varepsilon_f E_f \left(h - \frac{0.8x}{2} \right) \right] \tag{5}$$

In the case where CFRP sheets were bonded diagonally with an α angle of 45 degrees, the area of the CFRP sheets contributing to load resistance can be determined as follows:

$$A_f^* = 2A_f \cos \alpha = A_f \sqrt{2} \tag{6}$$

Table 4 compares the calculated and experimental results for the load-bearing capacity of all test specimens. The results show that the calculated values closely match the experimental findings. This calculation allows for a deeper understanding of the impact of the strengthening technique using CFRP sheets.

Table 4. Comparison of analytical and experimental results

Specimens	m (kN.m/m)	$P_{ul-calc}$ (kN)	$P_{ul-test}$ (kN)	$P_{ul-test}/P_{ul-calc}$
S-0	2.48	27.2	30	1.10
S-P-1	4.75	48.4	50	1.03
S-P-2			52	1.07
S-D-1	6.14	62.5	68	1.08
S-D-2			69	1.09

4. Conclusions

This paper presents the results of an experimental study investigating the effectiveness of strengthening openings in two-way RC slabs with externally bonded CFRP sheets. Based on the obtained results, the following main conclusions can be drawn as below:

- Strengthening two-way RC slabs with CFRP sheets is an effective solution, as the CFRP sheets significantly enhance the performance of slabs with openings by increasing both their load-bearing capacity and stiffness.

- Two strengthening schemes using CFRP sheets were studied. The results indicate that CFRP sheets bonded diagonally are more effective than those applied along the edges of the opening. The experimental results demonstrated increases of 70.0% and 128.3% in load-bearing capacity with the application of CFRP sheets along the four edges and diagonally at the four corners of the opening.

- The analytical calculation of the load-bearing capacity of strengthened RC slabs with openings, based on Eq. (2), can be applied to these tests with a reasonable degree of accuracy. The calculations also provide a deeper understanding of the effectiveness of the CFRP sheets.

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