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Strengthening of GFRP Reinforced Concrete Slabs with Openings

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ABSTRACT

Using fiber-reinforced polymer (FRP) could effectively improve the strength and endurance of reinforced concrete (RC) constructions. This study evaluated the flexural behavior of one-way concrete slabs with openings reinforced with glass fiber-reinforced polymers (GFRP) bars. It strengthened using carbon fiber-reinforced polymer (CFRP) sheets around the openings. The experimental program of this study is adopted by casting and testing four one-way concrete slabs with dimensions of (150*750*2650) mm. These slabs are divided into two groups based on whether they were strengthened or un-strengthened. For each group, two different openings (either one rectangular or two square) measured 250*500 mm and 250*250 mm, respectively, were fabricated within the pure flexural zone of the specimens. The experimental results indicate that using CFRP strips increases the maximum load capacity by around 29% for the slab with one rectangular opening and 21% for the slab with two square openings compared to the un-strengthened slabs. On the other hand, the deflection at a service load is decreased by about 35% and 37% for the slabs mentioned above, respectively.

Keywords: One-way slab, GFRP bars, CFRP sheets, Strengthening.

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تقوية البلاطات الخرسانية المسلحة ب GFRP مع فتحات

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الخلاصة

قد يكون استخدام البوليمر المقوى بالالياف (FRP) فعالا بتحسين تحمل وديمومة الهياكل الخرسانية المسلحة (RC) خاصة في الظروف القاسية. تهدف هذه الدراسة الى تقيم سلوك البلاطات الخرسانية احادية الاتجاه ذات الفتحات المسلحة بقضبان الالياف الزجاجية البولمرية (GFRP) والمعززه باستخدام الواح البوليمر المقواى بالياف الكاربون (CFRP) حول الفتحات. يعتمد العمل المختبري لهذه الدراسة على صب واختبار اربعة بلاطات خرسانية احادية الاتجاة ذات ابعاد (150*750*2650) ملم. قسمت البلاطات الى مجموعتين, بناء على وجود او عدم وجود التقوية. في كل مجموعة تم انشاء فتحتين مختلفتين,(اما فتحة واحدة مستطيلة او فتحتين مربعتين) بقياس 250*500 ملم و 250*250 ملم, على التوالي, داخل منطقة الانحناء للعينات. تشير نتائج الاختبار الى ان استخدام الواح CFRP يزيد من قدرة تحمل الاحمال بحوالي 29% بالنسبة للبلاطة ذات الفتحة الواحدة المستطيلة و21% بالنسبة للبلاطة ذات الفتحتين المربعة بالمقارنة مع البلاطات الغير مقواة. ومن ناحية اخرى قل الانحراف الخدمي بمقدار 35% و37% على التوالي, لنفس النماذج اعلاه بالمقارنة مع البلاطات الغير مقواة.

الكلمات المفتاحية: بلاطة احادية الاتجاة, قضبان GFRP, الواح CFRP ,التقوية.

1. INTRODUCTION

One of the main causes of the deterioration of RC structures is the corrosion of steel reinforcement. Non-corrosive FRP bars have replaced traditional steel bars in recent years. Frps are broadly used in areas WITH extreme conditions. FRP bars are considered cost-efficient and more effective for concrete constructions subjected to harsh environments. The GFRP is specified by its low weight, corrosion resistance, high tensile strength, and robustness in handling and installation.
(Raza and Ahmad, 2019; Al-Rubaye et al., 2020; Veljkovic et al., 2020; Zheng et al., 2012a; Zheng et al., 2012b; Adam et al., 2021; Ali and Said, 2022; Mohammed and Said, 2022; Chu et al., 2022). Slabs reinforced with FRP bars have been the focus of much research and investigation. Slabs reinforced with FRP bars have been the focus of much research and study. The flexural behavior of twelve one-way RC slabs reinforced with BFRP and GFRP bars are tested experimentally by **(Attia et al., 2019)** using a four-point loading arrangement. Every slab strip reported a steep linear elastic behavior up to the onset of the first crack, regardless of the kind of FRP bars utilized. Seven one-way spanning slabs reinforced with BFRP bars are tested **(Shamass and Cashell, 2020).** They conducted these experiments to compare three various forms of reinforcement with (6,10, and 12) mm diameters. The experimental results reported that the reinforced slabs with BFRP bars had a linear response to failure. It is recorded when the concrete reaches its maximum strength and is fractured apart. The slab fabrication requirements are focused on illumination, improvement of air circulation, provision of stairs and elevators, and ductwork for both

heating as well as cooling that require openings within the space **(Floruţ et al., 2010; Mostofinejad et al., 2020; Kaya and Anil, 2021; Hussein et al., 2021)**.
A significant decrease in the slab's strength and stiffness resulted from the presence of the opening in the concrete structure **(Floruţ et al., 2014; Aminitabar et al., 2021; Yooprasertchai et al., 2021; El-Mandouh et al., 2021; Ghanem et al., 2021)**, so recently much inspiration ideas are adopted for slab strengthening. FRP materials, utilized significantly nowadays, are the most typical approach. It is a common practice to use CFRP materials to reinforce and retrofit create structures since they can be formed into various configurations **(Khalaf et al., 2021; Allawi et al., 2021; Santos et al., 2019; Lye et al., 2020; Al-Rousan, 2022).** A substantial investigation achieved on slabs with openings and strengthened by CFRP strips is accomplished by **(Salman et al., 2018).** They tested and compared six RC specimens with one-way slabs with openings strengthened by CFRP sheets with a slab without an opening. The length and breadth of CFRP sheets were the two most essential studied characteristics, and all specimens were reinforced with steel bars 10 mm in diameter. The results showed that when compared to an un-strengthened slab with an opening, the ultimate load capacity of the strengthened slab was increased by about 90%. **(Shehab et al., 2017)** examine experimentally five rectangular cross-section one way RC flat slabs with strengthed openings using CFRP sheets.
The ultimate loads rose by almost 11.8 % when slabs were strengthened with CFRP sheets, and the deflection decreased by roughly 23% when slabs were reinforced with CFRP sheets. Experimental investigations on the utilization of FRP components for the objective of strengthening /or as a strengthening approach to increase the overall behavior of concrete structures has been carried out by a large number of researchers, especially for slabs with openings **(Yazdani et al., 2021; Naqvi, 2021; El-Mawsly et al., 2022; Al-fatlawi and Abed, 2015; Aman et al., 2020; Türer et al., 2023)**.
The present research focuses on such ways of strengthening methods to increase the overall strength of slabs, even when they have openings that may be problematic in certain applications. A significant amount of investigation has been recorded for slabs that include openings and are strengthening by utilizing CFRP strips **(Al-Rousan, 2022; Golham and Al-Ahmed, 2023).** Based on the findings of the preceding research, there is not a great deal of focus placed on examining the performance of concrete slabs with apertures reinforced with GFRP bars and strengthened utilizing CFRP strips because of the findings of earlier studies. The size and form of the openings and the type of strengthening used will be the primary focus of this investigation.
The major purpose of this work is to determine how the apertures could affect the maximum load and deflection of the concrete slab reinforced with GFRP bars. The flexural behavior of one-way concrete slabs with openings reinforced with GFRP bars and strengthening utilizing CFRP strips are examined. In addition, this work aims to assess the efficacy of the CFRP strengthening technique in enhancing the ultimate load capacity of slabs with openings.

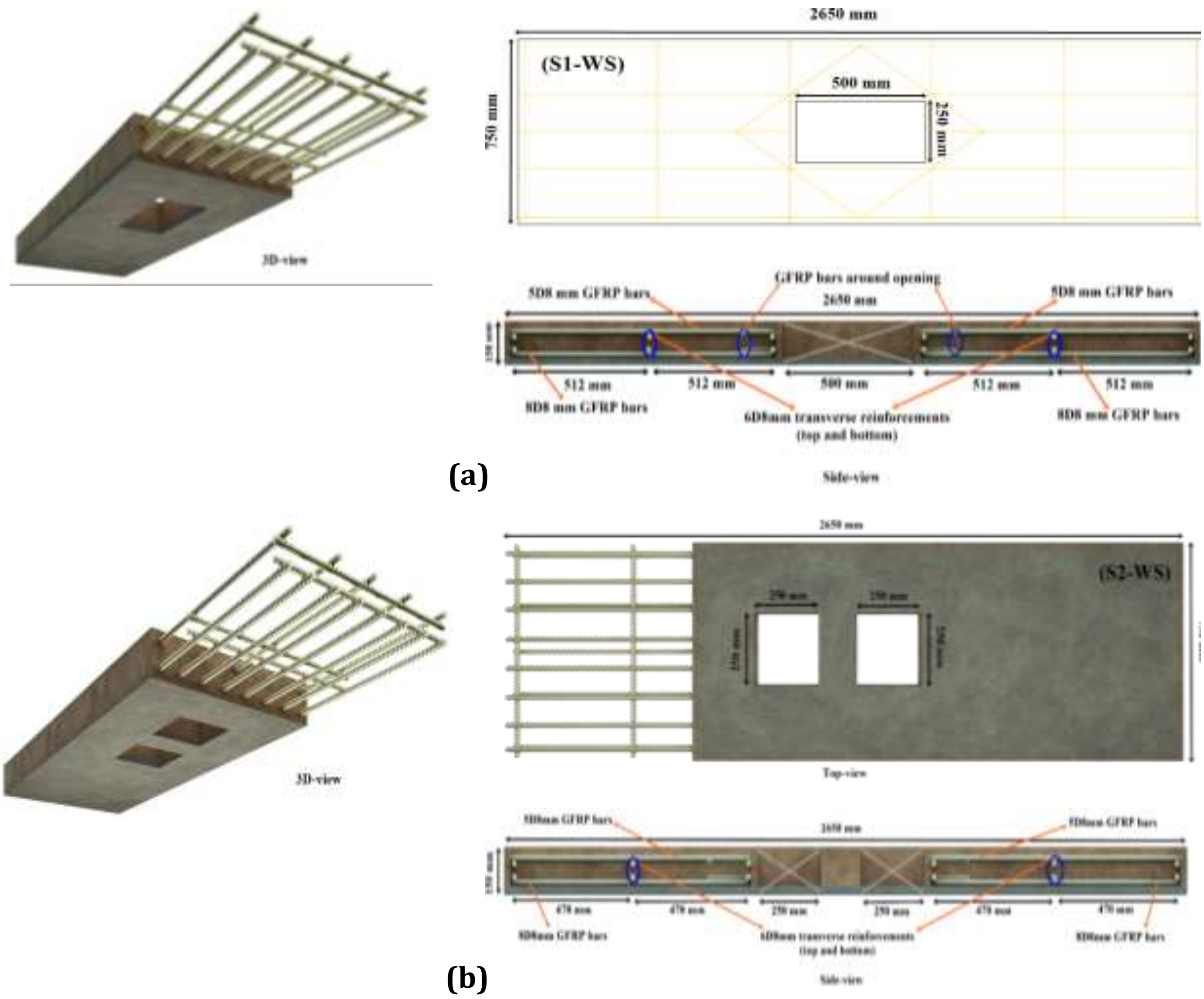
2. EXPERIMENTAL PROGRAM

The shape and dimension of the openings in the slabs and the strengthening technique are the main objectives of the investigation of this study. Typical procedures are carried out to determine the characteristics of the hardened concrete and the GFRP bars. Also, the testing procedures, experimental setup, and instruments used during this work are described.

2.1 Slabs Details

The experimental work tests four one-way concrete slabs reinforced with GFRP bars with openings at the flexural zone. All slabs have the same dimensions of (150*750*2650) mm. The slab specimens were divided into two groups based on the case of the strengthened or un-strengthened slabs around the openings, as shown in **Fig. 1.**

The Slab (S1-WS) of group one includes a mid-span rectangular opening of (250*500) mm dimensions. Specimen (S2-WS) includes two square openings, almost located in the middle of the slab, with dimensions of (250*250) mm. Two samples of the second group had openings the same as the slabs of group one but strengthened by utilizing CFRP sheets. The first is designated as (S1-OS), with a rectangular opening. The second slab is defined as (S2-OS), with two square openings. It is important to point out that the area of the single rectangular opening is equivalent to the combined two square openings area.



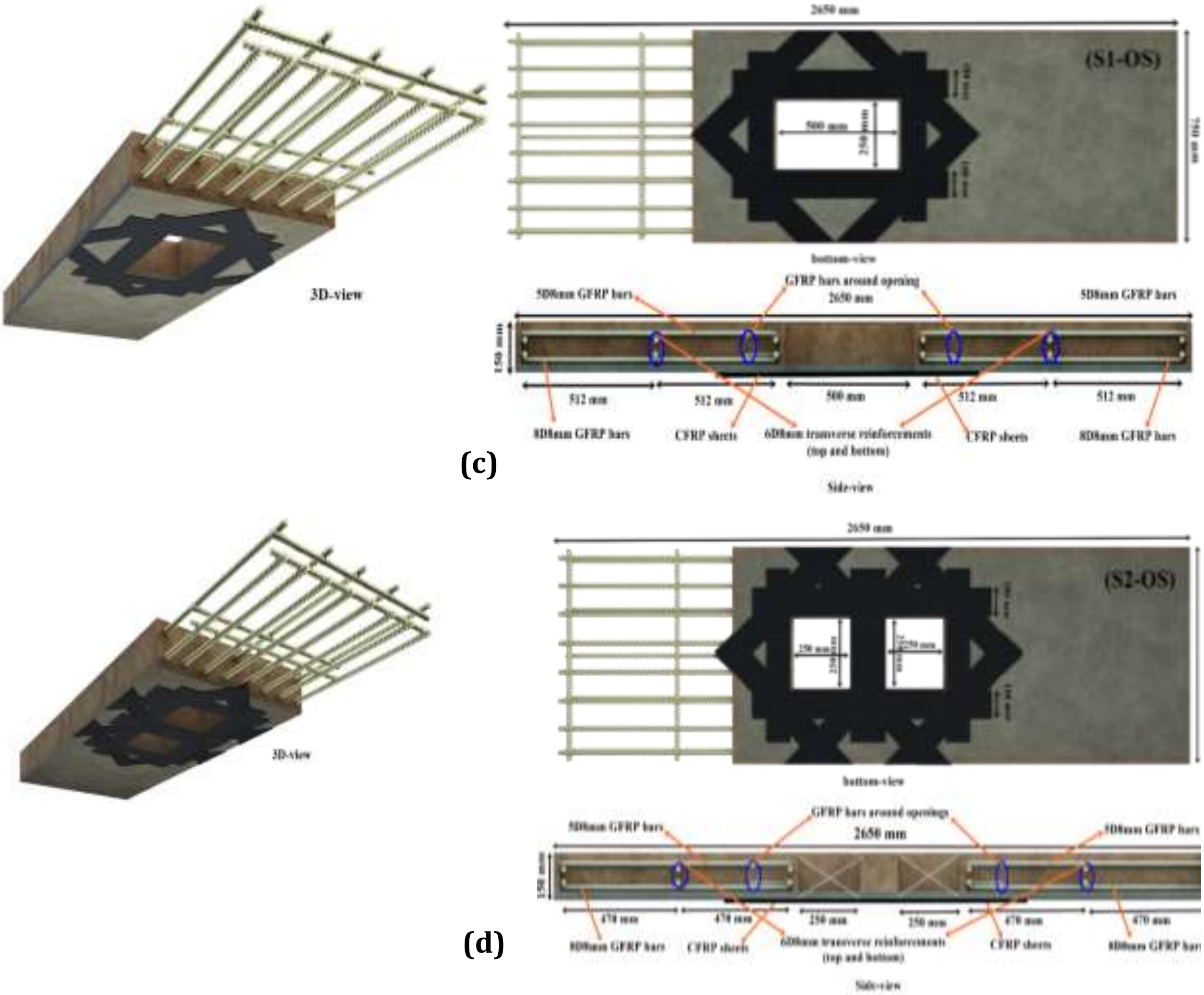


Figure 1. Schematic drawing of tested slab: a) S1-WS (slab with rectangular opening) (group one), b) S2-WS (slab with two square openings) (group one), c) S1-OS (slab featuring rectangular opening strengthened by CFRP sheets) (group two), d) S2-OS (slab featuring two square openings strengthened by CFRP sheets) (group two).

All slabs were reinforced with bidirectional meshes composed of deformed GFRP bars and placed on top and bottom. For flexure reinforcements, the bottom reinforcements consisted of eight longitudinal bars and six transverse bars, each with a diameter of 8mm. While the top reinforcements had five longitudinal bars with a diameter of 8mm and six transverse bars with a diameter of 8mm. Thus, the reinforcement ratio (ρ_f) is around 0.458%, which was less than the balanced reinforcement ratio (ρ_{fb}) (under-reinforced situation), as indicated by the standards presented in the ACI 440.1R–15 **(ACI Committee 440, 2015)**. The description of the tested slabs is listed in **Table 1**. For flexure reinforcements, the bottom reinforcements consisted of eight longitudinal bars and six transverse bars, each with a diameter of 8mm. While the top reinforcements had five longitudinal bars with a diameter of 8mm and six transverse bars with a diameter of 8mm. Thus, the reinforcement ratio (ρ_f) is around 0.458%, which was

Table 1. Test slab information.

Group	Slab designation	Characteristics	Opening size (mm)
One	S1-WS	Slab featuring one rectangular opening (un-strengthened	250*500
	S2-WS	Slab featuring two square openings (un-strengthened)	250*250
Two	S1-OS	Slab featuring one rectangular opening strengthened with CFRP strips	250*500
	S2-OS	Slab featuring two square openings strengthened with CFRP strips	250*250

2.2 Materials Properties

2.2.1 Cement

Ordinary Portland Cement (OPC) Type (I) is employed in this investigation. This cement was put through chemical and physical tests by the **(Iraqi Specification No.5, 1984)** for Portland cement.

2.2.2 Fine Aggregate

This investigation employed normal weight and naturally prepared from the Al-Akhaidher region as a fine aggregate. The largest particle size that may be found in this sand is 4.75 mm. After being cleaned with water, the sand was allowed to dry before being evaluated **(Iraqi Specification No. 5, 1984)**.

2.2.3 Coarse Aggregate

Crushed gravel with a maximum aggregate size of 12.5 mm was employed as the coarse aggregate in this investigation. The coarse aggregate is manufactured by **(Iraqi Specification NO.5, 1984).**

2.2.4 GFRP Reinforcement

In the current study, the reinforcement consisted of deformed GFRP bars with an 8 mm diameter. Tensile tests were performed on three samples to evaluate the mechanical properties of the GFRP bars in alignment with **('Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars 1', 2011)**. The testing results indicated that GFRP bars had a tensile strength of 1500 MPa, an ultimate strain of 20%, and a modulus of elasticity of 70 GPa.

2.2.5 CFRP Sheets

Sika Wrap-900c, a unidirectional woven carbon fiber fabric, is employed for external strengthening. Epoxy resin (Sikadur-330) is utilized in this work to apply CFRP sheets to the specimens. CFRP sheets were 100 mm in width, with a thickness of 0.167 mm. According to a data sheet provided by the company that made the CFRP strips, the ultimate tensile strength of these strips was 3500 MPa, and the modulus of elasticity was 230000 MPa.

2.3 Concrete Mix Design

To obtain the concrete mix components that produce a strength of 35 MPa. The following are the proportions, in terms of weight, for one cubic meter of concrete: 1 cement, 1.75 fine aggregate, and 2.75 coarse aggregates. **Table 2** shows the percentage of concrete material used.

Table 2. Proportions of the concrete mixture.

Materials	For 1 m^3 of concrete
Cement	400 (kg/m^3)
Sand	810 (kg/m^3)
Gravel	990 (kg/m^3)
Water	180 ($liters/m^3$)

2.4 Testing Procedure

After a curing period of 28 days, the surfaces of the specimens were painted white so that it would be easier to identify and record any cracks that appeared during the loading procedure. Four one-way slabs with a clear span of 2500 mm were tested and subjected to a two-line load until failure. Each slab was tested using a hydraulic jack with a capacity of 500 kN until it failed. After five minutes, the maximum and off-peak load values were recorded during each load step. During this period, the formation of cracks and the deflections of the slabs were monitored and recorded at each load stage. Each slab specimen has undergone individual testing. At each load increment, deflections and strains were measured using a mechanical strain gauge and data logger. Two LVDTs were installed at the center of their spans to measure deflections in the slabs. On the GFRP bottom bars reinforcement, strain gauges with a measuring length of 5 mm were mounted. Despite this, strain gauges measuring 60 mm were fastened to the concrete compression face of all specimens. These strain gauges were positioned in the middle of the span of the slab specimens, as shown in **Fig. 2**. The load was applied using a single hydraulic jack and split into two concentrated loads on each span using a spreader loading beam. As shown in **Fig. 3,** the specimens were examined using two different support reactions. Both were utilized on two ends, but one was roller-type support on one end, and the other was pinned-type support.

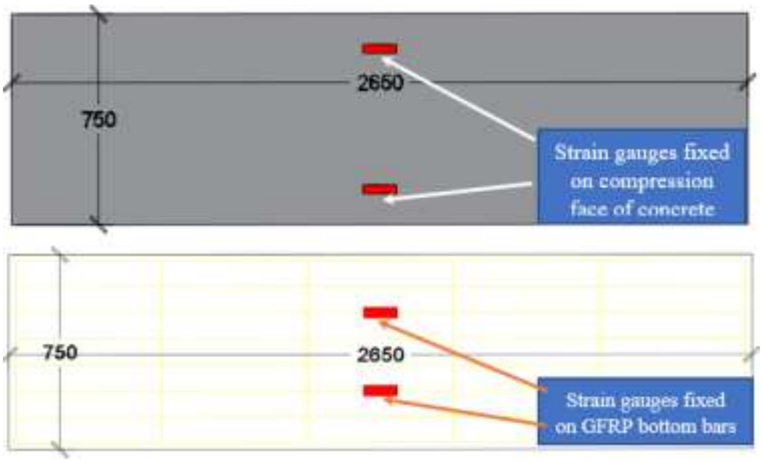


Figure 2. Strain gauges placement.

Figure 3. Setup of a typically tested slab specimen.

3. RESULTS AND DISCUSSION

3.1 Mechanism of Failure and Crack Patterns

Experimentally, concrete crushing in the maximum moment area was found to cause failure for each slab specimen. Even though there was no indication of a GFRP rupturing, which could be verified by the strains that were measured and occurred just before the GFRP bars touched their highest tensile stress, this was the case even though there was no evidence of a GFRP rupture. Even though the test specimens' GFRP reinforcement ratio was lower than the balanced ratio, the concrete crushing did not conform to the ACI-440 failure mode prediction where ($\rho \le \rho_{fb}$), the FRP rupture limit state controls. It was shown that the GFRP bars remained in the elastic region of their properties because all the slabs could rebound to some degree after collapsing. The patterns of cracking that developed due to the fracturing of the slabs are shown in **Fig. 4**.

- Side face for slab (S1-WS).

- Tension face for slab (S1-WS).

(a) (S1-WS)

- Side face for slab (S2-WS).

- Tension face for slab (S2-WS).

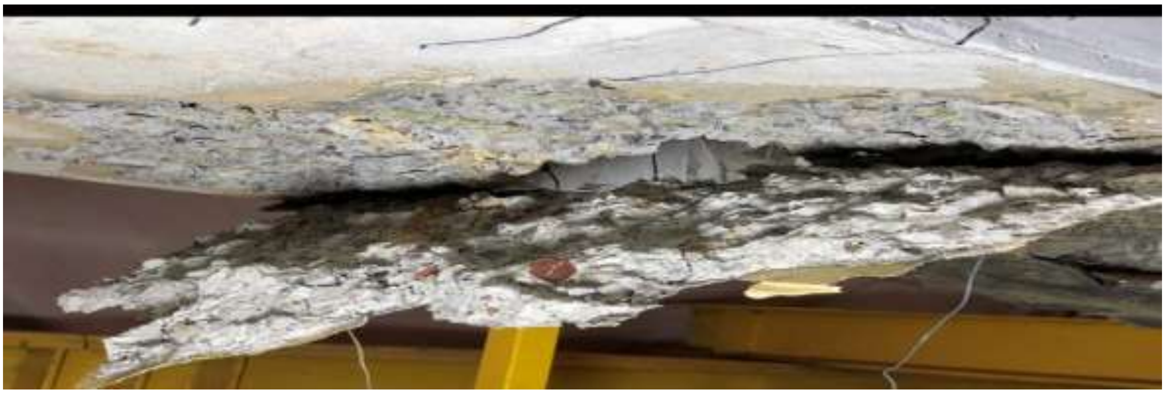
(b) (S2-WS)

- Side face for slab (S1-OS).

- Tension face for slab (S1-OS).

(C) (S1-OS)

- Side face for slab (S2-OS).



- Tension face for slab (S2-OS).

(D) (S2-OS)

Figure 4. Failure mechanisms for GFRP concrete slabs.

Due to the effect of the apertures on the reduction of the cracking load and the ultimate strength of the slab. It was determined that the un-strengthened specimen exhibited the smallest cracking load. The constant moment region in the center of the span is where flexural cracking first started. Flexural cracking is characterized by the fact that it is parallel to the line loading. **Table 3** shows that the first crack appeared in the first group of the slab with a load of 13 kN for slab (S1-WS) and 9 kN for slab (S2-WS). Consequently, the failure mechanism of un-strengthened slabs was a flexural failure, which occurred at a load of about 90 kN. Concrete in the compression area was crushed, which caused the failure.

Table 3. Test results.

Slab name	Cracking stage		Ultimate stage	
	P_{cr} (kN)	Δ_{cr} (mm)	P_u (kN)	Δ_u (mm)
S1-WS	13	1.4	90	93
S2-WS	9	2.1	87	102
S1-OS	17.5	1.4	116	79
S2-OS	14.6	1.7	105	82

As a consequence of the tests carried out, it was noticed that each strengthened slab failed due to concrete crushing at the compression face. For this group, the first crack was seen at a load of 17.5 kN for slab (S1-OS) and 14.6 kN for slab (S2-OS). In addition, the crack pattern for each of these specimens was identical. Based on the details in **Table 3**, it is feasible to determine that using CFRP sheets enhanced the cracking load. This is a direct result of the effect of the utilization of CFRP sheets on putting a halt to the propagation of the crack. The percentage increase in the occurrence of the first crack for slabs (S1-OS) and (S2-OS) was 40% and 46%, respectively, compared to the first group. It was also noticed that in the last stages of loading, the debonding of the CFRP sheets started in the middle of the slab and continued along to the end of the CFRP sheet. In addition to this, the failure of each slab that was tested is shown in **Fig. 5**.

Figure 5. Slabs with GFRP bars after failure.

3.2 Load–Deflection Response

Fig. 6 displays the load mid-span deflections measured for each slab. At the beginning of the loading process, none of the specimens cracked; consequently, the load-deflection response was linear. Because of the linear elastic deformation that was present in the GFRP bars, this was made possible.

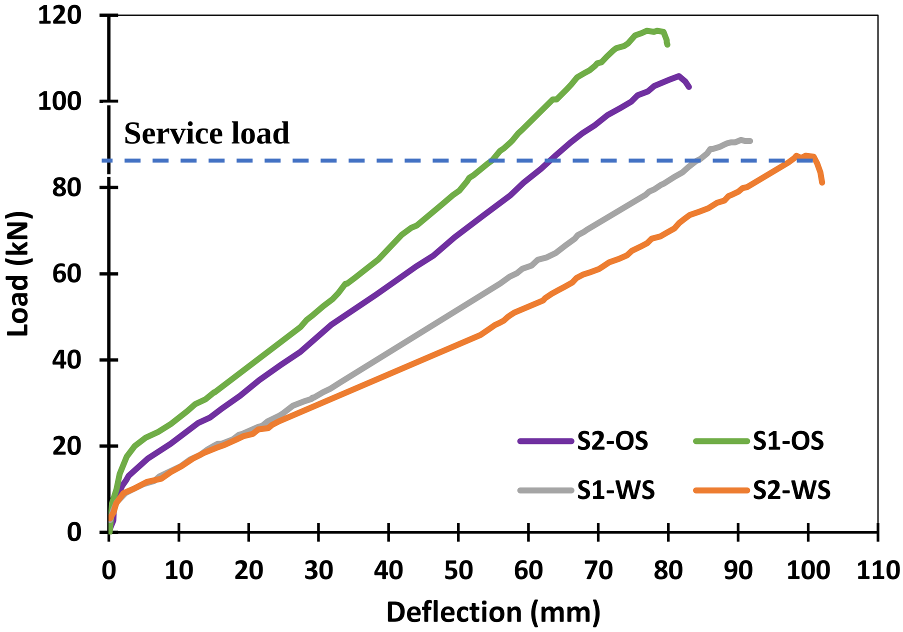


Figure 6. Load vs. mid-span deflection relationship for all test slabs.

There was a noticeable drop in the flexural stiffness after the cracking started. When the load increased, the slabs' overall stiffness decreased as a direct result of the appearance of further cracks. So, the overall stiffness was also reduced. It is possible to see that the behavior of the slab with the rectangular opening is stiffer than the response of the specimen with two square openings. The two openings within the slab (S2-WS) propagate more distance within the flexural area than a single rectangular opening, reducing flexural stiffness. At the service load level of about 87 kN, the midspan deflection of the slab (S1-OS) was decreased by about 35% compared to the slab (S1-WS). Also, for slab (S2-OS), there was a reduction in the midspan deflection at the service load of about 37% when compared to slab (S2-WS). On the other hand, for specimens with opening strengthening (S1-OS), the maximum load was

greater by roughly 29% compared with slab the (S1-WS). While for slab (S2-OS), the maximum load was greater by approximately 21% compared to slab (S2-WS).
As can be observed from **Table 4,** the strengthening operation carried out using CFRP sheets resulted in a good enhancement in the stiffness and the ultimate load of the strengthening slabs when compared to the slab without strengthening.

Table 4. Mid-span deflection values at all test slabs' service load and ultimate load level.

Slab designation	Ultimate load, (kN)	Deflection at ultimate load (mm)	Deflection at service load level (mm)	%Decreasing in deflection at the service load level	%Increasing in ultimate Load
S1-WS	90	93	85	----	----
S2-WS	87	102	101	----	----
S1-OS	116	79	55	35	29
S2-OS	105	82	64	37	21

3.3 Load-Strain Relationships

3.3.1 Concrete Strain

The mean readings from two strain gauges of concrete placed at the compression region in the midpoint of the slab specimens were used to represent the concrete compressive strain behavior to the applied load, as shown in **Fig. 7**.

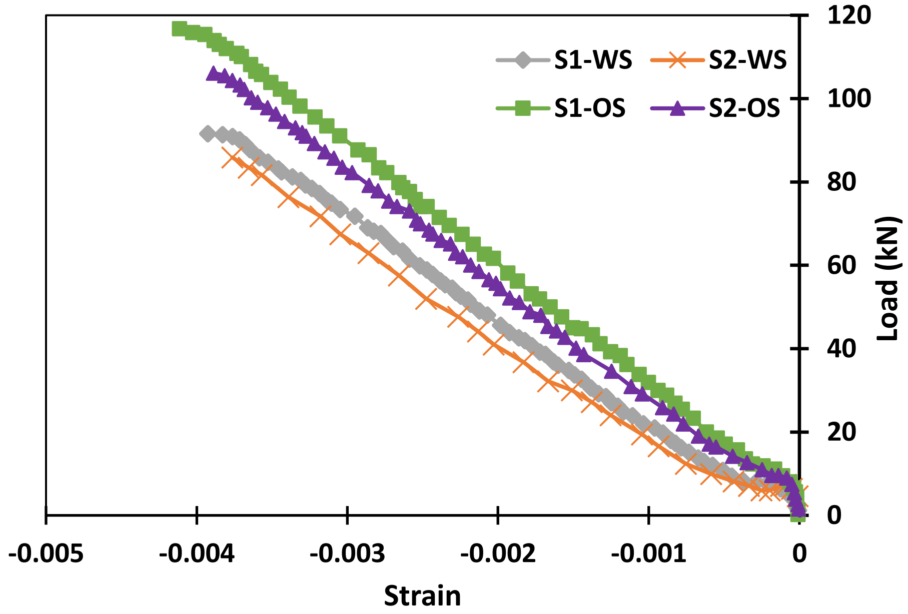


Figure 7. Concrete compressive strain versus applied load tests of tested slabs.

The slab with a rectangular opening had a maximum strain greater than the maximum strain of any of the slabs with two square openings. Additionally, it was noticed that the concrete strain in the slab specimen (S2-WS) was approximately 4% lower than the strain in the slab specimen (S1-WS). All the strengthened slabs that utilized CFRP sheets achieved a greater concrete strain than the un-strengthened specimens. It was feasible to conclude from this

Figure that the slabs (S1-OS) and (S2-OS) exhibited a concrete strain of roughly 6% and 3%, respectively greater, compared to the companion slabs to the first group.

3.3.2 GFRP Strain

Fig. 8 shows the bi-linear tensile strains in the GFRP longitudinal bars at the span's midpoint, as measured by the load-strain relationship. This relationship matched the load-deflection response of the slabs. At the load that caused the failure, it was seen that the strains that had been measured in the specimens with rectangular openings were greater than those that were observed in the specimens that had two square openings. Additionally, the strain in all strengthened slabs was decreased compared to the strain of un-strengthened slabs due to the impact of employing CFRP sheets, which greatly influenced the strain decrease of GFRP bars. The amount of GFRP strain reduced by strengthened specimens (S1-OS) and (S2-OS) were 8% and 9%, respectively, compared to the un-strengthened specimens of the first group. It is also essential to emphasize that the maximum strains measured in each slab came in significantly less than the maximum strains that the manufacturers indicated in the datasheets for their products. This points out that the failure of the examined slab was not caused by the rupturing of GFRP bars but rather by crushing concrete.

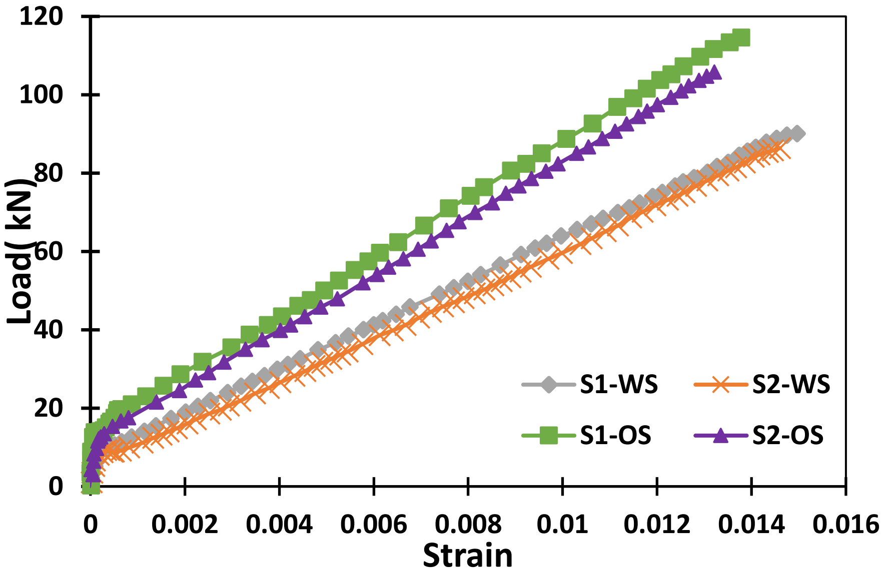


Figure 8. GFRP strain versus applied load tests of tested slabs.

4. CONCLUSIONS

The flexural response of one-way RC slabs with apertures reinforced with GFRP bars and strengthened with CFRP strips has been studied in this research. These slabs' structural performance was evaluated while subjected to a two-point load. The results of this research are presented below:

1. The responses of the GFRP-RC slabs are described as bilinear elastic. After the cracks had started, there was a discernible drop in the slabs' stiffness.
2. Using CFRP strips as a strengthening method efficiently improved the ultimate load and the strength of concrete slabs with openings. Strengthened slabs showed an increase in

ultimate load that was approximately 29% and 21% for specimens with rectangular and square openings, respectively, compared to the companion of their un-strengthened slabs.
3. At the level of service load, the amount of deflection that was induced by slabs strengthened by CFRP sheets decreased by roughly 35% and 37% for slabs with rectangular and square openings, respectively, as compared to the companion of their un-strengthened slabs.
4. Due to the use of CFRP sheets for strengthening, the strain in the GFRP reinforcement has been significantly reduced. Compared to those of un-strengthened specimens, strengthened slabs resulted in a reduction of between 8% and 9% at the final stage.
5. Despite the absence of any indication that the GFRP had ruptured, each slab had its compression face affected by concrete crushing. The debonding of the CFRP strips occurred during the last stage of loading for the strengthened slabs, which was subsequently followed by the crushing of the concrete.

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