IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Mathematical Modelling of Engineering Problems
Vol. 11, No. 4, April, 2024, pp. 1013-1020
Journal homepage: http://iieta.org/journals/mmep

Increasing the Punching Shear Capacity of Flat Plate Reinforced Concrete Utilizing CFRP Warp and Bar

Bilal Raheem Abed[1*], Salmia Beddu[1], Zarina Itam[1], Muslim Abdul-Ameer Khudhair[2]

[1] Institute of Energy Infrastructure, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, Kajang 43000, Selangor, Malaysia
[2] Civil Engineering Department, Faculty of Engineering, Kufa University, Al-Najaf 54001, Iraq

Corresponding Author Email: Eng.bilal1985@gmail.com

Copyright: ©2024 The authors. This article is published by IIETA and is licensed under the CC BY 4.0 license (http://creativecommons.org/licenses/by/4.0/).

https://doi.org/10.18280/mmep.110418

Received: 17 October 2023
Revised: 18 December 2023
Accepted: 30 December 2023
Available online: 26 April 2024

Keywords:
carbon fiber reinforced polymer, composite structures, composite, punching shear, structures, reinforced concrete

ABSTRACT

This research investigates the use of carbon fiber reinforced polymer (CFRP) sheet and bar in concrete to increase punching shear capacity. The study focuses on the use of 1000×1000×100 mm^3 reinforced flat plates and their flexure in both directions. The flat plates are subjected to a single-point load and a column stub. CFRP has a high modulus of elasticity and low coefficient of thermal expansion. Fifteen reinforced concrete flat plates were investigated, with three without FRP as control flat plates and twelve divided into two groups. The results showed that using CFRP composites to reinforce slabs at columns postponed the first slab flexural fractures, resulting in an increase in slab 2's ultimate punching shear capacity of 127.4 kN to 141.2 kN and a rise in sustained deflection from 33 mm to 46 mm. Strengthening slabs with CFRP delays the onset of concrete cracking and increases the initial slab stiffness by about 20% compared to an non-reinforced slab. Ultimate punching shear capacity improved using CFRP, making it on par with the slab without apertures. This research highlights the importance of using CFRP in concrete manufacturing systems to prevent failures and ensure long-term stability.

1. INTRODUCTION

Due to its simplicity of construction and numerous other advantages, flat slabs are growing in popularity in many developing nations. This type of slab is a structural element that bears loads in both the longitudinal and transverse directions, necessitating the presence of reinforcing steel in both directions, but because of its thinness and the fact that a column rests on it directly without the presence of a beam, it is susceptible to penetration failure because the column will penetrate as a result of the circular distribution of shear stress around it [1, 2].

1.1 CFRP sheets

Numerous studies have installed CFRP sheets on the tension surface of flat slabs as a retrofit, and they've found that it increases the slabs' flexural and shear capacities by 17 to 45%. They hypothesized that the failure mode would switch from flexural to shear as a result of an increase in load caused by greater flexural capacity [3]. There is a significant concentration of stresses near the flat slabs' supports, which are often columns, which can result in a variety of failure scenarios. A number of disastrous disasters have previously been caused by flat slabs' brittle punching failure mode [4]. To increase the punch shear capacity of flat slabs, shear reinforcement can be added. The most often used shear reinforcing systems are stirrups and headed studs, which were developed and tested under concentric monotonic loads [5].

1.2 EBR technique

The externally bonded reinforcing (EBR) approach is typically used in research on the FRP strengthening of structural RC elements, including studies on the FRP strengthening of two-way RC slabs [6]. Before attaching the FRP composites to the previously cleaned concrete surface, this procedure calls for removing a layer of the brittle concrete to reveal the coarse particles (Figure 1). The FRP sheet or laminate put using the EBR technique often separates from the concrete substrate at strains that are significantly lower than the FRP rupture strain, according to observations. Premature debonding of this kind impairs the strength and strain capacity of the FRP, thus decreasing the effectiveness of the FRP strengthening system [7]. The usage of FRP composites for structural strengthening during the end of the 1980s and the start of the 1990s caused this repairing method to catch on swiftly. The FRPs stand out thanks to their remarkable characteristics, including their lightweight, high strength, ease of installation and corrosion resistance [8].

1.3 Benefits of fiber reinforced polymer

In war-torn countries like Iraq, several infrastructures, including buildings and bridges, have been destroyed by the consequences of conflict, terrorist attacks, explosives, progressive collapse, and other unforeseeable calamities. Most of the damaged structural elements, including the slabs, beams, and columns have not totally collapsed and are still repairable. Nowadays, structural elements are often reinforced and retrofitted using carbon fiber reinforced polymer (CFRP) [9]. Although typical steel bolts are widely accessible everywhere, there are several drawbacks, such as corrosion and weight. The CFRP and AFRP, on the other hand, are regarded as high-performance, lightweight, and non-corrosive materials. Synthetic FRP rods have some drawbacks, including their comparatively expensive cost and negative environmental effects [10]. FRP rods could be considerably more beneficial in terms of sustainability and the environment. As a result, natural sisal Fiber-Reinforced Polymer rods were selected due to their sustainability, affordability, and availability as a natural resource. A thorough analysis of the studies that have already been done reveals that no direct comparison of various rod kinds has been published as of yet [11]. Therefore, it is necessary to compare the presentation of various Fiber-Reinforced Polymer rods in order to develop further design principles and suggestions. In order to improve the behavior of flawed flat slabs, this study compares investigational studies using carbon fiber reinforced polymer, aramid fiber reinforced polymer, standard steel bolts, and sisal [12]. To determine the best shear reinforcement type and configuration to use near columns in flat slabs, several configurations of the aforementioned shear reinforcements are also evaluated [13].

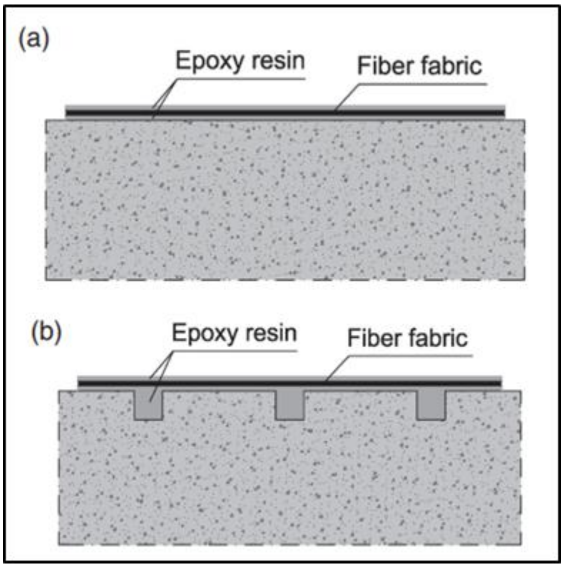


Figure 1. Approaches for bonding of Fiber-Reinforced Polymer on the concrete surface: (a) EBR; (b) EBROG [2]

The study takes into account flat plates of reinforced concrete that are supported at the edges. It will examine a reinforced concrete flat plate prototype with a straightforward geometrical design. The analysis takes into account how CFRP repairs and strengthening affect the failure mode under punching shear. In addition, the impact of concrete's compressive strength decreasing as cracks spread will be evaluated. According to studies, the flat plate was not supplied with CFRP sheets or bars to increase the shear capacity, even when mending and reinforcing, and this is true for concrete with high, medium, and normal strengths. Therefore, the goal of this study is to increase punching capacity by strengthening and mending the connection between a flat plate column and a CFRP-RC inside flat plate in concrete.

2. ADJUSTMENT OF CARBON FIBERS SURFACE

How to improve the interfacial features of composite materials that have been reinforced with carbon fibers is one of the study topics being examined by experts. The efficiency of the composite material is greatly influenced by the qualities of the interfacial interface between the reinforcement and the surrounding material. Interfacial bond has a great impact on composite materials' mechanical features. A new colloidal technology has been developed that uses nylon powder, surface-active compounds, or emulsion polymerization to create colloidal polymers, which are subsequently absorbed onto the surface of carbon fiber using the electrodeposition technique (which means action of an electric current on a conductive material immersed in a solution containing a salt of the metal to be deposited) [14]. In addition, it was described how carbon fibers' mechanical properties were improved by colloidal silica absorption (which means Enhanced bonding of waterborne adhesives). The resulting carbon fiber reinforced thermoplastics carbon fiber reinforcing polymer (CFRTP) demonstrated homogeneous strength since the silica particles acted as spacers amid the carbon fibers and the water-repellent properties of the nylon resin [15]. Nonetheless, above room temperature, CFRTP's mechanical properties continued to exist. According to the study published in works [16], coating a composite's surface with a colloid improves the material's mechanical and thermal stability. In addition, it offers the chance for CFRTP recycling, which is essential right now. Surface adhesion amid composite components is related to the mechanical characteristics of composite materials. To improve their mechanical properties, surface adhesion between thermosoft polymers reinforced with carbon fibers must be improved [17]. Polymer colloids were used, and carbon fibers were electrodepositively absorbed by them. The degree of adhesion amid adapted carbon fibers and thermoplastic resin determined through interfacial shear strength. Simple colloidal techniques were used to make a thermoplastic that had carbon fiber reinforcement. Thermoplastic that has been carbon fiber reinforced can be recycled and used like regular material [18].

A new work presented experimental cases of reinforced concrete slab foundations (RC slabs) with CFRP sheets and TRM sheets. Twelve slabs of different concrete grades were tested using different strengthening approaches. The load-deflection response showed two main peak loads in strengthened slabs and a plateau in control. The composite action and dowel action of reinforcing materials made interlock and transverse layers (cross reinforcement) were found to strengthen the concrete. The reinforced slabs showed a 9-17% increase in skew pressure, load force, energy transmittance, and total dissipation. An analytical model was derived, which correlated well with the experiments [19]. A study was conducted to assess the impact of reinforced concrete (CFRP) strips on the column-slab punching shear force of interior panels. A spine beam was made up of 16 flat plates with random openings and a central column. The specimens were divided into five groups using two different strengthening schemes. The first scheme used CFRP sheets with equal thickness to the opening breadth, while the second used two bandages with half the opening width. The non-reinforced specimens showed a decrease in punching shear capacity. The study found that applying FRP improved the punching shear capacity by 5.1% to 60.6% compared to the control. The ANSYS program was used to control the study, and the results showed that the optimization led to a good agreement with experimental data, with a maximum reduction in load of 16% [20].

3. EXPERIMENTAL WORK

The research considers reinforced concrete flat plate supported on their edges. A geometrically simple prototype of a reinforced concrete flat plate will be analyzed. The research also considers a flat plate that is neither provided with CFRP sheets or CFRP bars to enhancement of the punching shear capacity even for repairing and strengthened and for high and normal strengthen concrete. Samples will be modeled by nonlinear analysis using program, and additional factors will be investigated.

To confirm the quality and dependability of the simulation, verification by finite element analysis (FEA) using the ABAQUS software entails comparing the findings from a simulation to experimental data or analytical solutions. A model of the geometry is created, defining the material properties and boundary conditions of the system being analyzed.

4. EXPERIMENTAL PROGRAM

Fifteen reinforced concrete flat plates' specimens were investigated in this research. Three specimens without FRP as control flat plates, while the other twelve specimens were divided into two groups, first group was strengthened and repaired with CFRP sheets and the other was strengthened and repaired with CFRP bar. The two main groups were divided into normal, moderate and high strength concrete. When high strength concrete defined as concrete with a specified compressive strength of 55 and 80 kN while normal strength concrete between 20 and 40 kN at least the moderate strength concrete will be between 7 and 17 kN.

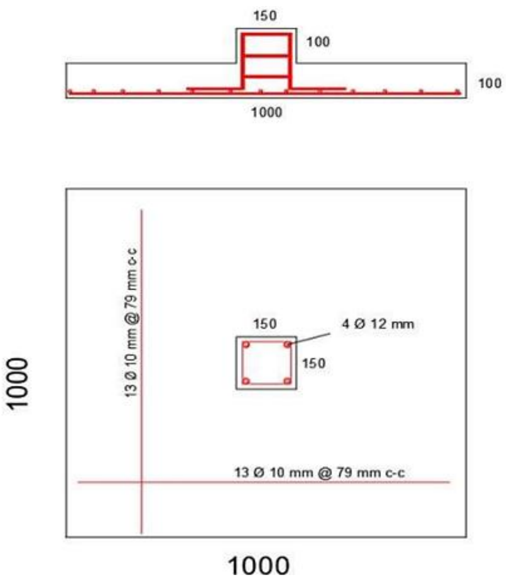
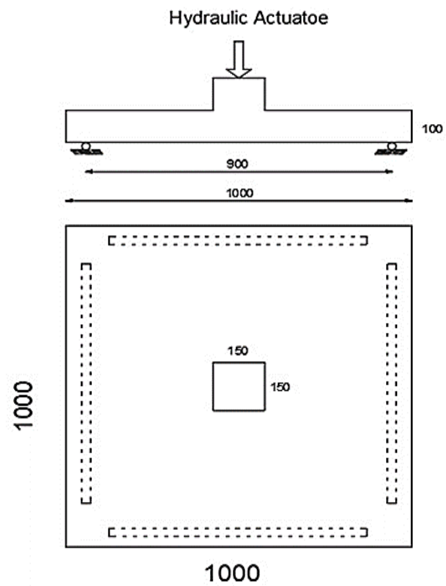


Figure 2. Details of flat plates

4.1 Details of flat plate specimens

All the RC flat plates are (1000×1000×100) mm^3 and reinforced based on design calculation (ACI 318- 19) with 13-Ø10 mm deformed bars for flexure in both directions. All flat plates are simply supported along all edges and subjected to single point load applied at the center of the flat plate. The applied load is transferred from testing machine and a column stub 150×150 mm is cast monolithically at the center of the flat plate. This is to simulate the actual interior flat plate-column connections, as shown Figure 2. All dimensions are in mm.



(a)

(b)

Figure 3. (a) Test setup (all dimensions in mm), (b) Test setup picture

4.1.1 Test setup

Figure 3 (a) depicts the test setup for simulating the slab-column subassembly. The concrete slab's four corners are supported by pins with a 900 mm pin-to-pin distance. A monotonically focused load was applied to the stub column using the hydraulic actuator, which is attempting to impart incremental displacement in order to record the post-failure behavior. The test is deemed finished when the load has been suitably dropped. The vertical deformation is captured by measuring the deflection at the middle of the slab using linear variable displacement transducers. The test setup is shown in Figure 3 (b).

4.1.2 Carbon fiber reinforced polymer

Carbon Fiber Reinforced Polymer CFRP doesn't show any plastic behavior (yield) under tension stress prior to rupture. Strengthening is accomplished with Sika wrap® Hex-230C.

The mechanical characteristics of CFRP laminate are listed in Table 1 in accordance with the Sika Company's manufacturing specifications.

Table 1. Technical properties of CFRP laminate

Properties	SikaWrap®hex-23℃
Elongation at break (strain)	1.8%
E-modulus N/mm^2	238000
Tensile strength N/mm^2	4300
Thickness mm	0.131
Density Kg/m^3	1760

5. REINFORCEMENT BARS

For all examples, deformed steel reinforcement bars of three sizes—16 mm, 12 mm, and 10 mm—are employed as longitudinal reinforcement and transverse reinforcement, respectively (closed stirrups). Table 2 displays the steel reinforcement's properties for all sizes.

Table 2. Material features for steel reinforcement

Diameter of Reinforcement Bar (mm)	Yield Stress f_y (N/mm^2)	Eventual Strength fu (N/mm^2)
10	557	713
12	510	667

6. REINFORCEMENT FRP BAR

The properties of reinforcement are very important parameters of this study. The moduli of elasticity, as well as their definitive stress and strain of steel and FRP reinforcement are explained here in details (Table 3).

Table 3. The mechanical properties of the FRP bars

Properties	FRP Bars
Density[g/cm^3]	1.6
Strength of tensile [MPa]	3100
Tensile modulus [GPa]	148
Elongation at rupture along the fiber [%]	1.7
Tensile strength/density ratio	1938

7. PREPARATION OF CONCRETE SURFACE

Figure 4. Surface grinding

(1) To eliminate the weak surface before adhering the CFRP to the concrete, grind the concrete surface with a scraper machine.

(2) Catting the line for samples mounted close to the surface as shown in the photo.

(3) Use water jutting to clean and clear the dust from the concrete surface (Figure 4).

8. CFRP SYSTEM APPLICATION

(1) Using a slow-speed electrical drill, combine parts A and B in accordance with the manufacturer's technical data until the mixture turns gray.

(2) After the carbon fiber laminate 81 has been installed on the concrete element, apply a layer of mixed epoxy (approximately 1.5 mm thick) to the concrete surface. The clean carbon fiber laminate should get a coat of mixed epoxy.

(3) Over the epoxy-coated region of the concrete surface, install the carbon fiber laminate and bar.

(4) To get rid of air bubbles that are tangled up behind the carbon fiber laminate, spin a ribbed roller in the direction of the laminate.

9. REINFORCEMENT

Appropriate lengths from FRP sheets, FRP bars and steel bars were cut using disc cutters and hydraulic guillotine. Column steel stirrups were bent according to design dimensions. The assembling was done using galvanized wires. Spacers of cement cubes were used to maintain suitable cover for concrete at sides and bottom of forms. Strain gauges were assembled with the reinforcement and then it was placed in forms. Figure 5 shows the assembly of reinforcement in formworks.

Figure 5. Assembly of reinforcement in formworks

10. CONCRETE

The concrete ingredients are mixed in a pan type mixer. The quantity is stated as shown in Table 4 for high strength concrete and for normal concrete will be without additive material and Glenium:

· Mixing silica and cement in dry condition

· Placement of half quantity of course and fine aggregate in mixer • Adding all the (Portland cement + silica)

· Adding the rest of fine and gravel
· Adding 70% of water in mixer
· Adding the Glenium then, add the rest of water
· Mixing for three minutes.

Table 4. Quantity mix for high and normal strength concrete

Material	Quantity For HSC	Quantity For MSC	Quantity For NSC
Type I cement (kg/m^3)	550	450	370
Fine aggregate (kg/m^3)	700	725	660
Coarse aggregate (kg/m^3)	1000	1000	1200
Silica fume (kg/m^3)	55	55	-
Water (kg/m^3)	150	155	165
Plasticizer (liter/m^3)	9.35	8.35	-
Water-cement ratio	0.3	0.34	0.45
Water- (cement + silica) ratio	0.27	-	-

11. RESULTS AND DISCUSSION

The experimental variables include effect of CFRP laminates and CFRP Bar on punching shear behavior of high and normal strength concrete, CFRP laminates in both repairing and strengthen of concrete. Fifty reinforced concrete Slab specimens are investigated in this study to observe the punching shear behavior of each one. To study the variables indicated above, twelve of the fifty slabs were strengthened with CFRP laminates & bar and three specimens were tested without strengthening to use as reference slabs for comparing the performance of CFRP strengthened slabs. All the reinforced concrete slabs are of the same dimensions and reinforced identically.

11.1 Normal strengthened slabs

11.1.1 NSB slab

In this slab, the paramount perceived crack happened at load about (45 kN). As the load was increased, punching shear cracks augmented in number and width, further. Many the diagonal shear cracks appeared at about 100 kN at the critical shear section. Some of these cracks were growth beside and parallel to CFRP bar and it tends an effort to cross the CFRP bar. The ultimate load was about 155 kN with an increase in ultimate load of about (47.6%) with respect to control slab (NSC). Figure 6 shows crack pattern for the slab (NSB). The load-deflection curve for the slab specimen (NSB) is shown in Figure 7.

11.1.2 NRB slab

The slab (NRB) is repairing with CFRP bar at critical section after initial preloading with 75%. In this slab, the first perceived crack happened at load about (35 kN). As the load was increased, punching shear cracks augmented in number and width, further. Many the diagonal shear cracks appeared at about 70 kN at the critical shear section. Some of these cracks were growth beside and parallel to CFRP bar and it tends an effort to cross the CFRP bar. The eventual load of about 150 kN with a growth in eventual load of about (42.8%) with respect to control slab (NSC). Figure 8 shows crack pattern for the slab (NRB). The load-deflection curve for the slab specimen (NRB) is exposed in Figure 9.

Figure 6. Crack pattern of slab (NSB) at failure

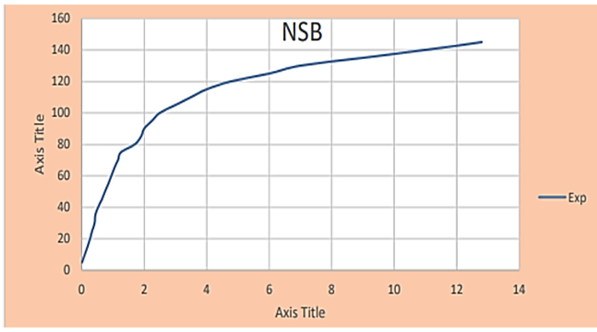


Figure 7. Load-deflection curves for slab (NSB)

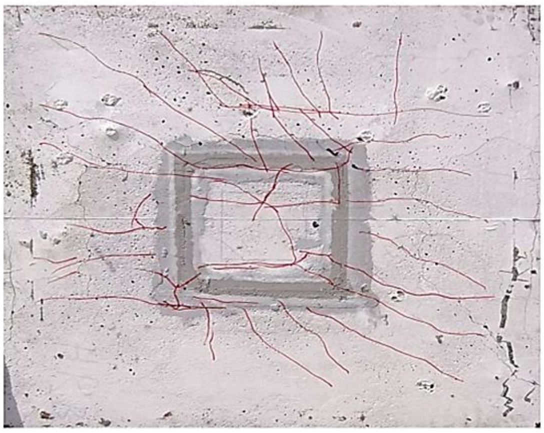


Figure 8. Crack pattern of slab (NRB) at failure

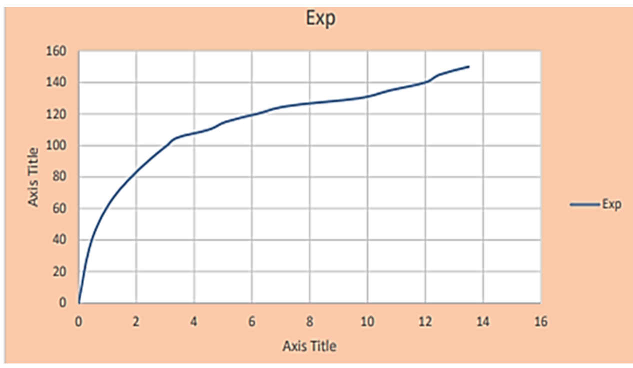


Figure 9. Load-deflection curves for slab (NRB)

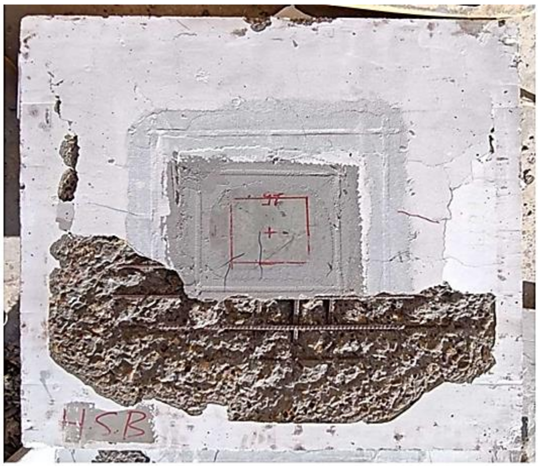


Figure 10. Crack pattern of slab (MSB) at failure

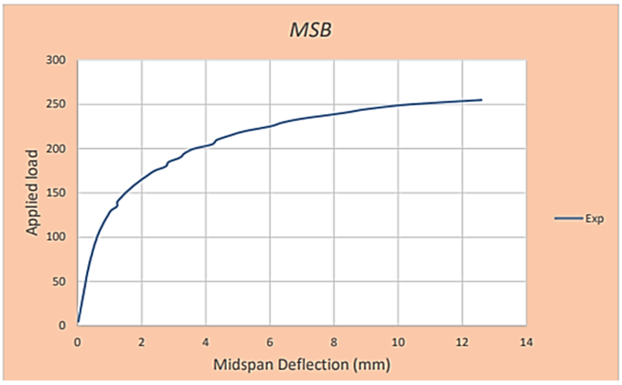


Figure 11. Load-deflection curves for slab (MSB)

11.2 Medium strengthened slabs

11.2.1 MSB slab

The slab (MSB) is strengthened with CFRP bar at critical section. In this slab, the paramount perceived crack happened at load about (60 kN). As the load increased, punching shear cracks augmented in number and width, further. Many the diagonal shear cracks appeared at about 180 kN at the critical shear section. Some of these cracks were growth beside and parallel to CFRP bar and it tends an effort to cross the CFRP bar. About 255 kN with an increase in ultimate load of about (24.4%) with respect to control slab (MSC). Figure 10 shows crack pattern for the slab (MSB). The load-deflection curve for the slab specimen (MSB) is revealed in Figure 11.

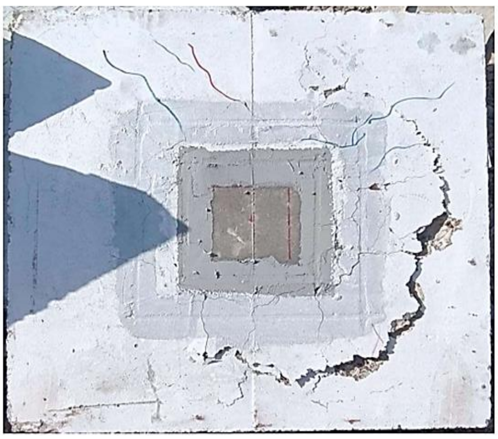


Figure 12. Crack pattern of slab (MRB) at failure

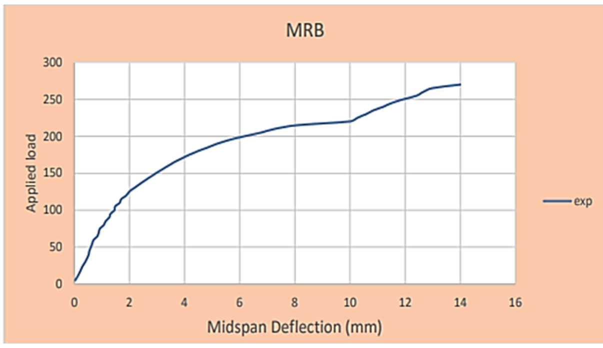


Figure 13. Load-deflection curves for slab (MRB)

Figure 14. Crack pattern of slab (HSB) at failure

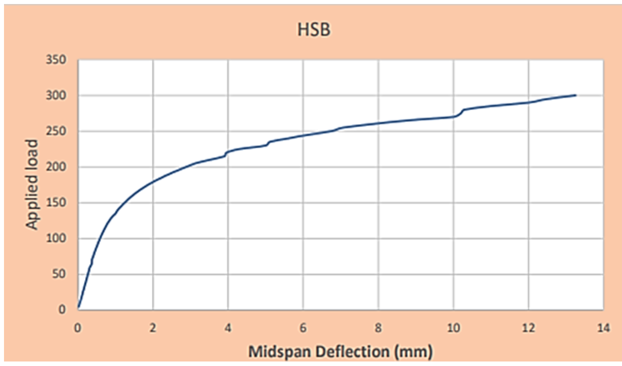


Figure 15. Load-deflection curves for slab (HSB)

11.2.2 MRB slab

The slab (MRB) is repairing with CFRP bar at critical section after initial preloading with 65%. In this slab, the first perceived crack happened at load about (50 kN). As the load was increased, punching shear cracks augmented in number and width, further. Many the diagonal shear cracks appeared at about 125 kN at the critical shear section. Some of these cracks were growth beside and parallel to CFRP bar and it tends an effort to cross the CFRP bar. About 240 kN with a growth in eventual load of about (17 %) with respect to control slab (MSC). Figure 12 shows crack pattern for the slab (MRB). The load-deflection curve for the slab specimen (MRB) is exposed in Figure 13.

11.3 High strengthened slabs

11.3.1 HSB slab

The slab (HSS) is strengthened with CFRP bar at critical section. In this slab, the first perceived crack happened at load about (80 kN). As the load was increased, punching shear cracks augmented in number and width, further. Many the diagonal shear cracks appeared at about 260 kN at the critical shear section. Some of these cracks were growth beside and parallel to CFRP bar and it tends an effort to cross the CFRP bar. About 310 kN with an upsurge in eventual load of about (24%) with respect to control slab (HSC). Figure 14 shows crack pattern for the slab (HSB). The load-deflection curve for the slab specimen (HSB) is shown in Figure 15.

11.3.2 HRB slab

The slab (HRB) is repairing with CFRP bar at critical section after initial preloading with 65%. In this slab, the first perceived crack happened at load about (60 kN). As the load increased, punching shear cracks improved in number and width, further. Many the diagonal shear cracks appeared at about 220 kN at the critical shear section. Some of these cracks were growth beside and parallel to CFRP laminates and it tends an effort to cross the CFRP laminates. About 305 kN with a growth in eventual load of about (22%) with respect to control slab (HSC). Figure 16 shows crack pattern for the slab (HRB). The load-deflection curve for the slab specimen (HRB) is revealed in Figure 17.

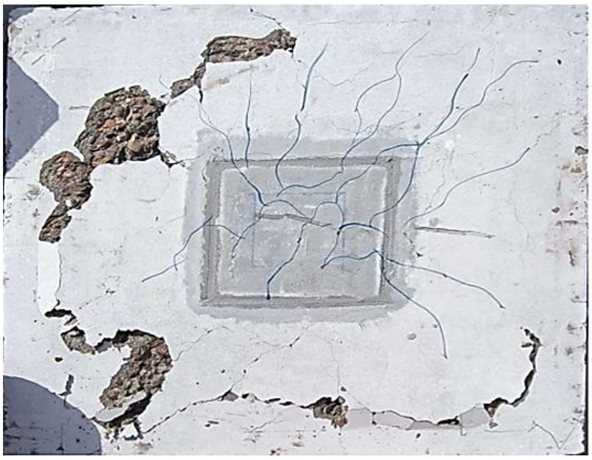


Figure 16. Load-deflection curves for slab (HRB)

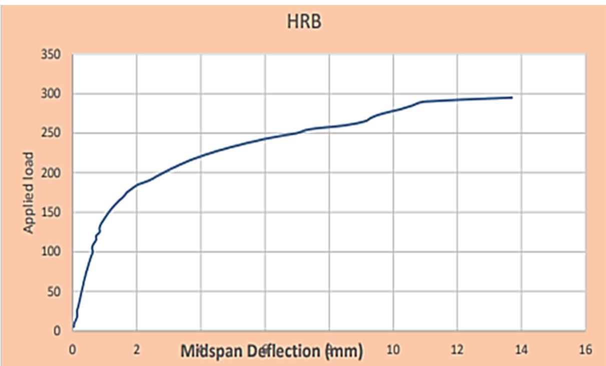


Figure 17. Load-deflection curves for slab (HRB)

12. CONCLUSIONS

To increase the punching shear capacity, the column-slab connection must be strengthened. Utilizing CFRP composites should increase the slab's ductility. Yet, regardless of the 141 higher total attainable loads, it is possible that less ductility results depending on the CFRP strengthening design. The most significant findings from the current investigation are:

(1) By means of fortifying the slabs at the column using Polymer area via growing width or number of layers. This increase can only be made so far before the connection between the CFRP and concrete prematurely collapses owing to the increasing horizontal shear amid concrete and CFRP.

(2) Composites, the early flexural cracks in the slabs were postponed. This delay has enhanced the slab response and may provide significant notice before failure rather than a quick punching shear failure by marginally raising slab 2's maximum punching shear strength of 141.2 kN compared to 127.4 kN, and steady deflection of 33 mm to 46 mm.

(3) The capacity for punching shear is increased by strengthening the connection between the FRP Concrete substrate and the punching shear. The bond strength can be improved by using FRP with a thinner layer or by boosting the FRP Young's modulus.

(4) By employing CFRP to strengthen slabs, concrete cracking can be postponed and the slab's initial stiffness can be 20% higher than it would be without reinforcement. This is due to a 12% rise in the first cracking stress and a 20% decrease in deflection. Using CFRP reinforcement reduces the stresses of the steel reinforcement across the column region because some of the total stresses applied to the steel reinforcement will be passed to the CFRP reinforcement.

(5) The maximum punching shear capacity was reduced by the opening. The slab's ultimate punching shear capacity was enhanced by utilizing Carbon Fiber Reinforced Polymer so that it was on par with the slab without apertures.

(6) The use of Carbon Fiber Reinforced Polymer reinforcement has no considerable influence on the location of the shear failure plane. It is less likely that the Carbon Fiber Reinforced Polymer sheets will be able to sustain the related tensile stresses and avoid the development of shear cracks in that direction since they have low tensile resistance perpendicular to their longitudinal axis.

(7) You can raise the Carbon Fiber Reinforced Polymer area via growing width or number of layers. This increase can only be made so far before the connection between the CFRP and concrete prematurely collapses owing to the increasing horizontal shear amid concrete and CFRP.

REFERENCES

[1] Shaaban, I.G., Hosni, A.H., Montaser, W.M., El-Sayed, M.M. (2020). Effect of premature loading on punching resistance of reinforced concrete flat slabs. Case Studies in Construction Materials, 12: e00320. https://doi.org/10.1016/j.cscm.2019.e00320

[2] Torabian, A., Isufi, B., Mostofinejad, D., Pinho Ramos, A. (2021). Shear and flexural strengthening of deficient flat slabs with post-installed bolts and CFRP composites bonded through EBR and EBROG. Structural Concrete, 22(2): 1147-1164. https://doi.org/10.1002/suco.202000236

[3] Akhundzada, H., Donchev, T., Petkova, D. (2019). Strengthening of slab-column connection against punching shear failure with CFRP laminates. Composite Structures, 208: 656-664. https://doi.org/10.1016/j.compstruct.2018.09.076

[4] Mostofinejad, D., Jafarian, N., Naderi, A., Mostofinejad, A., Salehi, M. (2020). Effects of openings on the

punching shear strength of reinforced concrete slabs. Structures, 25: 760-773. https://doi.org/10.1016/j.istruc.2020.03.061

[5] Hegger, J., Sherif, A. G., Kueres, D., Siburg, C. (2017). Efficiency of various punching shear reinforcement systems for flat slabs. ACI Structural Journal, 114(3): 631. https://doi.org/10.14359/51689434

[6] Mamdouh, H., Zenhom, N., Hasabo, M., Deifalla, A.F., Salman, A. (2022). Performance of strengthened, reinforced concrete shear walls with opening. Sustainability, 14(21): 14366. https://doi.org/10.3390/su142114366

[7] Elsayed, W.E., Ebead, U.A., Neale, K.W. (2009). Mechanically fastened FRP-strengthened two-way concrete slabs with and without cutouts. Journal of Composites for Construction, 13(3): 198-207. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000004

[8] Nagib, M.T., Sakr, M.A., El-khoriby, S.R., Khalifa, T.M. (2021). Cyclic behaviour of squat reinforced concrete shear walls strengthened with ultra-high performance fiber reinforced concrete. Engineering Structures, 246: 112999. https://doi.org/10.1016/j.engstruct.2021.112999

[9] Sahib, H.A., Al-Asadi, A.K. (2022). Prediction of shear strength of CFRP-strengthened reinforced recycled aggregate concrete beams using various strengthening methods. Przegląd Naukowy. Inżynieria i Kształtowanie Środowiska, 31(4): 238–248. http://dx.doi.org/10.22630/srees.4251

[10] Joyklad, P., Yooprasertchai, E., Wiwatrojanagul, P., Chaiyasarn, K., Ali, N., Hussain, Q. (2022). Use of natural and synthetic fiber-reinforced composites for punching shear of flat slabs: A comparative study. Polymers, 14(4): 719. https://doi.org/10.3390/polym14040719

[11] El Youbi, M., Tbatou, T., Kadiri, I., Fertahi, S.E.D. (2022). Numerical investigation of HSC columns retrofitted by CFRP materials under combined load. Civil Engineering Journal, 8(4): 765-779.

[12] Amli, A., Ahmed, A.S., Al-Ansari, N., Abtan, Y.G. (2018). Behavior of repairing composite I-sectionbeams with opening under ultimate torque. Engineering, 10(4): 202-214. https://doi.org/10.4236/eng.2018.104014

[13] El Ghadioui, R., Proske, T., Tran, N.L., Graubner, C.A. (2020). Structural behaviour of CFRP reinforced concrete members under bending and shear loads. Materials and Structures, 53: 1-16. https://doi.org/10.1617/s11527-020-01496-7

[14] Yamamoto, T., Uematsu, K., Irisawa, T., Tanabe, Y. (2018). A polymer colloidal technique for enhancing bending properties of carbon fiber-reinforced thermoplastics using nylon modifier. Composites Part A: Applied Science and Manufacturing, 112: 250-254. https://doi.org/10.1016/j.compositesa.2018.06.011

[15] Yamamoto, T., Yabushita, S., Irisawa, T., Tanabe, Y. (2019). Enhancement of bending strength, thermal stability and recyclability of carbon-fiber-reinforced thermoplastics by using silica colloids. Composites Science and Technology, 181: 107665. https://doi.org/10.1016/j.compscitech.2019.05.022

[16] Yamamoto, T., Terada, Y. (2021). Use of hollow colloids for generating nanovoids to mitigate the brittle fracture of carbon fiber-reinforced thermoplastics. Composites Part A: Applied Science and Manufacturing, 149: 106506. https://doi.org/10.1016/j.compositesa.2021.106506

[17] Pawlak, A.M., Górny, T., Dopierała, Ł., Paczos, P. (2022). The use of CFRP for structural reinforcement—Literature review. Metals, 12(9): 1470. https://doi.org/10.3390/met12091470

[18] Sager, R.J., Klein, P.J., Lagoudas, D.C., Zhang, Q., Liu, J., Dai, L., Baur, J.W. (2009). Effect of carbon nanotubes on the interfacial shear strength of T650 carbon fiber in an epoxy matrix. Composites Science and Technology, 69(7-8): 898-904. https://doi.org/10.1016/j.compscitech.2008.12.021

[19] Abbas, H., Abadel, A.A., Almusallam, T., Al-Salloum, Y. (2015). Effect of CFRP and TRM strengthening of RC slabs on punching shear strength. Latin American Journal of Solids and Structures, 12(9). https://doi.org/10.1590/1679-78251277

[20] Oukaili, N., Al-Gasham, T. (2015). Shear strengthening with CFRP sheets applied in reinforced concrete flat plates with openings. In First International Conference on Science, Engineering & Environment, Mie, Japan, pp. 1-7