Punching shear strength of flat slabs strengthened with internal flexible CFRP patches

Malik. H. Assi¹ and Noor. S. Taresh²

¹Department of Water Resources Engineering, Mustansiriyah University, Iraq, Baghdad
²Department of Roads and Transportation Engineering, Mustansiriyah University, Iraq, Baghdad

Email: malikallami@gmail.com

Abstract. This paper presents a strengthening method used for improving the punching shear strength of flat slabs. Square internal patches of carbon fiber reinforced polymer were placed at the center of 450x450mm fresh concrete slabs, through casting, at a distance from the bottom (tension) face, producing four specimens. The dimensions of these patches were from 60x60mm to 200x200mm. The results have shown that the strengthened specimens had higher punching shear strength in comparison to the control specimen, with an increasing rate ranging from 15 to 45 %. In addition to the sensibly improved shear strength, this strengthening method is capable of changing the mode of failure from combined flexural-punching to pure punching shear failure.

Introduction

Reinforced concrete flat plates lead to attractive and elegant thin flat slabs as well as simple and rapid construction and installation. Using flat slabs allows for tranquil and flexible dividing, and reduces the total height of buildings. Nevertheless, the absence of beams networks may develop high shear stresses around supporting columns, resulting in possible rapid punching shear failures at loads below the flexural strength of the slabs. This situation can be further aggravated if it is associated with unbalanced moments. Flat slabs may also fail in punching as a result of design or construction errors, corrosion of steel reinforcement, an alteration of building use and installing additional facilities that need openings in the slab. Several remediations can be employed to prevent punching shear failure, some of which have already been practiced.

These include:

- Decreasing the applied loads.
- Decreasing span length.
- Increasing slab thickness.
- Increasing the local slab thickness by a dropping panel or an inverted cone.
- Increasing dimensions of columns.
- Installing shear reinforcement.
- Installing shear heads, rods, collars at slab/column connection.
- Installing steel bolts/studs and/or steel plates through the slab.
- Gluing external FRP laminates to the slab tension face.

Nonetheless, the first five solutions may impose practical, architectural, and economic difficulties. Traditionally, inclined or perpendicular shear reinforcements are provided to the primary flexural reinforcement to prevent shear failure. However, in addition to causing a reduction in the durability and
the efficiency of the flexural reinforcement, anchoring conventional shear reinforcements, especially perpendicular reinforcement, in thin structural elements such as slabs is difficult. Also, using steel bolts/studs with or without steel plates through the slabs has been proven as an effective post-strengthening technique to enhance the structural performance and the ultimate capacity of the slabs [1-4]. Hassanzadeh and Sundqvist [3] for instance, inserted vertical steel bars passing through the slab around the column to boost the shear strength. Zhang et al. [4] employed steel plate bonding to enhance the strength flat slabs subjected to concentrated loads. Nevertheless, besides the difficulties associated with the implementation, the vulnerability of steel plates, studs, and bolts to corrosion is of primary fear for engineers and developers.

The availability of alternative materials like fiber reinforced polymer (FRP) has resulted in numerous studies, devoted to examining their effectiveness in rehabilitation and strengthening of reinforced concrete structures [5-11]. Fibre reinforced polymer (FRP) composites have a wide range of applications in the field of Civil Engineering. These involve, but not limited to, using epoxy resins to externally bond FRP sheets to reinforced concrete, steel or timber members. This strengthening method has several benefits owing to their strength, corrosion resistance and lightness. Binici [8] for example, investigated the use of CFRP stirrups fixed in holes drilled around columns subjected to eccentric and concentric loadings. Considerable improvement in the two-way punching strength capacity without anchorage ruptures was observed. Chen and Li [9] examined the influence of GFRP on the tension surface of slabs. Observing the improved punching capacity, they found that their technique becomes more effective if it is used with slabs having lower reinforcement ratios and compressive strength. Meisami et al. [10] improved the punching shear strength of two-way slabs using CFRP grids installed on the specimens using epoxy resin. The researchers reported that further enhancement in the strength and a change in the failure mode from punching to flexural could be obtained by increasing the number of CFRP grids.

It is clear that most of the researchers have tried to enhance the punching shear strength by strengthening the slab-column connections during or after the construction stage. No work was found in the copious amount of literature examined attempting to increase the punching strength of the flat plate using internal patches of CFRP as cheap and practical remediation. In this study, square CFRP sheets with dimensions ranging from 60x60mm to 200x200mm were placed inside 450x450 mm concrete slabs by casting at a selected distance from the bottom face, producing four samples.

**Experimental Program**

**2.1 Materials and Concrete Mechanical Properties**

Ordinary Portland cement Type (I) was mixed with washed natural sand from Al- Ukhaider region with a maximum size of (4.75mm) and crushed aggregate from AL- Nibaey region whose maximum size is 10mm to produce the concrete mixture. Both the sand (S) and the gravel (G) comply with the Iraqi standard IQS No.45/1984. Superplasticizer (SP) Glenium 51 manufactured by BASF construction chemicals was also used to decrease the water/cement (W/C) ratio and enhance the workability of the mixture. The SP is confirmed to ASTM C494. The mix proportion by weight of the concrete used in this study is summarised in Table 1.

For control purposes, six standard 150x300 mm cylinders and three 100x100x500 prismatic samples were casted and examined to determine the compressive strength, splitting tensile strength and modulus of rupture. The results and specifications used to carry out these tests are summarised in table 2. The steel used for flexural reinforcement was Ø6 deformed bars with a yield strength of 640MPa. The steel bars were tested in Al- Mustansiriyah University/college of Engineering according to ASTM A615/615M-18e1.
Table 1. Mix details and compressive strength (m³)

| (f'c) MPa | W/C | W (L/m³) | C (kg/m³) | S (kg/m³) | G (kg/m³) | SP% Wt. of Cement |
|-----------|-----|----------|-----------|-----------|-----------|------------------|
| 56        | 0.35| 147      | 450       | 675       | 925       | 1.5%             |

Table 2. Mechanical properties of concrete

| Property                        | Result | Specification  |
|---------------------------------|--------|---------------|
| Compressive strength (f'c) MPa  | 56     | ASTM C39/C39M-01 |
| Spliting tensile strength fsp MPa | 4.31  | ASTM C496/C496 M-17 |
| Modulus of Rupture f_r MPa     | 6.15   | ASTM C78-02   |

The bars were placed and distributed along with two perpendicular directions at (100mm c/c) with an effective depth of 35mm, measured from the center of the upper layers to the upper edge of the compression face of slabs as shown in Figure 1. No compression reinforcement was provided. The CFRP used herein had a Young modulus of 230GPa, a design thickness of 0.13mm, an ultimate tensile strength of 3500 MPa and an ultimate tensile strain of 1.5% according to the manufacturer's sheet. Single square sheets of CFRP were implanted at the center of each slab, and at a distance of 33mm measured from the top, compression, face of the slabs. While the sheets locations were kept throughout this study, the dimensions of the CFRP patches were varied from 60x60mm to 200x200mm, producing four specimens. The details of CFRP reinforcements are illustrated in Table 3.

2.2 Test Specimens
The examined specimens were chosen as square slabs of 450*450*50mm dimensions with an effective net depth of 35mm. All slabs were simply supported with clear spans of 400mm in both directions. The four corners were free to lift. The specimens had identical reinforcement ratio. A tension layer of a deformed steel reinforcement of (6mm) diameter was spread at (100mm c/c) in two directions, as shown in Fig. 1. No compression reinforcement was provided. A steel cube, whose side equal to 45mm, was used to resemble the column and placed at the center of the specimens. One strengthening technique was utilized herein, in which a single square sheet of CFRP was embedded inside the slabs during casting.
**Figure 1.** Specimen layout, reinforcement details, and strengthening technique.

**Table 3.** Test specimens details

| Specimen designation | Longitudinal reinforcement | Strengthening Details | Description |
|----------------------|---------------------------|----------------------|-------------|
| CS                   | 5 φ 6                     | None                 | Control slab |
| SFP-60               | 5 φ 6                     | 60mm FRP patch       | A 60 mm FRP patch installed in fresh concrete during casting |
| SFP-120              | 5 φ 6                     | 120mm FRP patch      | A 120 mm FRP patch installed in fresh concrete during casting |
| SFP-160              | 5 φ 6                     | 160mm FRP patch      | A 160 mm FRP patch installed in fresh concrete during casting |
| SFP-200              | 5 φ 6                     | 200mm FRP patch      | A 200 mm FRP patch installed in fresh concrete during casting |

The sheets were located at the center of each specimen, and at a distance of 33mm measured from the top, compression, the face of the slabs. The dimensions of the CFRP patches were varied from 60*60mm to 200*200mm, producing four specimens. Slabs details are summarised and presented in Table 3. The specimen named CS is the control specimen without any strengthening. Specimens SFP-60 to SFP-200 are the strengthened slabs with CFRP square sheets.

2.3 Test Procedure and Measurements

Slabs were placed on a rigid and flipped truncated pyramidal steel frame, as shown in figure 2, providing simply supported with clear spans of 400mm in both directions. Slabs were loaded centrally and monotonically through a rigid 45mm cubic steel column stub until failure using a hydraulic universal testing machine (MFL system) with a 3000 KN capacity with a loading increment of 5KN up to failure.
Figure 2. Test Setup and instrumentation

Test Results and Discussion
The complete load-deflection curve for each examined specimen was plotted, and the cracks propagation was recorded. These are shown in figures 3 and 4, respectively. The acquired results were analyzed and discussed to find the effect of CFRP patches on the mechanical performance of the slab-column connections under punching shear. Table 4 summarizes the test results, the failure mode, and the ultimate capacity of each specimen.

Table 4. Experimental Test Results

| Specimen | Failure mode | P_u (kN) | P_u/P_u control | P_cr (kN) | δ_cr (mm) | δ_u (mm) | E_uncracked (GPa) | E_Cracked (GPa) |
|----------|--------------|----------|-----------------|-----------|-----------|-----------|-------------------|-----------------|
| CS       | Flex-punch   | 28       | 1.00            | 7.0       | 0.22      | 3.5       | 32                | 6.4             |
| SFP-60   | Flex-punch   | 33       | 1.18            | 10.0      | 0.28      | 3         | 36                | 8.5             |
| SFP-120  | Punch        | 40       | 1.43            | 12.5      | 0.3       | 2.9       | 42                | 10.6            |
| SFP-160  | Punch        | 44       | 1.57            | 16.5      | 0.36      | 2.3       | 46                | 14.2            |
| SFP-200  | Punch        | 50.6     | 1.81            | 19.0      | 0.4       | 1.9       | 48                | 21.1            |

3.1 Failure Mode and Cracks Patterns
Specimen CS and SFP-60 experienced combined flexural-punching shear in which punching shear cracks and flexural yield lines, which diagonally extended from the corner of the column and forked out as approaching the corners of the specimen, were noticed to form instantaneously at failure. Specimens SFP-120, SFP-160, and SFP-200 present obvious signs of two-way punching shear failure. Shear failure in these specimens was apparent through the development of inclined cracks that expanded a distance away from the projection of column stub at the tension face of the slab. Crack patterns of specimens are shown in figure 4. Except for specimen CS and SFP-60, which experienced flexural-punching failure, all slabs failed in a brittle mode. Harajli and Soudki [12] reported a similar trend in behavior. However, the difference is that they used externally bonded flexible CFRP laminates as strengthening technique. Flexural cracks initiated on the tension side of the samples shortly after loading, starting as fine cracks from the center of the examined slabs. The number of cracks, their width, and propagation increased with the rise of the amount of the applied load. As the load was continuously increasing, diagonal cracks appeared from or nearby the corners of the column and extended toward the edges and corners of slabs.
Depending on the provided area of CFRP patches, these diagonal cracks were fully or partially linked together, causing the specimens to fail in either pure punching or flexural punching modes. Finally, it has been noticed that providing internal CFRP patches has helped in delaying the onset of these cracks, as shown in Table 3. This can be attributed to the contribution of these patches in sharing and redistributing the stresses and strains from the central column region.

3.2 Load-Deflection Response and Ultimate Capacity

The load-deflection behavior of slabs involved a stiff pre-cracked phase succeeded by a linearly elastic stage up until punching failure suddenly took place, leading to a sharp reduction in the load resistance. For the specimens that failed in combined flexural-punching (i.e., CS & SFP-60), the post-cracking phase was succeeded by a yield plateau until the combined failure has occurred. The strengthened specimens had higher punching shear strength in comparison to the control specimen, with an increasing rate ranging from 15 to 45%. Upon comparing the load-deflection of all slabs shown in figure 3 with the ultimate resistance of shown in table 3 it can be seen that providing CFRP patches has increased crack strength, flexural stiffness and led to a significant increase in the ultimate shear strength of the slabs. This improvement in the strength relied on the provided area of the strengthening patches. Since the provided CFRP patches cannot resist transverse loads, the observed enhancement in the ultimate capacity of the strengthened slabs can be attributed to the presence of CFRP patches. These patches have improved the flexural tensile capacity of the slabs and restricted the growth shear and tensile cracks. This increase in the flexural tensile strength has not only increased the punching shear strength but also led to changing the mode of failure from combined flexural-punching to pure punching.

Figure 3. Load-deflection curve of the test specimens
3.3 Stiffness Characteristics and Deflection Profile

Table 3 shows the stiffness values of the examined specimen. Pre-cracked and post-cracked stiffnesses are taken as the slope of load-deflection curves. The stiffness values of all slabs at the pre-cracking stage are higher than those in the post-cracking stage. The initial (pre-cracking) stiffness's of the strengthened specimens were 11 to 33% of the control specimen, relying on the area of the CFRP patches. At any loading level, the control specimen has experienced the highest deflection in comparison with the strengthened specimens. This reduction in the deflection values is proportional to the area of CFRP patches. Although providing CFRP patches has resulted in increasing the flexural stiffness's of the strengthened specimens, it has slightly reduced their ability to deflect (i.e., their ductility). However, upon comparing the ultimate deflection values of the strengthened slabs with the value of the ultimate deflection of the control sample, it can be deduced that this reduction is minimal. This can be attributed to the light bond between the CFRP and the concrete as a result of the absence of epoxy. This, in turn, has led to more compliant and ductile bond slip behavior.

![Figure 4](image)

**Figure 4.** Tension face crack patterns of specimens at failure load (1=CS, 2=SFP-60, 3=SFP-160, 4=SFP-120)

**Conclusions**
The following conclusions can be drawn from this study:
The strengthened specimens had higher punching shear strength in comparison to the control specimen, with an increasing rate ranging from 15 to 45%.

This increase in the ultimate punching shear is proportional to the CFRP patches.

All strengthened specimens had a stiffer response in comparison with the control slab, and this increase in stiffness (reduction in ductility) is proportional to the area of CFRP patches.

Installing CFRP sheets inside the concrete panels could provide protection against fire and environmental damages owing to the additional embedment from the concrete cover. However, further research must be carried out regarding this point.

Acknowledgment
The authors gratefully acknowledge Mustansiriyah University /College of Engineering for its support in completing this research.

References
[1] Ghali A, Sargious M A & Huizer A 1974 Vertical pre-stressing of flat plates around columns. Shear in Re-inforced Concrete (SP-42) American Concrete Institute, Detroit, MI, USA pp 905-20
[2] Menétrey P, Brühwiler E 1997 Punching shear strengthening of reinforced concrete: Experimental & analytical investigations Proc., 7th Int. Conf. on Structural Faults and Repair, Vol. 2, pp 451–458
[3] Hassanzadeh G and Sundqvist H 1998 Strengthening of bridge slabs on columns. Nordic Conc. Res., 1 21, pp 25–36
[4] Zhang J W, Teng J G, Wong Y L and Lu Z T 2001 Behavior of two-way RC slabs externally bonded with steel plate J. Struct. Eng. 127 4 pp 390–397
[5] Erki M A and Heffernan P J 1995 Reinforced concrete slabs externally strengthened with fibre reinforced plastics materials. Proc., 2nd Int. Symp. on Non-Metalic FRP Reinforcement for Concrete Structures, L. Taerwe, ed., pp 509–516
[6] Chen C C and Li C Y 2000 Experimental study on the punching shear behaviour of RC slabs. Proc., Int. Workshop on Punching Shear Capacity on RC Slabs, pp 415–422
[7] Ospina C E, Alexander S D B and Cheng J J R 2001 Behaviour of concrete slabs with fibre-reinforced polymer reinforcement Structural Engineering Rep. No. 242, Dept. of Civil and Environmental Engineering, Univ. of Alberta, Alberta, Canada
[8] Binici B 2003 Punching shear strengthening of reinforced concrete slabs using fiber reinforced polymers. PhD dissertation, Department of Civil and Environmental Engineering, University of Texas at Austin, Austin, Texas p 279
[9] Chen C C and Li C Y 2005 Punching shear strength of reinforced concrete slabs strengthened with glass fiber-reinforced polymer laminates. ACI Struct. J., 102(4) pp 535–542
[10] Meisami M H, Mostofinejad D and Nakamura H 2013 Punching shear strengthening of two-way flat slabs using CFRP rods. Compos.Struct. 99 pp 112–122
[11] J L Yu and Y C Wang 2018 Punching shear behavior and design of an innovative connection from Steel Tubular Column to Flat Concrete Slab Journal of Structural Engineering pp 144–9
[12] Harajli M and Soudki K 2003 Shear strengthening of interior slab-column connections using carbon fiber reinforced polymer sheets Journal of composites for construction 7(2) pp 145–153