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Review of Punching Shear Behaviour of Flat Slabs Reinforced with FRP Bars

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Abstract. Using Fibre Reinforced Polymer (FRP) bars to reinforce two-way concrete slabs can extend the service life, reduce maintenance cost and improve-life cycle cost efficiency. FRP reinforcing bars are more environmentally friendly alternatives to traditional reinforcing steel. Shear behaviour of reinforced concrete structural members is a complex phenomenon that relies on the development of internal load-carrying mechanisms, the magnitude and combination of which is still a subject of research. Many building codes and design standards provide design formulas for estimation of punching shear capacity of FRP reinforced flat slabs. Building code formulas take into account the effects of the axial stiffness of main reinforcement bars, the ratio of the perimeter of the critical section to the slab effective depth, and the slab thickness on the punching shear capacity of two-way slabs reinforced with FRP bars or grids. The goal of this paper is to compare experimental data published in the literature to the equations offered by building codes for the estimation of punching shear capacity of concrete flat slabs reinforced with FRP bars. Emphasis in this paper is on two North American codes, namely, ACI 440.1R-15 and CSA S806-12. The experimental data covered in this paper include flat slabs reinforced with GFRP, BFRP, and CFRP bars. Both ACI 440.1R-15 and CSA S806-12 are shown to be in good agreement with test results in terms of predicting the punching shear capacity.

1. Introduction

When the applied load causes negative moment at the appropriate level in flat plate systems the slab, the first crack pattern to form is a roughly circular around the perimeter of the loaded area with radial cracks emanating from the column and tangential cracks forming around the loaded area.

Figure 1 shows a typical crack pattern along with symmetric punching shear failure [1]. Negative moments at column centreline decrease rapidly away from the loaded area, therefore, tangential cracks are concentrated near the loaded area, as shown in Figure 1. Significant load levels are needed for tangential cracks can extend further in the slab.

In flat plate structures, the diagonal tension cracks that develop in the slab near the loaded column area tend to originate near mid-depth, similar to traditional web-shear cracks, rather than flexural-shear cracks [2]. The main variables affecting the punching capacity include concrete strength, slab thickness, column shape and size, reinforcing material, reinforcement pattern (individual bars or grids), flexural reinforcement ratio, and shear reinforcement (if any).

Therefore, it is possible to enhance punching shear capacity in two-way slabs by increasing slab thickness, increasing column dimensions, using drop panels and/or column heads, increasing concrete compressive strength (f_c'), and placing shear reinforcement in the punching-shear zone of the slab. Well-designed punching-shear reinforcement significantly improves the slab behaviour, as it not only increases the punching-shear strength but also the deformation capacity of the slab [3].

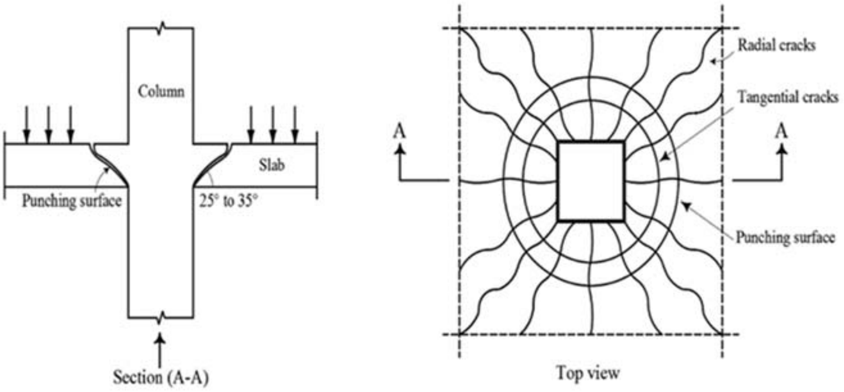

Figure 1: Typical symmetrical punching failure around an interior column [1]

1.1. Experimental studies on punching shear capacity of two-way slabs reinforced with GFRP bars

Several studies examined the punching shear behaviour of two-way flat plates reinforced with GFRP bars. The following section summarizes the results of some of the studies.

Ospina *et al* [4] investigated the punching shear behaviour of four full-scale interior slab-column connections measuring 2150 x 2150 x 155 mm in dimensions reinforced with GFRP bars and grids. All slabs were tested under a concentric load applied to the column stub. This load reacted against eight loading points on the slab, at a distance of 0.9 m from the center of the column stub. The main variables were the reinforcement material (steel or GFRP), the type of reinforcement mat (individual bars or two-dimensional grid), and the slab reinforcement ratio which ranged from 0.73% to 1.46%. Two test specimens were reinforced with GFRP deformed bars, the third specimen was reinforced with a GFRP NEFMAC grid, and the fourth was reinforced with conventional steel bars. Results of this study showed that the punching shear failure in FRP-reinforced specimens is affected by the elastic stiffness of the FRP mat as well as its bond characteristics. Two-way flat slabs reinforced with FRP grids do not provide the same punching-shear capacity as FRP bars due to the difference in bond behaviour and concentration of stresses in the grids where the orthogonal reinforcement intersect.

Hussein *et al.* [5] investigated the punching-shear behaviour of two-way slabs reinforced with GFRP bars. Four isolated interior slab-column connections were tested. The reinforcement ratio of the slabs varied between 0.95% and 1.67%. The slabs dimensions were 1900 mm x 1900 mm and thickness was 150 mm. A concentric load was applied on the slabs through a 250 x 250 mm column stub. The test results revealed that the crack pattern at failure and the strain distribution of the FRP reinforcement were different from those reported in the literature from similar investigations. The cracking along the reinforcement reported by other investigators was not observed in this study and there was no apparent bond failure. The test results revealed that increasing the reinforcement ratio does not increase the connection punching shear capacity significantly.

Nguyen-Minh and Rovnak [6] investigated the punching shear behaviour of concrete two-way slabs reinforced with GFRP bars. A total of six large-scale interior GFRP and steel reinforced slab-column connections were tested. The slab-column connections measured 2200 x 2200 x 150 mm with a column dimension of 200 x 200 mm. Three of the six connections were reinforced with GFRP bars and the remaining three were reinforced with conventional steel bars. The flexural reinforcement ratios varied between 0.4% and 0.8% with no compression reinforcement used in any of the slabs. All slabs simply supported on all four sides were tested under a concentrated load, acting on the column stub in the middle of each slab. The study concluded that increasing GFRP reinforcement ratio resulted in increasing the punching shear strengths up to 36% and deflection was reduced by nearly 35%.

1.2. Experimental studies on flexural capacity of BFRP-reinforced slabs

The environmentally friendly Basalt fiber reinforced polymer (BFRP) bars possess many favourable properties such as the high tensile strength and modulus of elasticity, good chemical resistance, and extended operating temperature range. Limited studies, however, have investigated the performance of concrete structural elements reinforced with BFRP bars. The following section summarizes the findings of some of the studies.

Mahroug *et. al.* [7] studied four continuously-supported and two-simply supported concrete slabs reinforced with BFRP bars. In addition, the investigators tested one continuously supported steel-reinforced concrete slab for comparison purposes. All slabs tested were 500 mm wide and 150 mm deep. The simply supported slabs were 2000 mm in span, whereas the continuous slabs consisted of two equal spans, each of which measured 2000 mm long. Different combinations of BFRP reinforcement at the top and bottom layers of slabs were investigated. The continuously supported BFRP-reinforced concrete slabs exhibited larger deflections and wider cracks at failure, compared to the counterparts reinforced with steel bars. Over-reinforced BFRP reinforced concrete slabs at the top and bottom layers showed the highest load capacity and the least deflection of all of the slabs reinforced with BFRP bars. All continuous BFRP reinforced concrete slabs failed due to combined shear and flexure at the middle support region. ISIS-M03-07 and CSA S806-06 [16] design guidelines reasonably predicted the deflection of the tested BFRP slabs. However, ACI 440-1R-06 underestimated the BFRP slab deflections and overestimated the moment capacities at mid-span and over support sections.

Akiel *et. al.*[8] tested a total of six continuous concrete slabs, 200 x 500 x 5000 mm each, internally-reinforced with BFRP bars. The main variables were the BFRP reinforcement ratio in the sagging region ($2.5\rho_{fb}$ and $0.8\rho_{fb}$), where ρ_{fb} is the BFRP balanced reinforcement ratio, and the hogging-to-sagging BFRP reinforcement ratio (0.5, 0.72, and 1). The flexural response of the slabs with the BFRP rupture mode of failure was more sensitive to the hogging-to-sagging BFRP reinforcement ratio than that of the slabs with the concrete crushing mode of failure. For the slabs with the concrete crushing mode of failure, doubling the hogging-to-sagging BFRP reinforcement ratio resulted in approximately 18% and 10% increases in the load capacity and ultimate deflection, respectively. For the slabs with the BFRP rupture mode of failure, doubling the hogging-to-sagging BFRP reinforcement ratio resulted in approximately 34% and 33% increases in the load capacity and ultimate deflection, respectively.

Elgabbas *et.al.*[9] investigated the behaviour of edge-restrained concrete bridge-deck slabs reinforced with BFRP bars. The tests included six full-scale edge-restrained concrete deck slabs simulating a slab-on-girder bridge deck and one full-scale unrestrained concrete deck slab. The deck slabs measured 3,000 mm long × 2,500 mm wide × 200 mm thick. The test parameters included reinforcement type (BFRP and steel), BFRP bar size (12 and 16 mm), reinforcement ratio in each direction (0.4–1.2%), and edge-restraining effects. The slabs were tested up to failure over a center-to-center span of 2,000 mm under a single concentrated load applied at the center of each slab over a contact area of 600 × 250 mm to simulate the footprint of a sustained truck wheel load as specified in Canadian standards. The observed mode of failure for the edge-restrained deck slabs was punching-shear, with carrying capacities exceeding the design-factored load specified by Canadian standards.

1.3. Experimental and analytical studies on punching shear capacity of flat slabs reinforced with CFRP and GFRP bars.

El-Ghandour *et al.*[10] investigated the punching shear behaviour of GFRP reinforced two-way slabs with and without GFRP shear reinforcement . The investigators conducted a two-phase experimental program to test eight 2.0 m x 2.0 m square simply supported specimens. All specimens were 175 mm thick with a 200x200 mm square column. All specimens were tested using a concentrated load at the center of the slabs. The first phase consisted of testing four specimens. Two slabs were reinforced with GFRP bars (ρ =0.18%) and two were reinforced with CFRP bars (ρ = 0.15%). In the second phase, the flexural reinforcement ratio was increased to 0.38%. In the first phase, the specimens had rather low reinforcement ratio and wide spacing between the reinforcement bars and consequently failed due to bond slip of the flexural bars at loads less than their expected flexural and punching shear capacities.

Esfahani *et al.* [11] studied the punching shear strength of flat slabs strengthened using CFRP sheets located at the tension side of the slabs. They found that the punching shear strength of slabs could be increased by using of CFRP sheets, in addition to steel reinforcing bars, as flexural reinforcement.

Metwally [12] evaluated the punching shear strength of reinforced concrete flat slabs reinforced with different types of FRP bars. The experimental punching shear strengths were compared with the available theoretical predictions and a number of existing models. The author proposed two approaches for predicting the punching shear strength of FRP-reinforced slabs.
Mohamed [13] discussed the vulnerability of flat slab structures to progressive collapse and the effect of enhanced punching shear capacity on mitigating the collapse of flat slab structures. The influence of vertical and horizontal tie systems on arresting collapse mechanism in flat slab structures was emphasized.

2. Punching strength capacity equations of concrete members reinforced with FRP bars

There is a multitude of punching-shear provisions in the design codes for steel-reinforced concrete members. However, limited information is available in the literature or building codes on shear capacity of FRP-reinforced concrete slabs. The following equations were proposes in the literature and certain building codes.

El-Ghandour *et al.* [10]:

$$Vc = 0.79\left[100\rho_f\left(E_f/E_s\right)\cdot\left(0.0045/\varepsilon_y\right)\right]^{1/3}\left(f_{cu}/25\right)^{1/3}\left(400/d\right)^{1/4} b_o d \tag{1}$$

Ospina *et al.*[4]:

$$Vc = 2.77\left(\rho_f f_c'\right)^{1/3}\sqrt{\frac{E_f}{E_s}}\, b_o d \tag{2}$$

El-Gamal *et al.* [14]:

$$Vc = 0.33\sqrt{f_c'}\, b_o d\alpha \tag{3}$$

$$\alpha = 0.5\left(\rho_f E_f\right)^{1/3}\left(1 + 8d/b_o\right) \quad , \; E_f \; in \; GPa \tag{4}$$

ACI 440.1R-15 [15]:

$$Vc = \frac{4}{5}\sqrt{f_c'}\, b_o k d \tag{5}$$

$$k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f \tag{6}$$

$$\text{Where } n_f = E_f/E_c \quad ; \quad E_c = 4750\sqrt{f_c'} \tag{7}$$

Canadian Building Cod CAN/CSA S806-12 [16]:

The punching shear capacity is the least of the following equations:

$$V_c = 0.028\lambda\phi_c\left(1 + \frac{2}{\beta_c}\right)\left(E_f\rho_f f_c'\right)^{1/3}\; b_o d \tag{8}$$

$$V_c = 0.147\lambda\phi_c\left(\frac{\alpha_s d}{b_o} + 0.19\right)\left(E_f\rho_f f_c'\right)^{1/3}\; b_o d \tag{9}$$

$$V_c = 0.056\lambda\phi_c\left(E_f\rho_f f_c'\right)^{1/3}\; b_o d \tag{10}$$

where,

f_c' = the specified concrete compressive strength.
b_o = the perimeter of the critical section at a distance of d/2 from the concentrated load.
d = the distance from extreme compression fibre to the centroid of the tension reinforcement.
λ = factor accounting for concrete unit weight.
α_s = a factor that adjusts V_c for support location.
β_c = the ratio of the long side to short side of the concentrated load or reaction area.

In the following section of the paper, test results available in the literature are compared to punching shear capacity formulas in North American codes including ACI 440.1R-15 [15] and CSA S806-12 [16].

3. Comparison of experimental results and punching shear capacity in building codes

Table 1 shows a comparison between experimental punching shear capacity (V_{test}) and code-predicted (V_{pred}) punching-shear capacity for slabs reinforced with FRP bars.

Table 1. Comparison of experimental and predicted results for FRP-reinforced slabs

Reference	Specimen		V_{test}	V_{test} / V_{pred}	
				ACI 440.1R-15	CAN/CSA S806-12
Hassan *et al.*[17&18]	G(0.7)30/20	GFRP	329	2.08	1.11
	G(1.6)30/20	GFRP	431	1.90	1.11
	G(1.6)30/20-H	GFRP	547	1.98	1.15
	G(1.2)30/20	GFRP	438	1.91	1.12
	G(0.3)30/35	GFRP	825	2.59	1.25
	G(0.7)30/35	GFRP	1071	2.30	1.22
	G(1.6)30/35	GFRP	1492	2.12	1.26
	G(0.7)30/35-H	GFRP	1600	2.00	1.16
	G(0.7)30/20-B	GFRP	386	2.36	1.25
	G(1.6)45/20-B	GFRP	400	1.74	0.92
	G(1.6)45/20	GFRP	511	1.67	0.97
	G(0.3)30/35-B	GFRP	781	2.37	1.13
	G(0.7)30/35-B-2	GFRP	1195	2.45	1.29
	G(0.3)45/35	GFRP	911	2.08	0.98
	G(1.6)30/20-B	GFRP	451	2.09	1.23
	G(1.6)45/20	GFRP	504	1.74	1.02
	G(0.7)30/35-B-1	GFRP	1027	2.38	1.29
	G(0.3)45/35-B	GFRP	1020	2.59	1.26
	G(0.7)45/35	GFRP	1248	2.30	1.24
Mean				2.16	1.17
S.D.				0.27	0.10
COV(%)				12.5	8.8
Elgabbas *et al.* [9]	S2-B	BFRP	548.3	1.53	0.92
	S3-B	BFRP	664.6	1.86	1.13
	S4-B	BFRP	565.9	1.64	1.00
	S5-B	BFRP	716.4	1.67	1.06
	S6-B	BFRP	575.8	2.23	1.22
	S7-B	BFRP	436.4	1.69	0.93
Mean				1.77	1.04
S.D.				0.25	0.12
COV(%)				14.1	11.3
El-Ghandour *et al.* [10]	SC1	CFRP	229	2.23	0.93
	SC2	CFRP	317	2.15	1.12
El-Gamal *et al.* [14]	C-S1	CFRP	674	2.08	1.02
	C-S2	CFRP	799	1.87	1.02
Zaghloul A. [19]	ZJF5	CFRP	234	1.38	0.91
Bouguerra *et al.* [20]	c175n	CFRP	530	2.01	1.09
Mean				1.95	1.02
S.D.				0.31	0.08
COV(%)				15.7	8.2

Average value of V_{test} / V_{pred} closer to 1.0 is an indication of accurate prediction while ratios significantly higher than 1.0 indicate some level of conservativeness. Average value of V_{test} / V_{pred} below 1.0 show that the code expression overestimates the shear capacity of the slab and therefore, unsafe. CSA S806-12[16] equation yielded safe predictions of punching shear capacity with average V_{test} / V_{pred} of 1.17, 1.04, and 1.02 for slabs reinforced with GFRP, BFRP, and CFRP bars, respectively.

The corresponding coefficients of variation (COV) were 8.8%, 11.3% and 8.2%, for GFRP, BFRP, and CFRP, respectively. ACI 440.1R-15 [15] showed very conservative predictions with average V_{test} / V_{pred} of 2.16, 1.77, and 1.95 for slabs reinforced with GFRP, BFRP, and CFRP bars, respectively. The corresponding COVs were 12.5%, 14.1% and 15.7%, for GFRP, BFRP, and CFRP respectively.

4. Conclusions

Significant interest is developing on reinforcing concrete slabs with FRP bars instead of conventional steel due to desirable engineering properties, especially in harsh environments that may affect reinforcing bars. Concrete slabs use the largest number of reinforcing bars in a typical building structure; therefore, replacing conventional steel with FRP bars offers significant reduction in environmental footprint. Punching shear is a critical failure mode in flat slab floor systems; therefore, it is important to understand the punching shear behaviour of flat slabs reinforced with FRP bars. This study compares punching shear capacity data available in the literature to punching shear capacities in two building codes, namely, ACI 440.1R-15 [15] and CAN/CSA S806-12 [16]. Experimental data reviewed in this paper show that the equation proposed by CAN/CSA S806-12 [16] is a reliable predictor of the punching shear capacity of concrete flat slabs reinforced with various types of FRP bars. ACI 440.1R-15 [15] equation showed very conservative predictions with average V_{test}/V_{pred} ranging from 1.77 to 2.16.

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