Punching Shear Model for Normal and High-Strength Concrete Slabs Reinforced with CFRP or Steel Bars

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ABSTRACT

In this study, the punching shear behavior of concrete slabs reinforced with single or double layer of steel or CFRP bars has been investigated. Ten slabs with different parameters have been studied. The parameters of the specimens were: the shape of the columns (circular and square), the type of internal reinforcement (steel or CFRP bars) and the reinforcement ratio. The concrete compressive strength of the slabs ranged from 45 MPa to 60 MPa. Specimens were tested on simply supported edges on four sides with load applied on column at the center of the slab. The results obtained indicate that the compressive strength of concrete, as well as ratio and type of internal reinforcement affect the punching shear capacity of the slab. Finite element modeling (FEM) analysis for the tested specimens was carried out using the commercial finite element program ABAQUS. The results of FEM were in reasonable agreement with experimental ones. Based on the experimental results, previous studies and FEM results, a punching shear formula was presented to estimate the ultimate punching shear of such concrete slab. This new formula is taking into account the type and ratio of internal reinforcement, the shape of the column and the compressive strength of concrete. The average values of ratios between the proposed formula and current and previous experimental results were 1.04 and 0.95, respectively.

KEYWORDS: Punching shear equation, Concrete slab with CFRP bars, Punching shear of high-strength concrete slab, ABAQUS analysis of slab.

INTRODUCTION

Concrete slabs/plates on columns or flat slabs are commonly used in various structures around the world. Understanding these concrete components is very substantial for structural engineers. One of the famous failure modes of flat slabs is punching shear failure. Punching shear is a brittle failure which occurs suddenly without any warnings. There are many factors in the plates and columns that control the punching shear strength, such as slab's thickness, column dimensions, reinforcements and concrete compressive strength. Carbon fiber-reinforced polymer (CFRP) materials have been used as main reinforcement for many concrete components in many different shapes and types. The main benefits of using CFRP materials are their light weight, high strength and being non-corroded materials. Many studies have implemented CFRP materials as a strengthening reinforcement for punching shear (Soudki

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et al., 2012; Chen and Li, 2005; Esfahani et al., 2009). However, in this study, 6-mm diameter CFRP rods were used as main internal reinforcement for slabs. In most of the specimens in the literature, columns were attached to the slabs from one side, which is correct only for roofs, but not for floors (Esfahani et al., 2009). In this research, columns were attached to the slabs from both sides to simulate the condition of the floor system. This range covered most of the existing reinforced concrete components. However, high concrete compressive strength nowadays is widely used in reinforced concrete structures. In this study, a high concrete compressive strength ranging from 46 MPa to 60 MPa was used to investigate its effect on the punching shear strength. Since the test is for punching shear behavior, most of the specimens were tested on four simply supported edges with the load applied through the central column. As stated previously, there are many factors in the plates and columns that control the punching shear strength. Therefore, most of the factors mentioned were investigated in this research, including the shape of the column (circular and square), the type of internal reinforcement (steel or CFRP bars), single and double layers of reinforcement and the reinforcement ratio.

Load deflection curves of the tested specimens were compared with the corresponding ones obtained from modeling the specimens on the commercial finite element analysis program ABAQUS. Many studies have proposed equations to estimate the punching shear value for flat slabs (El-Gamal et al., 2005; Hassan et al., 2014; Ammash et al., 2012; AlKroosh and Ammash, 2015). However, the proposed equations were limited to specific parameters. In this study, an equation was introduced to calculate the punching shear value considering all the mentioned parameters. The results of the proposed equation show a good agreement with those obtained from the current experimental work and previous studies.

Research Significance

The main objective of this research is to investigate and suggest a new model for punching shear of concrete slabs reinforced with steel or CFRP bars by implementing many factors of slabs and columns. A formula for estimating the punching shear value is presented, so that the predicted value of punching shear at failure can be well understood and simulated. This research contributes to providing more knowledge regarding punching shear failure, so that engineers can judge and demonstrate the design of such slabs.

Experimental Procedure

In the current research, ten reinforced concrete slabs were designed and fabricated to investigate the punching shear behavior of concrete slabs. All slab specimens have dimensions of 600*600 mm with square and circular columns. Square columns have dimensions of 100*100 mm, while circular columns have a diameter of 100 mm. Also, all columns were reinforced with 4ø10 mm rebar as longitudinal reinforcement and ø 6 mm rebar @ 100mm c/c as stirrup reinforcement. Geometry and details of the specimens are shown in Table 1 and Fig. (1).

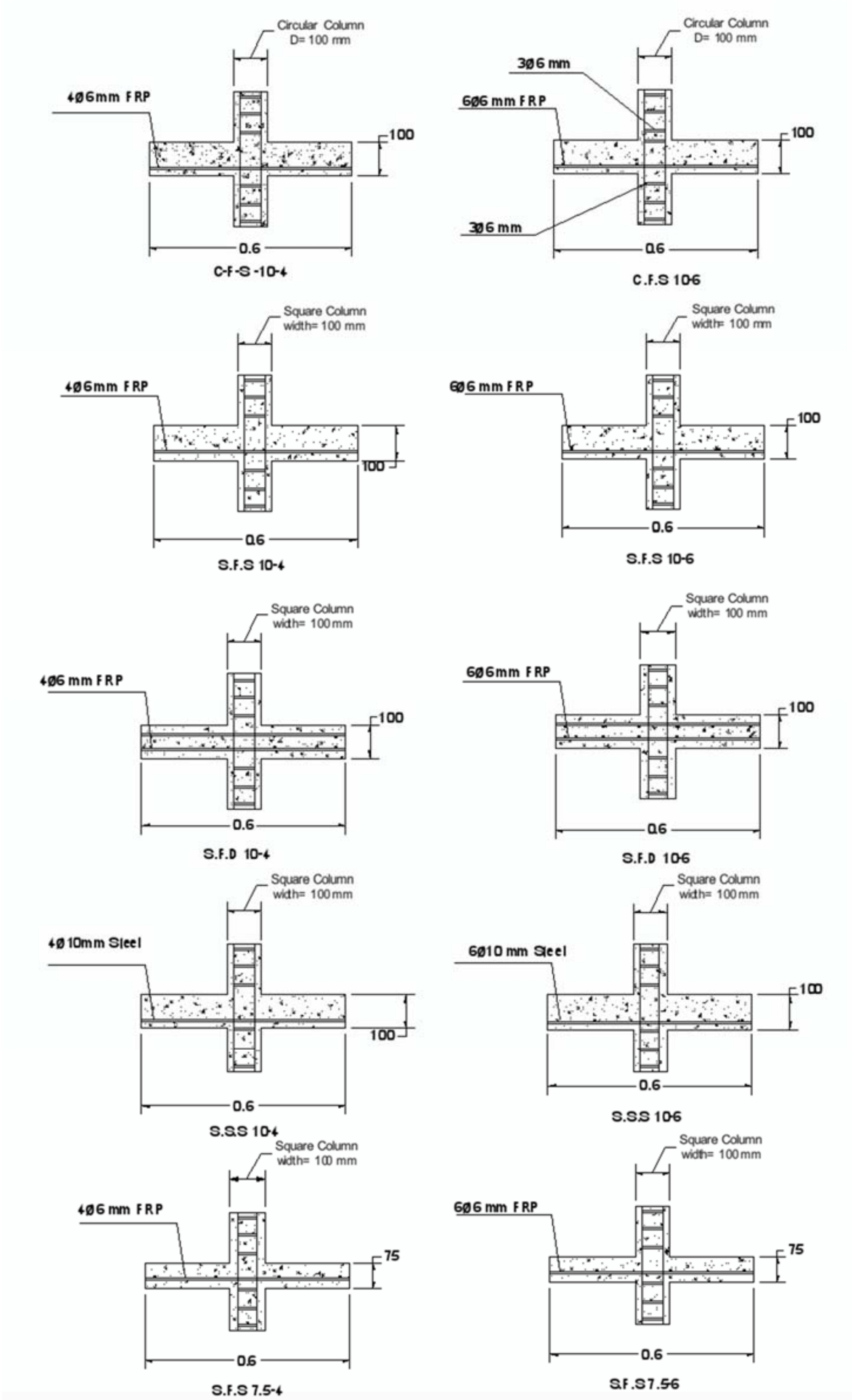

Figure (1): Geometry and details of the tested specimens

Table 1. Specimen properties and details

Specimen's Label	f_c' (MPa)	Reinforcement Type	Single/ Double Layer	Column Shape	Slab Thickness (mm)	Reinforcement Ratio (ρ)%
C-F-S-10-4	51	CFRP	Single	circular	100	0.3
C-F-S-10-6	52	CFRP	Single	circular	100	0.45
S-F-D-10-4	46	CFRP	Double	Square	100	0.6
S-F-D-10-6	60	CFRP	Double	Square	100	0.9
S-F-S-10-4	52	CFRP	Single	Square	100	0.3
S-F-S-10-6	48	CFRP	Single	Square	100	0.45
S-F-S-7.5-4	49	CFRP	Single	Square	75	0.41
S-F-S-7.5-6	49	CFRP	Single	Square	75	0.61
S-S-S-10-4	46	Steel	Single	Square	100	0.75
S-S-S-10-6	50	Steel	Single	Square	100	1.13

Materials

The materials used in this project were concrete, steel and CFRP bars. All materials were tested according to American Society for Testing and Materials (ASTM) in the laboratory at the University of Al-Qadisiyah, College of Engineering. A compressive strength of concrete at more than 45 MPa was selected for all specimens. Some concrete additives were used to gain the required compressive strength.

Table 2. Concrete mix proportions

Component	Sand kg/m^3	Gravel kg/m^3	Cement kg/m^3	Water l/m^3	SBR l/m^3	Silica Fume kg/m^3	Glenium l/m^3
Quantity	650	1050	430	162	8.0	35	4.6

The trend of the tensile stress-strain relationship of 6-mm diameter CFRP is elastic until failure. This trend was reported by the manufacturer and pointed out by the ASTM test. Therefore, a yield stress of 2413 and modulus of elasticity of 144 GPa will be used for the analysis and design of the specimens that contain the CFRP bars. Steel bars of 10-mm diameter were used as flexural reinforcement for some specimens. The tensile strength and modulus of elasticity were obtained by testing 40-cm specimens according to ASTM A615 (1987). The mechanical properties of both steel and CFRP bars used in the current study are shown in Table 3.

Table 3. Mechanical properties of steel and CFRP bars

Material	Modulus of Elasticity E (MPa)	F_y (MPa)	F_u (MPa)	Ultimate Strain
Steel	200	450	690	0.05
CFRP	144	2413	2413	0.018

Instruments and Procedure

Specimens were tested on simply supported edges on four sides with load applied on the column at the middle of the slab by using a 500 kN hydraulic cylinder connected to an electrical pump as shown in Fig.2. The displacement of the slabs was captured by using a dial gage that was placed under the bottom side of the column. The specimens were tested under a monotonically increasing load until failure. The crack paths were observed and marked at specific load stages.

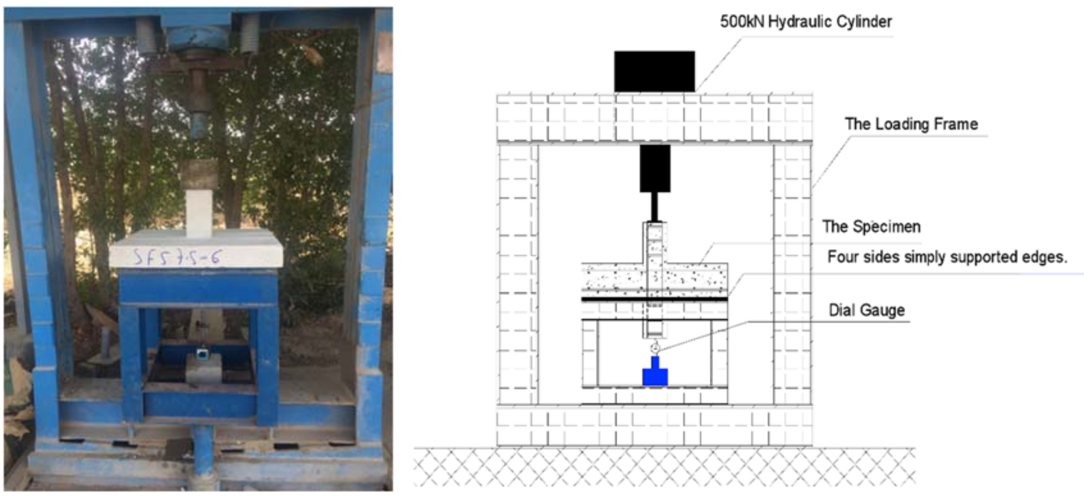

Figure (2): Test setup of the specimens in hydraulic machine

Experimental Results

The central deflection under the middle column of each tested specimen was recorded and the values are plotted against different load stages as shown in Fig.3. Crack and failure patterns were also marked.

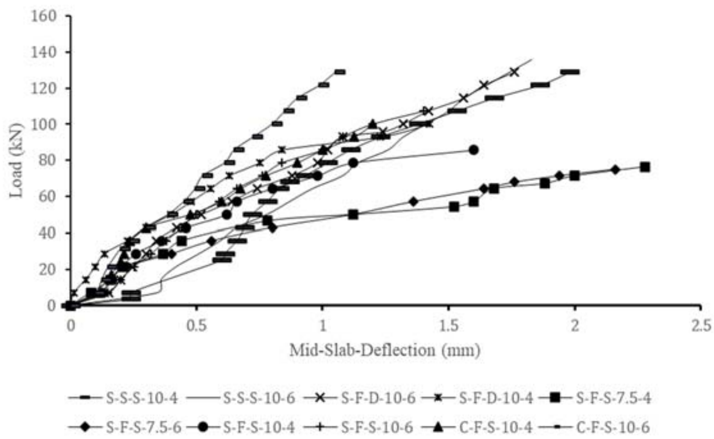

Figure (3): Load-central deflection curves for tested specimens

In general, all specimens had punching shear failure as expected, where the cracks initiated in the vicinity of the column and gradually extended toward the supports (Hassan et al., 2013). Fig. 4 explains the failure modes for all the slabs. Since samples S-S-S-10-4 and S-S-S-10-6 have higher steel internal reinforcement than the other samples, their load -deflection curves seem to be stiffer. This observation was also reported by Nguyen et al. (2012). On the other hand, specimens S-F-S-7.5-4 and S-F-S-7.5-6 had lesser capacity and stiffness than the other specimens due to the slab thickness of 7.5 cm which is less than the thickness of the other slabs. It can also be observed from the load-deflection curves that specimens with six bars as internal reinforcement had higher overall capacity and were stiffer than specimens with four bars as internal reinforcement. As reported by Hassan et al. (2013) and El-Ghandour et al. (2003), the ratio of internal reinforcement affects the punching shear capacity. The load-deflection curves also indicate that the shape of the column has an effect on the punching shear capacity which is included in the present equation. The load-deflection curves show that double-layer reinforcement gave higher values of punching shear compared with single-layer reinforcement. Finally, specimen S-F-D-10-6 had higher concrete compressive strength which increased the punching shear resistance (Nguyen et al., 2012).

Finite Element Modeling

ABAQUS finite element software was adopted to verify the obtained results. The brick elements were used to model the concrete slab and column as shown in Fig. 5, whereas the steel and CFRP bars were modeled by using the truss elements. The failure mode of all specimens was as expected which is a typical punching shear failure as explained in Fig. 6.

Punching shear results of both experiments and FEM modeling are listed in Table (4). It can be noted that the difference between experimental and finite element load is in the range of (4%-15%). Figure 7 shows the middle slab load-deflection curve comparison between FEM and experimental results for all specimens.

Table 4. Experimental *versus* FEM punching load results

Specimen Label	$f_c^{'}$ (MPa)	Exp. Load (kN)	FEM Load (kN)	Difference (Δ)%
C-F-S-10-4	51	102.96	117.4	14
C-F-S-10-6	52	127.27	139.3	9.4
S-F-D-10-4	46	111.54	119.6	7.2
S-F-D-10-6	60	128.7	144.5	12.2
S-F-S-10-4	52	78.65	90.5	15
S-F-S-10-6	48	107.25	111.6	4
S-F-S-7.5-4	49	57.2	65.4	14.3
S-F-S-7.5-6	49	78.65	84.2	7
S-S-S-10-4	46	121.55	140	15.1
S-S-S-10-6	50	135.85	141.7	4.3

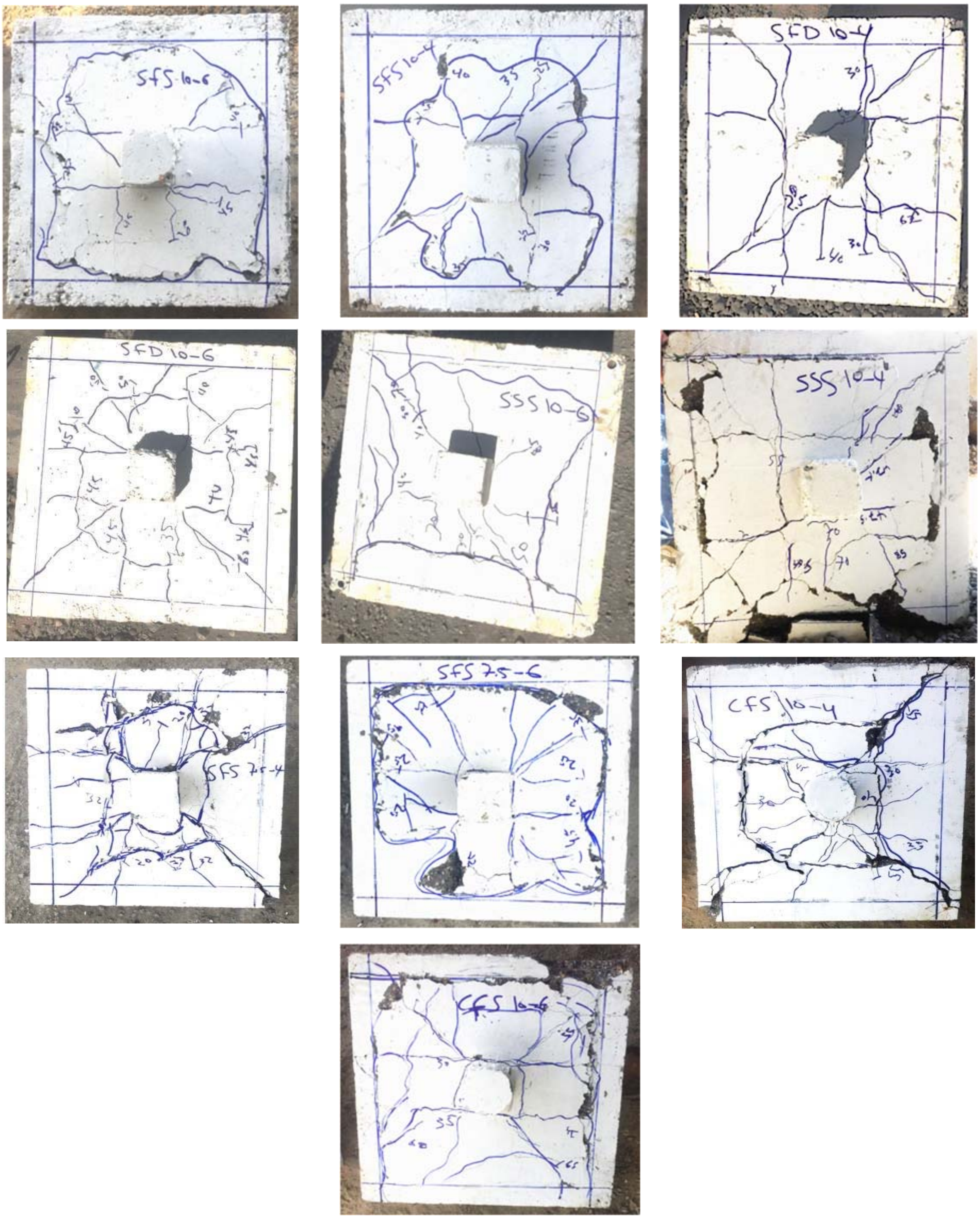

Figure (4): Failure modes of tested specimens

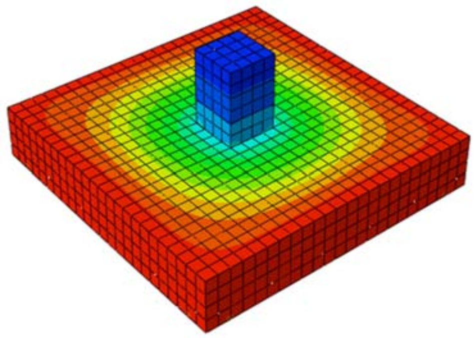

Figure (5): Failure mode of the slab by ABACUS

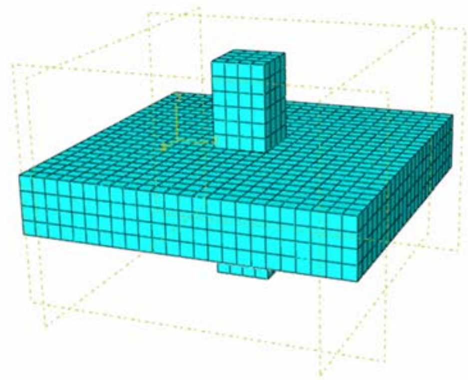

Figure (6): ABACUS modeling of the slab

Proposed Equation

Based on finite element analysis and experimental results of previous studies, a new punching shear equation has been proposed. The proposed equation is based on ACI 318-18 (2014) punching shear equation. However, the new equation takes into account the effects of the reinforcing materials (the modulus of elasticity of steel or CFRP), the reinforcement ratio, the concrete compressive strength and the column shape. The proposed equation is:

$$Vc = (\frac{1}{3}\sqrt{fc'}b_o d)[m](k) \quad (1)$$

The first term of Eq. (1) is the ACI 318-18 punching shear equation. The next term "m" is a modifying factor which takes into account the effects of the concrete compressive strength, the reinforcement ration (p) and the modulus of elasticity as explained in Eq. (2) below.

$$m = \left[\left(\frac{90}{fc'}\right)^{0.33}(5p)^{0.39}\left(\frac{E}{Est}\right)^{0.3}\right] \quad (2)$$

The "k" factor is also a modifying factor for the column's shape which is taken as 0.77 for circular columns and as 0.55 for square or rectangular columns. The proposed formula is a general formula to predict the punching shear capacity of thick and thin slabs reinforced with steel or CFRP as single-or double-layer reinforcement.

The equation above has been verified with the extensive experimental results carried out by many studies (Hassan et al., 2013; Nguyen et al., 2012; El-Ghandour et al., 2003; Lee et al., 2009; ACI, 2014; Zhang et al., 2005; Zaghloul and Razaqpur, 2004; Ospina et al., 2003; Matthys and Taerwe, 2000; Banthia et al., 1995; Ahmad et al., 1994; Hussein et al., 2004). A good agreement was obtained by verifying Eq. (1) with the above-mentioned studies. The resulting comparison of the proposed equation and the experimental studies is shown in Table (5) for circular columns and in Table (6) for rectangular columns. Furthermore, the proposed formula was then verified with obtained experimental results carried out in this study. A very good agreement was obtained as explained in Table (7). Tables (8) and (9) show the comparison of the punching shear values obtained by ACI 440-08, CSA and the proposed formula against the corresponding experimental values reported by the above-mentioned studies. It can be observed that the proposed formula is better in predicting the punching shear values than the ACI440-06 formula (2006) and CSA formula (2012).

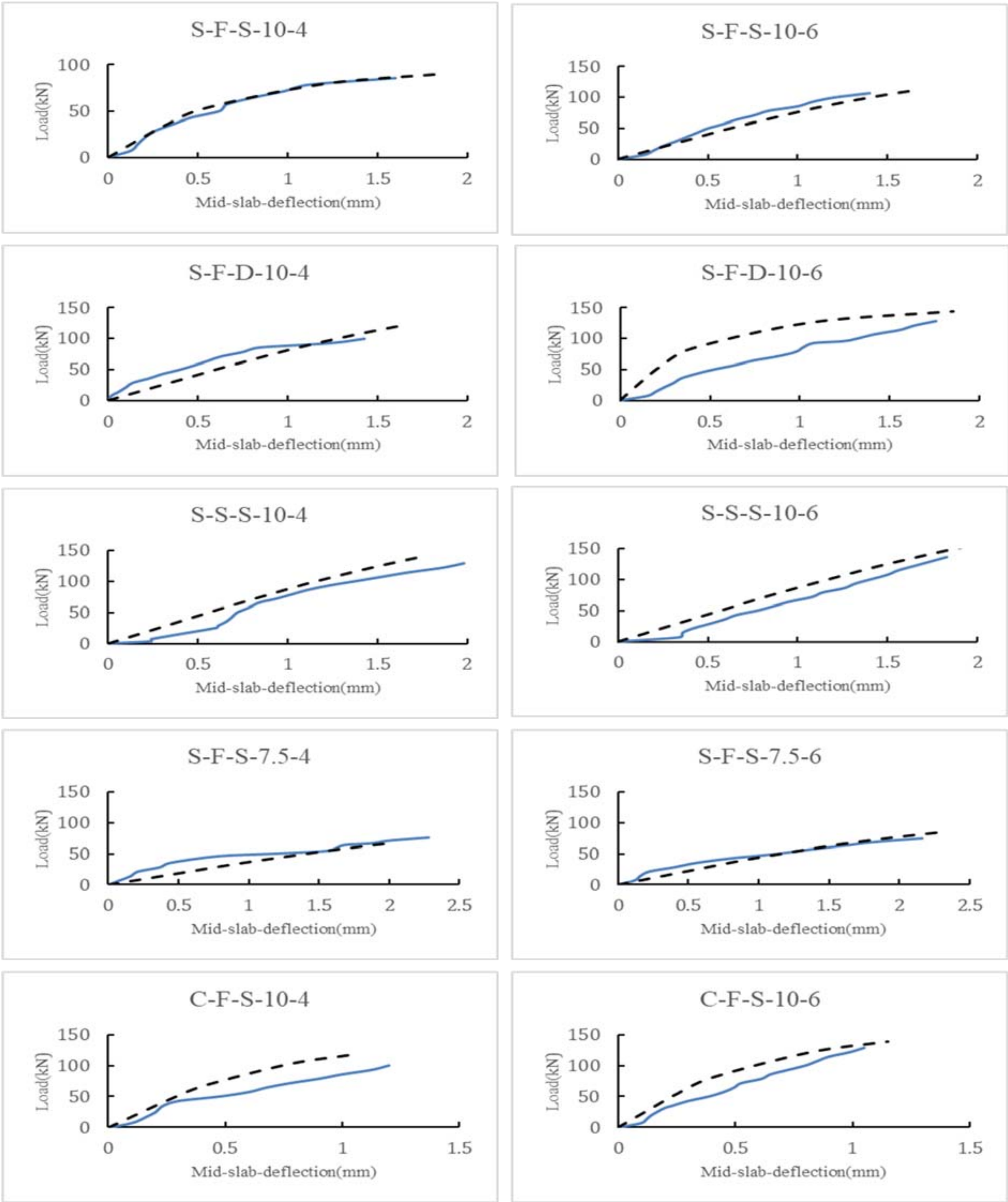

Figure (7): Experimental *versus* FEM load-deflection curves: (-----) FEM, (–) experimental

Table 5. Proposed equation verification for slabs with circular columns

Reference	**Label**	**L mm**	**D mm**	**d mm**	**f_c' MPa**	**ρ%**	**E MPa**	**V. tes. kN**	**V.pro. kN**	**$\frac{v.tes.}{v.pro.}$**
Matthys and Taerwe (2000)	C1	900	150	96	36.7	0.27	91.8	181	138.56	1.31
	C1'	900	230	96	37.3	0.27	91.8	189	184.12	1.03
	C2	900	150	95	35.7	1.05	95	255	234.14	1.09
	C2'	900	230	95	36.3	1.05	95	273	311.46	0.88
	C3	900	150	126	33.8	0.52	92	347	260.52	1.33
	C3'	900	230	126	34.3	0.52	92	343	336.86	1.02
	CS	900	150	95	32.6	0.19	147.6	142	134.49	1.06
	CS'	900	230	95	33.2	0.19	147.6	150	178.94	0.84
	H2	900	150	89	35.8	3.76	40.7	231	274.00	0.84
	H2'	900	80	89	35.9	3.76	40.7	171	193.84	0.88
	H3	900	150	122	32.1	1.22	44.8	237	277.64	0.85
	H3'	900	150	122	32.1	1.22	44.8	217	277.64	0.78
	H1	900	80	95	118	0.62	37.3	207	125.38	1.65
Banthia et al. (1995)	1	500	100	55	41	0.31	100	65	55.19	1.18
	11	500	100	55	52.9	0.31	100	61	57.59	1.06
Ahmad et al. (1993)	CFRC-SN1	590	75	61	42.4	0.95	113	93	86.98	1.07
	CFRC-SN2	590	75	61	44.6	0.95	113	78	87.72	0.89
	CFRC-SN3	590	100	61	39	0.95	113	96	101.55	0.95
	CFRC-SN4	590	100	61	36.6	0.95	113	99	100.5	0.99

Table 6. Proposed equation verification for slabs with square columns

Reference	Label	L mm	C mm	d mm	f_c' MPa	p	E MPa	V. tes. kN	V. pro. kN	$\frac{V. tes.}{V. pro.}$
Hassan et al. (2013)	$G_{(0.7)}$ 30/20	2000	300	134	34.3	0.71	48.2	329	354.3	0.93
	$G_{(1.6)}$ 30/20	2000	300	131	38.6	1.56	48.1	431	477.6	0.90
	$G_{(1.6)}$ 30/20-h	2000	300	131	75.8	1.56	57.4	547	566.5	0.97
	$G_{(1.2)}$ 30/20	2000	300	131	37.5	1.21	64.9	438	474.8	0.92
	$G_{(0.3)}$ 30/35	2000	300	284	34.3	0.34	48.2	825	756.6	1.09
	$G_{(0.7)}$ 30/35	2000	300	284	39.4	0.73	48.1	1071	1044	1.03
	$G_{(1.6)}$ 30/35	2000	300	275	38.2	1.61	56.7	1492	1427	1.05
	$G_{(1.6)}$ 30/35-h	2000	300	275	75.8	1.61	56.7	1600	1600	1.00
	$G_{(0.7)}$ 30/20-b	2000	300	134	38.6	0.71	48.2	386	361.3	1.07
	$G_{(0.7)}$ 45/20	2000	450	134	44.9	0.71	48.2	400	498.6	0.80
	$G_{(1.6)}$ 45/20-b	2000	450	131	39.4	1.56	48.1	511	646.0	0.79
	$G_{(0.3)}$ 30/35-b	2000	300	284	39.4	0.34	48.2	781	774.3	1.01
	$G_{(0.7)}$ 30/35-b2	2000	300	281	46.7	0.73	48.1	1195	1057	1.13
	$G_{(0.3)}$ 45/35	2000	450	284	48.6	0.34	48.2	911	1007	0.90
	$G_{(1.6)}$ 30/20-b	2000	300	131	32.4	1.56	48.1	451	463.8	0.97
	$G_{(1.6)}$ 45/20	2000	450	131	32.4	1.56	48.1	504	625.3	0.81
	$G_{(0.7)}$ 30/35-b-1	2000	300	281	29.6	0.73	48.1	1027	980.4	1.05
	$G_{(0.3)}$ 45/35-b	2000	450	284	32.4	0.34	48.2	1020	942.0	1.08
	$G_{(0.7)}$ 45/35	2000	450	281	29.6	0.73	48.1	1248	1233	1.01
Nguyen -Minh and Rovank (2013)	GSL-PUNC-0.4	2000	200	129	39	0.48	48	180	226 .2	0.80
	GSL-PUNC-0.6	2000	200	129	39	0.68	48	212	259.3	0.82
	GSL-PUNC-0.8	2000	200	129	39	0.92	48	248	292.0	0.85

Lee et al. (2000)	GFU1	2000	225	110	36.3	1.18	48.2	222	276.6	0.80
Zhang et al. (2005)	GS2	1830	250	100	35	1.05	42	218	238.4	0.91
	GSHS	1830	250	100	71	1.18	42	275	280.8	0.98
Zaghloul and Razaqpur (2004)	ZJF5	1500	250	75	44.8	1.33	100	234	252.7	0.93
Hussein et al. (2004)	GS1	1830	250	100	40	1.18	42	249	255.2	0.98
	GS2	1830	250	100	35	1.05	42	218	238.4	0.91
	GS3	1830	250	100	29	1.67	42	240	277.2	0.87
	GS4	1830	250	100	26	0.95	42	210	218.1	0.96
Ospina et al. (2003)	GFR-1	1670	250	120	29.5	0.73	34	199	237.6	0.84
	GFR-2	1670	250	120	28.9	1.46	34	249	310.9	0.80
	NEF-1	1670	250	120	37.5	0.87	28.4	203	249.7	0.81
El-Ghandour et al. (2003)	SG1	1700	200	142	32	0.18	45	170	166.7	1.02
	SC1	1700	200	142	32.8	0.15	110	229	209.3	1.09
	SG2	1700	200	142	46.4	0.38	45	271	237.9	1.14
	SG3	1700	200	142	30.4	0.38	45	237	221.7	1.07
	SC2	1700	200	142	29.6	0.35	110	317	287.0	1.10

Table 7. Proposed equation verification for slabs carried out in this study

Specimen's label	Slab Thickness mm	Depth mm	f_c' MPa	p	E MPa	V. Exp. kN	V. Pro. kN	$\frac{\text{V. Exp.}}{\text{V. pro.}}$
S-F-D-10-4	100	75	46	0.6	144	111.54	113.9	1.02
S-F-D-10-6	100	75	60	0.9	144	128.7	139.6	1.08
S-F-S-10-4	100	75	52	0.3	144	78.65	88.5	1.13
S-F-S-10-6	100	75	48	0.45	144	107.25	102.4	0.96
S-F-S-7.5-4	75	55	49	0.41	144	57.2	53.9	0.94
S-F-S-7.5-6	75	55	55	0.61	144	78.65	64.3	0.82
S-S-S-10-4	100	75	46	0.75	200	121.55	137.2	1.13
S-S-S-10-6	100	75	50	1.13	200	135.85	163.4	1.20
C-F-S-10-4	100	75	51	0.3	144	102.96	97.0	0.94
C-F-S-10-6	100	75	52	0.45	144	127.27	114.1	0.90
Average								**1.012**

The average values of proposed to tested value ratio were about 1.02 and 0.995 according to data from both present and previous studies, respectively, which are very reasonable compared to the same values obtained based on ACI and CSA provisions which turned out to be about 2.1 and 1.13, respectively, for slabs with rectangular columns and 2.35 and 1.35 for slabs with circular columns. It is obvious that the CSA provision overestimates the punching shear capacity of slabs reinforced with CFRP bars. On the other hand, the ACI provision reasonably estimates the punching shear capacity of slabs reinforced with CFRP bars.

Table 8. Proposed equation comparison against ACI and CSA for slabs that have square columns

Reference	Label	V. tes. kN	V. pro. kN	V. tes. / V. pro.	V. tes. / V.ACI	V. tes. / V.CSA
Hassan et al. (2012)	G (0.7) 30/20	329	354.30	0.93	2.07	1.11
	G (1.6) 30/20	431	477.60	0.90	1.9	1.11
	G (1.6) 30/20-H	547	566.57	0.97	1.84	1.15
	G (1.2) 30/20	438	474.86	0.92	1.91	1.12
	G (0.3) 30/35	825	756.66	1.09	2.58	1.25
	G (0.7) 30/35	1071	1044.6	1.03	2.29	1.22
	G (1.6) 30/35	1492	1427.3	1.05	2.11	1.26
	G (1.6) 30/35-H	1600	1600.0	1.00	1.87	1.16
	G (0.7) 30/20-B	386	361.35	1.07	2.35	1.25
	G (0.7) 45/20	400	498.65	0.80	1.74	0.92
	G(1.6) 45/20-B	511	646.03	0.79	1.66	0.97
	G (0.3) 30/35-B	781	774.35	1.01	2.36	1.13
	G (0.7) 30/35-B-2	1195	1057.90	1.13	2.44	1.29
	G (0.3) 45/35	911	1007.8	0.90	2.07	0.98
	G (1.6) 30/20-B	451	463.86	0.97	2.08	1.23
	G (1.6) 45/20	504	625.30	0.81	1.73	1.02
	G (0.7) 30/35-B-1	1027	980.47	1.05	2.37	1.29
	G (0.3) 45/35-B	1020	942.02	1.08	2.58	1.26
	G (0.7) 45/35	1248	1233.6	1.01	2.29	1.24
Nguyen -Minh and Rovank (2013)	GSL-PUNC-0.4	180	226.20	0.80	1.8	0.91
	GSL-PUNC-0.6	212	259.36	0.82	1.81	0.96
	GSL-PUNC-0.8	248	292.06	0.85	1.84	1.01

Lee et al. (2000)	GFU1	222	276.68	0.80	1.72	0.98
Zhang et al. (2005)	GS2	218	238.41	0.91	2.02	1.12
	GSHS	275	280.83	0.98	1.99	1.13
Zaghloul and Razaqpur (2004)	ZJF5	234	252.77	0.93	1.78	1.1
Hussein et al. (2004)	GS1	249	255.21	0.98	2.11	1.17
	GS2	218	238.41	0.91	2.02	1.12
	GS3	240	277.25	0.87	1.9	1.12
	GS4	210	218.14	0.96	2.21	1.23
Ospina et al. (2003)	GFR-1	199	237.67	0.84	1.98	1.03
	GFR-2	249	310.98	0.80	1.82	1.03
	NEF-1	203	249.73	0.81	1.9	0.97
El-Ghandour et al. (2003)	SG1	170	166.77	1.02	2.46	1.14
	SC1	229	209.37	1.09	2.61	1.2
	SG2	271	237.95	1.14	2.55	1.25
	SG3	237	221.76	1.07	2.36	1.26
	SC2	317	287.09	1.10	3.2	1.29
Average				**0.95**	**2.1**	**1.13**

Table 9. Proposed equation comparison against ACI and CSA for slabs that have circular columns

Reference	Label	V. tes. kN	V. pro. kN	V. tes. / V. pro.	V. tes. / V. ACI	V. tes. / V. CSA
Matthys and Taerwe (2000)	C1	181	138.56	1.31	2.51	1.64
	C1'	189	184.12	1.03	2.46	1.28
	C2	255	234.14	1.09	1.97	1.49
	C2'	273	311.46	0.88	3.15	1.19
	C3	347	260.52	1.33	2.4	1.76
	C3'	343	336.86	1.02	2.48	1.34
	CS	142	134.49	1.06	1.97	1.3
	CS'	150	178.94	0.84	2.03	1.03
	H2	231	274.00	0.84	2.12	1.28
	H2'	171	193.84	0.88	2.15	1.34
	H3	237	277.64	0.85	2.65	123
	H3'	217	277.64	0.78	2.82	1.65
	H1	207	125.38	1.65	2.79	1.46
Banthia et al. (1995)	1	65	55.19	1.18	2.444	1.26
	11	61	57.59	1.06	2.32	1.4
Ahmad et al. (1993)	CFRC-SN1	93	86.98	1.07	1.92	1.16
	CFRC-SN2	78	87.72	0.89	2.07	1.26
	CFRC-SN3	96	101.55	0.95	2.17	1.32
	CFRC-SN4	99	100.48	0.99	2.2	1.2
Average				**1.04**	**2.35**	**1.35**

CONCLUSIONS

Ten flat slabs were fabricated and tested in this research. Four different factors (column shape, compressive strength, ratio and type of internal reinforcement) were incorporated in the study to investigate the punching shear behavior. Load-deflection curves of middle slab were constructed and compared with ones obtained from FEM analysis. Furthermore, a new punching shear formula was proposed and verified with experimental and previous study results. Based on the results and discussion, the following conclusions can be drawn.

1- The failure mode of all samples reinforced with steel or CFRP bars was typical punching failure.
2- Compressive strength values and thickness of slab have significant effects on ultimate punching strength of slabs with different types of reinforcement.
3- Yield lines due to punching load are affected by shape of columns (circular/ rectangular), which will change the punching capacity of concrete slabs.
4- Presence of steel or CFRP reinforcement in a single layer has an important effect on punching shear strength.
5- Double-layer reinforcement (steel or CFRP) also increases the ultimate punching strength of the slab if compared with single-layer reinforcement.
6- The new proposed model takes into account reinforcement type and ratio, compressive strength of concrete and column shape and predicts the punching shear strength of tested slabs and those of previous studies to be in a very good agreement if compared with experimental results and ACI and CSA code equations.
7- The average difference in the ratios of punching strength predicted by the current study and the experimental one was about 1.04% for slabs with circular column cross-section, while this difference was about 2.35% and 1.35% for ACI and CSA codes, respectively.
8- Also, for slabs with rectangular cross-section, the average difference in the ratios of punching strength predicted by the current study and the experimental one was about 0.95%, while this difference was about 2.35% and 1.35% for ACI and CSA codes, respectively.

REFERENCES

Abdullah, A., C. G. Bailey, and Z. J. Wu. (2013). "Tests investigating the punching shear of a column-slab connection strengthened with non-prestressed or prestressed FRP plates." Construction and Building Materials, 48, 1134-1144.

ACI Committee 440. (2006). “Guide for the design and construction of concrete reinforced with FRP bars (ACI 440.1R-06).” Farmington Hills, MI: American Concrete Institute, 44.

Ahmad, S.H. et al. (1994). "Punching shear tests of slabs reinforced with 3-dimensional carbon fiber fabric." Concrete International, 16 (6), 36-41.

Alkroosh, Iyad, and Hayder Ammash. (2015). "Soft computing for modeling punching shear of reinforced concrete flat slabs." Ain Shams Engineering Journal, 6 (2), 439-448.

Al-Rousan, R., M. Issa, and H. Shabila. (2012). "Performance of reinforced concrete slabs strengthened with different types and configurations of CFRP." Composites-Part B: Engineering, 43 (2), 510-521.

American Concrete Institute. (2014). “ACI 318-18: Building code requirements for structural concrete and commentary.” ACI Manual of Concrete Practice, Farmington Hills, Michigan.

Ammash, Haider K., Muhammad Jawad Kadhim, and Dunya Sahib Ellk. (2012). "A new punching shear equation of normal and high-strength reinforced concrete flat slabs." Journal of Engineering and Development, 16 (4).

ASTM A 615-86. (1987). "Standard specification for deformed and plain billet-steel bars for concrete reinforcement." Annual Book of ASTM Standards, ASTM.

Banthia, N., M. Al-Asaly, and S. Ma. (1995). "Behavior of concrete slabs reinforced with fiber-reinforced plastic grid." Journal of Materials in Civil Engineering, 7 (4), 252-257.

Canadian Standards Association (CSA). (2012). “Design and construction of building structures with fiber-reinforced polymers (CAN/CSA S806-12)”. Rexdale, ON, Canada.

Chen, Cheng-Chih, and Chung-Yan Li. (2005). "Punching shear strength of reinforced concrete slabs strengthened with glass fiber-reinforced polymer laminates." ACI Structural Journal, 102 (4), 535.

El-Gamal, S., E. F. El-Salakawy, and B. Benmokrane. (2005). "A new punching shear equation for two-way concrete slabs reinforced with FRP bars." ACI Special Publication, 230, 877-894.

El-Ghandour, Abdel Wahab, Kypros Pilakoutas, and Peter Waldron. (2003). "Punching shear behavior of fiber-reinforced polymers reinforced concrete flat slabs: experimental study." Journal of Composites for Construction, 7 (3), 258-265.

Esfahani, Mohammad Reza, M. Reza Kianoush, and A.R. Moradi. (2009). "Punching shear strength of interior slab–column connections strengthened with carbon fiber-reinforced polymer sheets." Engineering Structures, 31 (7), 1535-1542.

Hassan, Mohamed, Ehab A. Ahmed, and Brahim Benmokrane. (2014). "Punching-shear design equation for two-way concrete slabs reinforced with FRP bars and stirrups." Construction and Building Materials, 66, 522-532.

Hassan, Mohamed, Ehab Ahmed, and Brahim Benmokrane. (2013). "Punching-shear strength of normal and high-strength two-way concrete slabs reinforced with GFRP bars." Journal of composites for construction, 17 (6), 04013003.

Hussein, Amgad, I. Rashid, and Brahim Benmokrane. (2004). "Two-way concrete slabs reinforced with GFRP bars." In: Proceedings of the 4th International Conference on Advanced Composite Materials in Bridges and Structures, CSCE, Calgary, Alberta, Canada, July.

Lee, Joo-Ha et al. (2009). "Improving punching shear behavior of glass fiber-reinforced polymer-reinforced slabs." ACI Structural Journal, 106 (4), 427.

Matthys, Stijn, and Luc Taerwe. (2000). "Concrete slabs reinforced with FRP grids. II: Punching resistance." Journal of Composites for Construction, 4 (3), 154-161.

Nguyen-Minh, Long, and Marián Rovňák. (2012). "Punching shear resistance of interior GFRP-reinforced slab-column connections." Journal of Composites for Construction, 17 (1), 2-13.

Ospina, Carlos E., Scott, D.B. Alexander, and J.J. Roger Cheng. (2003). "Punching of two-way concrete slabs with fiber-reinforced polymer reinforcing bars or grids." Structural Journal, 100 (5), 589-598.

Soudki, Khaled, Ahmed K. El-Sayed, and Tim Vanzwol. (2012). "Strengthening of concrete slab-column connections using CFRP strips." Journal of King Saud University-Engineering Sciences, 24 (1), 25-33.

Widianto, T.Y. et al. (2006). "Rehabilitation of earthquake-damaged reinforced concrete flat-plate slab-column connections for two-way shear." Proceedings of the 8th US National Conference on Earthquake Engineering.

Zaghloul, A., and A.G. Razaqpur. (2004). "Punching shear strength of concrete flat plates reinforced with CFRP grids." Proceedings of 4th Conference on Advanced Composite Materials in Bridges and Structures, ACMBS-IV, Calgary, Alberta.

Zhang, Q., H. Marzouk, and A. Hussein. (2005). "A preliminary study of high-strength concrete two-way slabs reinforced with GFRP bars." Proceedings of the 33rd CSCE Annual Conference: General Conference and International History Symposium, CSCE, Toronto, Ont., Canada.