Journal of Engineering and Development, Vol. 16, No.4, Dec. 2012 ISSN 1813- 7822

A New Punching Shear Equation of Normal and High Strength Reinforced Concrete Flat Slabs

Dr. Haider K. Ammash
Lecturer
University of Al-Qadisyia
Engineering College
Civil Eng. Dep.
amashhk@gmail

Dr. Muhammad Jawad Kadhim
Lecturer
Babylon University
Engineering College
Civil Eng. Dep.
dr.muhammad.jawad76@gmail

Dunya Sahib Ellk
Assistant Lecturer
Al-Mustansiriyah University
Engineering College
Highway and Transportation
dunia-eng@yahoo

Abstract

The aims of this study is to present a new simple accurate equation to determine the punching shear strength of normal and high strength reinforced concrete flat slabs. The punching shear strength prediction of the proposed equation is compared with the experimental data collected from 58 experimental cases. The proposed equation takes into account some effects such as concrete compressive strength, slab depth, slab tension reinforcement ratio at the critical section, shape and dimension of column, and the position of critical section. The proposed equation gives a better agreement with experimental data than AS3600, CEB-FIP MC-90, ECP, ACI-318, and BS-8110. It is noticed that the tension reinforcement ratio has an effect on the punching shear strength where increasing the tension reinforcement ratio from (0.6%) to (2.2%) increase the strength of punching shear strength by (17%).

Keywords: flat slabs; reinforced concrete; punching shear strength, high strength concrete

اقتراح معادلة جديدة لحساب قص الثقب للبلاطات الخرسانية المستوية عادية وعالية المقاومة

الخلاصة

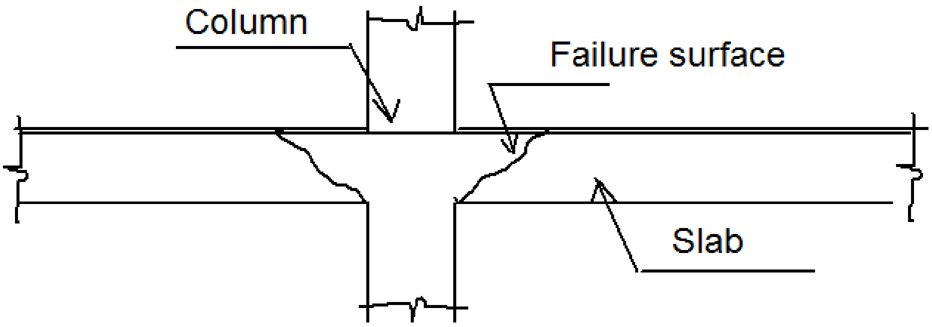
تهدف هذه الدراسة إلى تقديم معادلة جديدة بسيطة ودقيقة لحساب قوة قص الثقب للبلاطات الخرسانية المسطحة عادية وعالية المقاومة. تمت مقارنة النتائج لقوة قص الثقب المحسوبة باستخدام المعادلة المقترحة مع البيانات العملية التي تم جمعها من 58 نتيجة فحص عملي لستة دراسات انجزت من قبل الباحثين Ramdane, Hallgren and Kinnunen, Marzouk and Hussein, Tomaszewicz, Metwally et.al., Abdel Hafez . المعادلة المقترحة اعطت توافق جيد مع النتائج العملية بالمقارنة مع AS3600 , CEB-FIP MC-90, ECP, ACI – 318, and BS – 8110 . المعادلة المقترحة تأخذ بنظر الاعتبار بعض المؤثرات مثل مقاومة الانضغاط للخرسانة، سمك البلاطة، نسبة حديد التسليح في البلاطة عند المقطع الحرج، شكل و ابعاد العمود وكذلك موقع المقطع الحرج نسبة للعمود. يمكن الاستنتاج بأن حديد

التسليح في منطقة الشد يؤثر على مقاومة القص حيث زيادة نسبة حديد تسليح الشد من (0.6%) الى (2.2%) يزيد مقاومة القص بحوالي (17%).

الكلمات الدالة: البلاطات المسطحة، خرسانة مسلحة، مقاومة قص الثقب

Introduction

The reinforced concrete flat slab is an economical and popular structural system. Its framework is very simple. It consists of a two-way slab of a uniform thickness cast monolithically with columns. In flat slabs the load transfer between the slab and the column induces high stresses near to this last that incite to cracking and even failure. The punching shear failure is associated to the formation of a cone-shaped element(3) (see Figure(1)). This shape is a result of the interaction between the shear effects and flexion in a region close to the column. Now, there is a considerable attention to use the high-strength concrete (HSC) technique. Therefore, the study of punching shear phenomena of HSC flat slabs must be done as well as for normal-strength concrete (NSC) flat slabs. **Marzouk** and **Hussein** (1991) tested 17 square specimens to investigate the punching shear behavior of high-strength concrete slabs. The structural behavior with regard to the deformation and strength characteristic of high-strength concrete slabs of various thicknesses and different reinforcement ratios (0.49-2.33%) were studied. **Tomaszewicz** (1993) tested 19 square flat slabs with orthogonal, equally spaced flexural reinforcement and without shear reinforcement. Slabs were supported along the edges and loaded at mid-span by a concentrated load to failure in punching. The variables in the test series were concrete strength (64-112 MPa), slab thickness (120, 240 and 320 mm) and reinforcement ratio. Parameters were chosen such that punching shear failure proceeded flexural failure.



Figure(1): Punching failure surfaces of flat slab(3)

Ramdane (1996) experimented 18 circular slabs of 125 mm thickness and 1700 mm in diameter. They were divided into three groups in terms of main steel ratio with different concrete cylinder strengths varying from 32 to 102 MPa. The slabs were equally reinforced in orthogonal directions and were without shear reinforcement. The punching load was applied upward by a 550 kN hydraulic jack through a thick steel disk with a diameter of 150 mm situated in the center beneath the slab. The reactions were provided by 12 high tensile steel rods equally spaced around a circle with a diameter of 1372 mm. **Hallgren** and **Kinnunen**(1996) tested 10 circular HSC slabs, supported on circular concrete column stubs. The total diameter of the slabs was 2540 mm and the diameter of the circle along which the load was uniformly distributed was 2400 mm. The slabs had a nominal thickness of 240 mm with an effective depth of 200 mm. The compressive strengths of HSC specimens were between 85 and 108 MPa. All slabs were provided with two-way flexural reinforcement consisting of deformed bars with a mean flexural reinforcement ratio of 0.003 to 0.012. Three slabs had shear reinforcement. **Ngo** (2001) compared the results from 4 research studies with AS3600 and CEB-FIP MC 90 codes for punching shear failure of slabs. In AS3600 the punching shear strength was expressed as proportional to $f_c^{1/2}$. However in CEB-FIP MC 90 punching shear strength was assumed to be proportional to $f_c^{1/3}$. It was shown that the provisions in AS3600 were applicable up to 100 MPa. **Taha, et.al.** (2006) presented an alternative approach for predicting the punching shear strength of interior slab-column connections using fuzzy logic (FL). A total of 176 data points were used in the training and testing of the fuzzy system. The model predictions were compared to current strength models most widely used in design practice such as CEB-FIP MC 90, Eurocode 2, and ACI 318 codes. It was found that a significant enhancement in the prediction of the punching shear strength of interior slab-column connections can be achieved by means of the fuzzy system. **Metwally, et.al.** (2008) studied the punching shear strength of normal and high strength reinforced concrete flat slabs**.** The tension steel reinforcement ratio, concrete compressive strength and the slab thickness were investigated by testing a 55 reinforced concrete flat slabs and the results were compared with the ECP-203, ACI-318, and BS-8110 code's provisions.

This paper proposes a new equation to determine the punching shear strength of reinforced concrete flat slabs. The punching shear strength predictions of the proposed equation are compared with the experimental data collected from review, the Egyptian code equation, the ACI Code equation, the British Standard equation, equation of Standards Association of Australia (AS3600), and CEB-FIP code equation.

Methods of Punching Shear Strength

1-The Egyptian Code of Practice (ECP-203)

The critical perimeter is located at 0.5***d*** away from the column face, and v_c is the smallest of the following:

$$v_c = 0.8\left[\frac{\alpha d}{b_o}\right]\sqrt{\frac{f_{cu}}{\gamma_c}} \qquad (\text{N/mm}^2) \qquad (1)$$

$$v_c = 0.316\left[0.5 + \frac{a}{b}\right]\sqrt{\frac{f_{cu}}{\gamma_c}} \qquad (\text{N/mm}^2) \qquad (2)$$

$$v_c = 0.316\sqrt{\frac{f_{cu}}{\gamma_c}} \qquad (\text{N/mm}^2) \qquad (3)$$

In which $\alpha = 0.4$ for interior column, ***a***/***b***=1, for circular column, and $\gamma_c = 1.0$ (material safety factor). In calculation, the code limit for concrete strength is ignored.

2-The American Building Code (ACI- 318)

The critical perimeter is assumed at **0.5*d*** from the perimeter of the loaded area, and v_c is the smallest of the following:

$$v_c = 1/6\left[1 + \frac{2}{\beta_c}\right]\sqrt{f'_c} \qquad (\text{N/mm}^2) \qquad (4)$$

$$v_c = 1/12\left[\frac{\alpha_s d}{b_o} + 2\right]\sqrt{f'_c} \qquad (\text{N/mm}^2) \qquad (5)$$

$$v_c = 1/3\sqrt{f'_c} \qquad (\text{N/mm}^2) \qquad (6)$$

where β_c =long side/short side of the column and should be taken greater than or equal to $2\ (\beta_c \geq 2)$.

f'_c= concrete cylinder compressive strength = 0.85f_{cu} for cube strength.

α_s = 40 for interior columns.

The requirement of the ACI code that f'_c is not exceed 68MPa was disregarded in computations.

3-The British Standard (BS – 811)

The critical section was adopted by the British Standard at 1.5d from the column face, and v_c was calculated as follow:

$$v_c = 0.79(100\rho)^{1/3}\left(\frac{400}{d}\right)^{1/4}\left(\frac{f_{cu}}{25}\right)^{1/3} \qquad (\text{N/mm}^2) \qquad (7)$$

Where:

ρ is the effective flexural reinforcement ratio for the critical section.

$f_{cu} \leq 40$ MPa, $\rho \leq 3\%$ and $400/d \geq 1$.

4- Concrete Structures Standard. Standards Association of Australia, 1994 (AS3600):

In AS3600 (Cl. 9.2.3) the punching shear strength is expressed as proportional to $\sqrt{f_c'}$. f'_c is limited to 50 MPa in this code. The square-root formula in AS3600 is adopted from the ACI code. ACI provisions for punching shear are derived from Moe's work on low strength concrete. The ultimate shear strength for slabs without prestress is given by $V_{uo} = ud\,(f_{cv})$.

where:

u= length of the critical perimeter, taken at a distance of ***d*/2** from the column (mm).

f_{cv} = punching shear strength (MPa).

$$f_{cv} = 0.17\left(1+\frac{2}{\beta_c}\right)\sqrt{f_c'} \le 0.34\sqrt{f_c'} \qquad (\text{N/mm}^2) \qquad \textbf{(8)}$$

β_c= ratio of longest column dimension to shorter column dimension.

5-CEB-FIP Model Code 1990:

In this study, CEB-FIP MC-90 model code is also considered for comparison. In MC-90 the punching shear resistance, F_{sd} is expressed as proportional to $(f_{ck})^{\frac{1}{3}}$, Where f_{ck} is the characteristic compressive strength of concrete. The highest concrete grade considered in MC90 is C80, which corresponds to f_{ck} equal to 80 MPa. Influences of reinforcement and slab depth are also considered in this design code.

$$F_{sd} = 0.12\,\xi(100\,\rho f_{ck})^{\frac{1}{3}} u_1 d \qquad \textbf{(9)}$$

where:

$\xi = 1+\sqrt{\frac{200}{d}}$ is a size-effect coefficient.

u_1 = the length of the control perimeter at 2***d*** from the column.

$\rho = \sqrt{\rho_x \rho_y}$

In the ultimate limit state the partial safety factor is 1.5. For the calculation of punching load capacity F_{sd} is multiplied by 1.5, which gives the following equation.

$$F_{sd} = 0.18\,\xi(100\,\rho f_{ck})^{\frac{1}{3}} u_1 d \qquad \textbf{(10)}$$

6-Proposed Equation

The proposed equation for the punching shear strength of reinforced concrete flat slabs takes into account several effects such as the depth of slab at the critical section, diameter of column, if its circular section or the longest dimension, if its rectangular section, tension reinforcement ratio of slab at the critical section, and compressive strength of concrete. The critical perimeter is located at 0.5***d*** away from the column face. The proposed equation takes the following form:

$$v_c = \alpha\,(f_{c'})^{\gamma}\,\beta_o\,d \qquad (N) \qquad \textbf{(10)}$$

where:

$\gamma = 0.5$ for $f'_c < 80$ MPa

$\gamma = 0.71 - 0.0028\ f'_c$ for $f'_c \geq 80$ MPa but $\gamma \geq 0.45$

$\alpha = 0.8\left[\frac{(15+350\rho)\rho a}{B_o\,d} + 0.425\right]$

$a = D_c =$ for circular column.

$a = H_c =$ for rectangular column.

$f_{c'}$ = Concrete cylindrical compressive strength.

d = Effective depth of slab.

ρ = Tension reinforcement ratio of slab at the critical section.

β_o =The critical section perimeter.

D_c=Column diameter (circular column).

H_c=The longest dimension of rectangular column section.

Numerical Examples

A total of 58 test results from six research studies conducted by **Ramdane**, **Hallgren** and **Kinnunen**, **Marzouk** and **Hussein**, **Tomaszewicz**, **Metwally et.al.**, and **Abdel Hafez** were compared to values of punching strength calculated using the proposed equation. In all cases, tests were conducted on square or circular slabs supported by column stubs or loading plates. A considerable variety of concrete strengths, slab reinforcement ratios and slab depths are represented in the various studies.

Table (1) shows the variables used for each study, and the comparison of the experimental ultimate loads (P_{exp}) of the slabs to the values predicted by AS3600, CEB-FIP MC-90, and the proposed equation are shown in **Table (2)** and **Figure(2)**. In these expressions, the limits with respect to the concrete strength have been ignored. The capacity reduction factor is assumed to be equal to (1). The compressive strength is used from 68MPa to 108.8MPa and the tension reinforcement ratio from (0.6-2.49)% , and tow shapes of column (circular and square).

Table (1): Geometrical and material properties of experimental concrete slabs tested by Hallgren and Kinnunen, Marzouk and Hussein, and Tomaszewicz.

Researcher	Specimen	Type	Slab diameter or width (mm)	Col. Dia. Or col. width (mm)	Slab Depth (mm)	Slab ρ_t	$f_{c'}$ (MPa)
Hallgren and Kinnunen	HSC0	Circular	2400	250	240	0.8	90.3
	HSC2	Circular	2400	250	240	0.8	85.7
	HSC4	Circular	2400	250	240	1.2	91.6
	HSC6	Circular	2400	250	240	0.6	108.8
Marzouk and Hussein	HS2	Square	1500	150	120	0.84	70.2
	HS7	Square	1500	150	120	1.19	73.8
	HS3	Square	1500	150	120	1.47	69.1
	HS5	Square	1500	150	150	0.64	68.1
	HS13	Square	1500	150	90	2	68
	HS14	Square	1500	220	120	1.47	72
	HS15	Square	1500	300	120	1.47	71
Tomaszewicz	nd65-1-1	Square	2500	200	320	1.42	64.3
	nd95-1-1	Square	2500	200	320	1.42	83.7
	nd115-1-1	Square	2500	200	320	1.42	112
	nd65-2-1	Square	2200	150	240	1.66	70.2
	nd95-2-1	Square	2200	150	240	1.66	88.2
	nd95-2-3	Square	2200	150	240	2.49	89.5
	nd115-2-1	Square	2200	150	240	1.66	119
	nd115-2-3	Square	2200	150	240	2.49	108.1
	nd95-3-1	Square	1100	100	120	1.72	85.1

Table (2): The comparison of the proposed method, AS3600, and CEB-FIP equations with experimental data for the specimens

Researcher	Specimen	Exp. (kN)	AS3600 (kN)	CEB-FIP (kN)	Proposed	Pu(exp)/Pu(pred)		
						AS3600	CEB-FIP	Proposed
Hallgren and Kinnunen	HSC0	965	913.5	975.1	1037.8	1.06	0.99	0.929852
	HSC2	889	851.7	915.4	1073.1	1.04	0.97	0.828441
	HSC4	1041	920.1	1120	1060.3	1.13	0.93	0.981798
	HSC6	960	1010	950.2	873.6	0.95	1.01	1.098901
Marzouk and Hussein	HS2	249	265.2	288.7	308.14	0.94	0.86	0.808074
	HS7	356	271.9	329.2	325..52	1.31	1.08	1.093635
	HS3	356	263.1	345.4	323.13	1.35	1.03	1.101724
	HS5	365	261.2	261.3	413.05	1.4	1.4	0.88367
	HS13	267	172.7	253.7	281.42	1.55	1.05	0.94876
	HS14	498	345.3	404.8	523.9	1.44	1.23	0.950563
	HS15	560	430	465.1	649.42	1.3	1.2	0.862308
Tomaszewicz	nd65-1-1	2050	1532.7	1863.1	1931.1	1.34	1.1	1.061571
	nd95-1-1	2250	1748.7	2032.5	1978	1.29	1.11	1.137513
	nd115-1-1	2450	2022.8	2237.6	2013.18	1.21	1.09	1.21698
	nd65-2-1	1200	861.4	1163.5	1149.9	1.39	1.03	1.043569
	nd95-2-1	1100	965.6	1254.6	1092.26	1.14	0.88	1.007086
	nd95-2-3	1250	921.3	1390.4	1137.5	1.36	0.9	1.098901
	nd115-2-1	1400	1121.6	1384.9	1179	1.25	1.01	1.187447
	nd115-2-3	1550	1069	1533.8	1187.16	1.45	1.01	1.305637
	nd95-3-1	330	228.8	340.9	320.3	1.44	0.97	1.030284
Mean						1.267	1.0425	1.028836

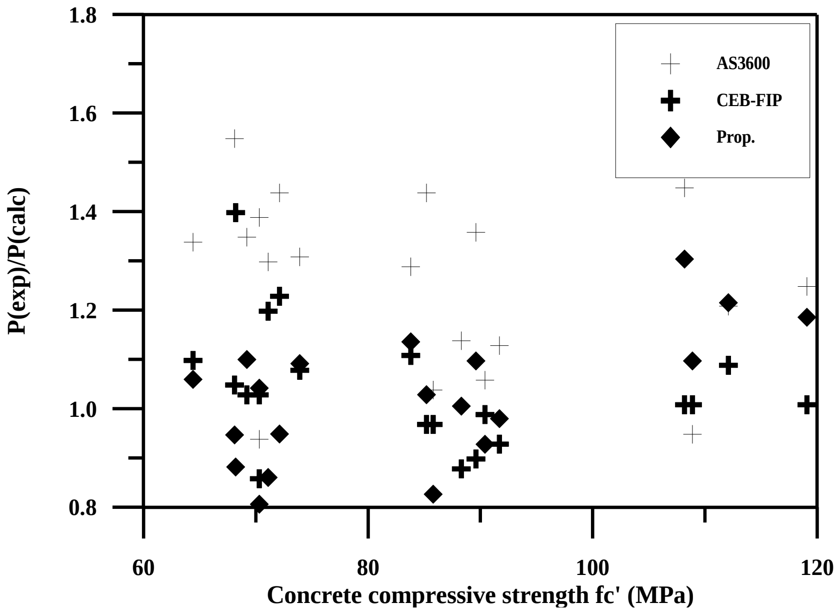


Fig. (2): Ratios of experimental and predicted punching shear strengths for all the specimens

From **Table(2)** and **Figure(2)**can be noticed that the mean of the proposed equation to experimental punching strength about 1.028 closer than other equations were introduced. The largest difference between the proposed value and the experimental data is about 23.75% $((|exp - prop|/prop) * 100)$ which is for the **HS2** specimen where the $P_{u(exp)}/P_{u(pred)}$ equal to **0.808** for the same specimen. While the smallest difference between the proposed value and the experimental data is about 0.703% which is for the **nd95-2-1** specimen where the $P_{u(exp)}/P_{u(pred)}$ equal to 1.007 for the same specimen.

Table (3) shows the variables used for each specimen, and the comparison of the experimental ultimate loads (P_{exp}) of the slabs to the values predicted by ECP, ACI-318, BS-8110, and the proposed equation are shown in **Table (4)** and **Figures (3 and 4)**. Very good agreement can be noted between the proposed equation and experimental results rather than other equations. If the specimen (**HS1**) is excluded, the largest difference between the proposed value and the experimental data is about 35.03% which is for the **slab2** specimen where the $P_{u(exp)}/P_{u(pred)}$ equal to 0.74 for the same specimen. While the smallest difference between the proposed value and the experimental data is about 0.187% which is for the **HS-19** specimen where the $P_{u(exp)}/P_{u(pred)}$ equal to 1.0018 for the same specimen. The mean value of the experimental/prediction punching strength was 0.996 for the proposed equation while its equal to 1.089 for the **BS-8110** equation, 1.442 for the **ACI-318** equation, and 1.362 for the **ECP** equation.

Parametric Study

a. Effect of Concrete Compressive Strength on the Punching Strength of Reinforced Concrete Slab

A reinforced concrete flat slab with 100mm depth and supported on circular column (diameter=150mm) was analyzed with compressive strength for slab varies from 20 MPa to 120 MPa for five slab tensile reinforcement ratio (0.6%, 1%, 1.4%, 1.8%, and 2.2%).

Table (5) and **Figure (5)** show the calculated punching shear strength for the reinforced concrete slab with various value of concrete compressive strength for each value of tensile reinforcement ratio(0.6%, 1%, 1.4%, 1.8%, and 2.2%)

Table (3): Geometrical and material properties of experimental concrete slabs tested by Metwally et.al., Ramdane, Hallgren and Kinnunen, Abdel Hafez, and Marzouk and Hussein

Researcher	Specimen	Type	Slab diameter or width (mm)	Column Dia. Or width (mm)	Slab Depth (mm)	Slab pt	f_{cu} (MPa)
Metwally et.al	N10-1	Square	1100	circular 140	100	0.714	29.89
	N10-2	Square	1100	circular 140	100	1.36	29.89
	N15-1	Square	1100	circular 140	150	0.595	29.89
	N15-2	Square	1100	circular 140	150	1.6	29.89
	H10-1	Square	1100	circular 140	100	0.714	66.6
	H10-2	Square	1100	circular 140	100	1.36	66.6
	H15-1	Square	1100	circular 140	150	0.595	66.6
	H15-2	Square	1100	circular 140	150	1.6	66.6
Ramdane	Slab2	Circular	1372	circular 150	125	0.58	66.07
	Slab12	Circular	1372	circular 150	125	1.28	71.06
	Slab14	Circular	1372	circular 150	125	1.28	71.53
	Slab16	Circular	1372	circular 150	125	1.28	116.7
	Slab22	Circular	1372	circular 150	125	1.28	99.06
	Slab5	Circular	1372	circular 150	125	1.28	66.35
Hallgren and Kinnunen	HSC1	Circular	2400	circular 250	240	0.8	99.7
	HSC8	Circular	2400	circular 250	240	0.8	128
Abdel Hafez	NS-3	Square	540	Square 100	60	2.31	31.1
	NS-4	Square	540	Square 100	60	1.27	31.1
	NS-5	Square	540	Square 100	60	1.72	31.1
	NS-7	Square	540	Square 100	60	1.27	30
	NS-9	Square	540	Square 100	60	1.72	33.2
	NS-10	Square	540	Square 100	60	1.72	32.3
	NS-11	Square	540	Square 100	60	2.31	32.3
	NS-12	Square	540	Square 100	60	2.81	33.2
	NS-15	Square	540	Square 100	60	4.24	33.2
	HS-16	Square	540	Square 100	60	1.72	79.1
	HS-17	Square	540	Square 100	60	2.81	79.1
	HS-18	Square	540	Square 100	60	2.81	82
	HS-19	Square	540	Square 100	60	4.24	82
Marzouk and Hussein	NS2	Square	1500	Square 150	150	0.94	35.3
	HS1	Square	1500	Square 150	120	0.49	78.8
	HS4	Square	1500	Square 150	120	2.37	81.3
	HS6	Square	1500	Square 150	150	0.94	82.3
	HS8	Square	1500	Square 150	150	1.11	81.1
	HS9	Square	1500	Square 150	150	1.61	87
	HS10	Square	1500	Square 150	150	2.33	94.1
	HS11	Square	1500	Square 150	90	0.95	82.3
	HS12	Square	1500	Square 150	90	1.52	88.2

Table (4): The comparison of the proposed method, ECP, ACI-318, and BS-8100 equations with experimental data for the specimens

Researcher	Specimen	Exp. (kN)	Pu(exp)/Pu(pred)			
			ECP	ACI-318	BS-8110	prop
Metwally et.al	N10-1	138	1.06	1.09	1.14	1.012695
	N10-2	145	1.11	1.15	0.98	1.004225
	N15-1	237	1	1.03	1.21	0.976072
	N15-2	288	1.22	1.25	1.07	1.098733
	H10-1	196	1	1.05	1.03	0.963145
	H10-2	258	1.33	1.38	1.09	1.196439
	H15-1	388	1.1	1.14	1.19	1.069961
	H15-2	410	1.16	1.21	0.91	1.047361
Ramdane	Slab2	212	0.76	0.79	0.9	0.740585
	Slab12	319	1.11	1.15	1.02	1.014534
	Slab14	314	1.09	1.13	1	0.995372
	Slab16	362	0.98	1.02	0.98	1.226661
	Slab22	405	1.19	1.24	1.15	1.222937
	Slab5	341	1.23	1.27	1.11	1.122338
Hallgren and Kinnu	HSC1	1021	0.87	0.91	1.15	0.94537
	HSC8	944	0.83	0.86	1.08	0.847321
Abdel Hafez	NS-3	87.5	1.7	1.8	0.95	1.089935
	NS-4	73	1.5	1.59	1.03	0.996995
	NS-5	78	1.6	1.7	0.99	1.025641
	NS-7	80	1.54	1.64	1.05	1.112502
	NS-9	70	1.47	1.56	0.92	0.890812
	NS-10	82	1.76	1.86	1.1	1.058065
	NS-11	77	1.65	1.74	0.93	0.94109
	NS-12	92.5	1.95	2.06	1.03	1.061388
	NS-15	105	2.35	2.48	1.09	1.033261
	HS-16	129.5	1.77	1.78	1.28	1.067689
	HS-17	158	2.15	2.18	1.32	1.174721
	HS-18	136	1.93	1.95	1.19	0.979122
	HS-19	160	2.27	2.29	1.22	1.001879
Marzouk and Hussein	NS2	396	0.58	1.7	1.37	1.124521
	HS1	178	0.68	0.7	0.81	0.480691
	HS4	418	1.74	1.78	1.22	0.990756
	HS6	489	1.32	1.35	1.25	0.909344
	HS8	436	1.18	1.22	1.06	0.808156
	HS9	543	1.42	1.47	1.15	0.939934
	HS10	645	1.62	1.66	1.17	1.017045
	HS11	196	1.11	1.15	1.06	0.749751
	HS12	258	1.41	1.45	1.17	0.910856
Mean			1.361579	1.441579	1.088684	0.995998

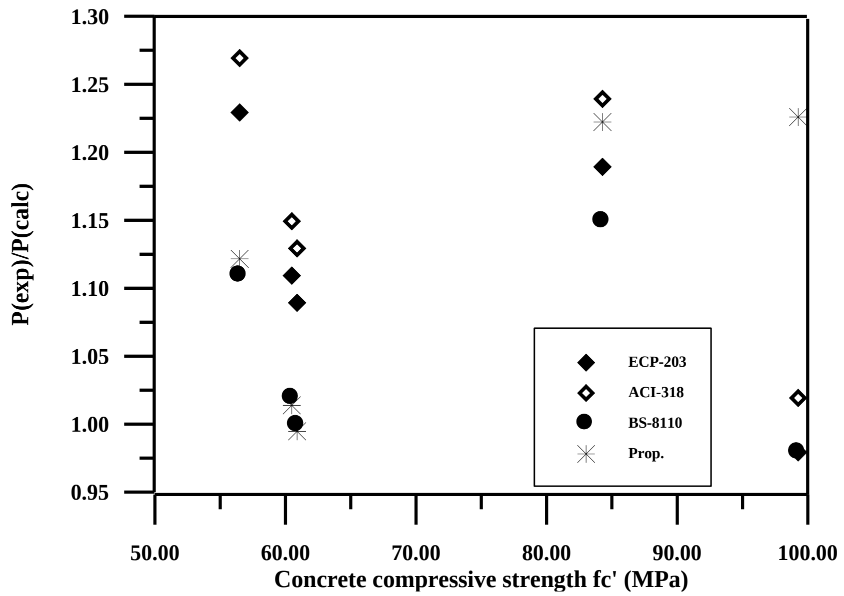


Figure (3): Ratios of experimental and predicted punching shear strengths for the specimens (slab5, slab12, slab 14, slab 16, and slab 22)

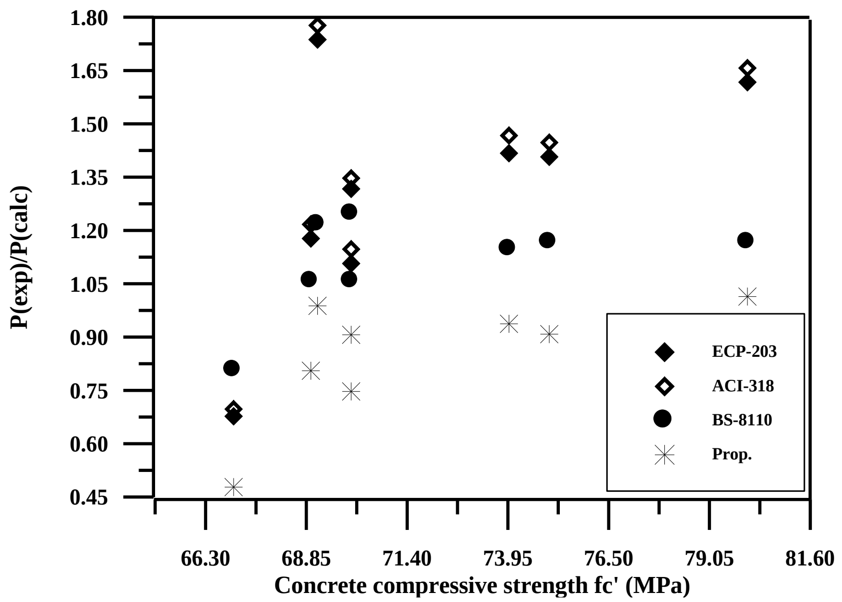


Figure (4): Ratios of experimental and predicted punching shear strengths for the specimens (HS-1, HS-4, HS-6, HS-8, HS-9, HS-10, HS-11, and HS-12)

Table (5): Calculated punching shear strength value (kN) using proposed equation for reinforced concrete flat slab with various value of tensile reinforcement ratio and concrete compressive strength

compressive strength fc' (mPa)	Slab tensile reinforcement ratio				
	ρ=0.6%	ρ=1.0%	ρ=1.4%	ρ=1.8%	ρ=2.2%
20	124.9	129.35	134.4	140	146.2
30	153	158.4	164.6	171.5	179
40	176.67	182.9	190	198	206.8
50	197.51	204.5	212.5	221.35	231.2
60	216.4	224	232.74	242.5	253.3
70	230	240	250	262	273.5
80	235	243	252	264	275.5
90	236.5	244.8	253.5	266	277.4
100	238.5	247	255.5	267.8	279
110	240	248.1	257	268.9	280.7
120	241	249.5	258.5	270	282

The ultimate punching shear strength is increased as the concrete compressive strength was increased but the rate of increasing in punching strength is decreases with increasing the compressive strength. For the five values of tension reinforcement ratio shown in **table (5)**, the punching shear strength is increased by about (85%) when the compressive strength increase from (20 MPa) to (70 MPa) and (7%) when the compressive strength increase from (70 MPa) to (120 MPa).

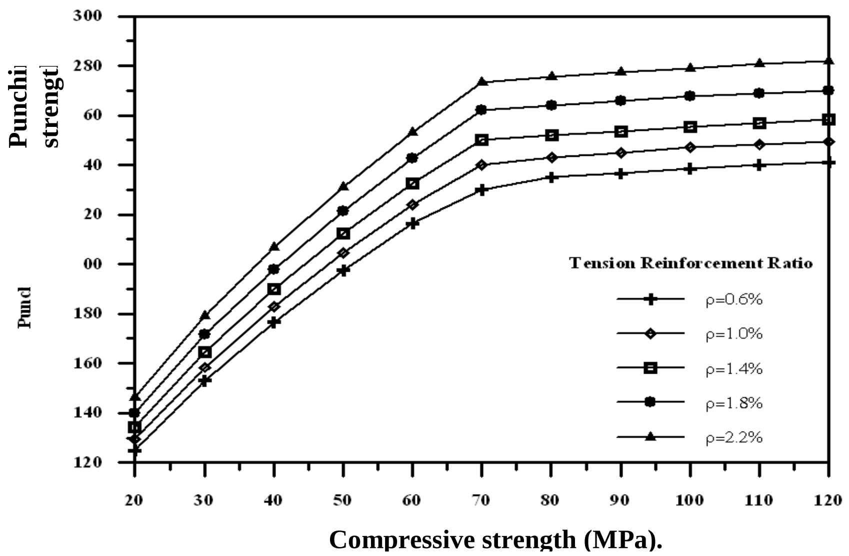


Figure (5): The relation between the calculated punching shear strength (using proposed equation) and the concrete compressive strength for (0.6%, 1%, 1.4%, 1.8%, and 2.2%) slab tensile reinforcement ratio.

b. Effect of The Slab Tension Steel Reinforcement Ratio on The Punching Strength of Reinforced Concrete Slab

To study the effect of slab tension reinforcement ratio on punching strength of reinforced concrete flat slab, **Table (5)** and **Figure (5)** can be redraw as shown in **Table (6)** and **Figure (6)**. From this study**,** it can be noticed that the general trend of the relation between the tension reinforcement ratio and the ultimate punching shear strength is the increasing in the first one cause increasing in the second one. When increasing the tension reinforcement ratio from 0.6% to 2.2% cause increasing in punching shear strength about 17% for all values of concrete compressive strength**.**

c. Effect of The Slab Thickness on The Punching Strength of Reinforced Concrete Slab

Two flat slabs with properties shown in **Table (7)** are analyzed to study the effect of the slab thickness on the punching strength of reinforced concrete flat slab. **Table (8)** and **Figures (7 and 8)** show the calculated punching shear strength of slabs (SS1 and SC1) with three values of tension steel reinforcement ratio of slab (0.01, 0.02, and 0.03) and with slab thickness varies from (75mm) to (300mm). From this study, it's can be noticed that the slab thickness increase the punching strength increase. The increasing in punching strength for slab (SS1) are about (700%) with tension reinforcement ratio (1% and 2%) and (660%) with tension reinforcement ratio (3%) when the slab thickness increase from (75mm) to (300mm). The increasing in punching strength for slab (SC1) are about (660%) with tension reinforcement ratio (1%) and (600%) with tension reinforcement ratio (2% and 3%) when the slab thickness increase from (75mm) to (300mm).

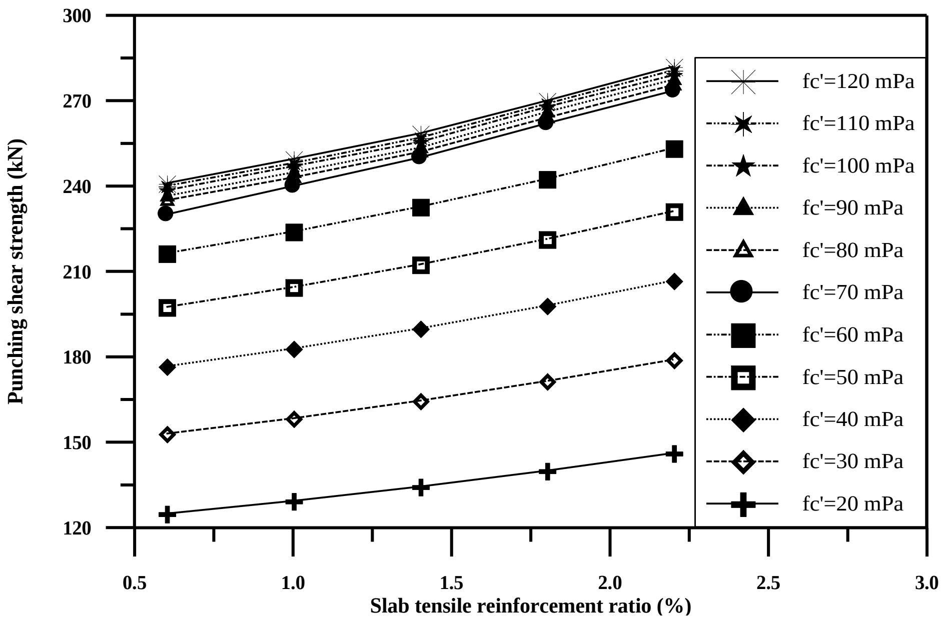
d. Effect of The Column Shape on The Punching Strength of Reinforced Concrete Slab:

Curves in **Figures (7 and 8)** are redrawn together in one figure as shown in **Figure (9)** to study the effect of column section shape on the punching shear strength of flat slabs (SS1 and SC1). Note that the square column which support slab (SS1) and the circular column which support slab (SC1) have the same circumference. From this study, it's can be noticed that slab supported on square column (SS1) give punching shear strength greater than the slab supported on circular column (SC1) for the same value of slab thickness and tension reinforcement ratio. For reinforcement ratio (1%) and slab thickness (75mm), the slab (SS1) give punching shear strength greater than punching shear strength of slab (SC1) by about (12%) and this difference reach (16%) for slab thickness (300mm). For reinforcement ratio (2%) and slab thickness (75mm), the slab (SS1) give punching shear strength greater than punching shear strength of slab (SC1) by about (3%) and this difference reach (14%) for slab thickness (300mm). For reinforcement ratio (3%) and slab thickness (75mm), the slab (SS1) give punching shear strength greater than punching shear strength of slab (SC1) by about (0.6%) and this difference reach (11%) for slab thickness (300mm).

Table (6): Calculated punching shear strength value (kN) using proposed equation for reinforced concrete flat slab with various value of tensile reinforcement ratio and concrete compressive strength.

fc' (mPa)		20	30	40	50	60	70	80	90	100	110	120
Slab tensile reinforcement ratio	ρ=0.6%	124.9	153	176.67	197.51	216.4	230	235	236.5	238.5	240	241
	ρ=1.0%	129.35	158.4	182.9	204.5	224	240	243	244.8	247	248.1	249.5
	ρ=1.4%	134.4	164.6	190	212.5	232.74	250	252	253.5	255.5	257	258.5
	ρ=1.8%	140	171.5	198	221.35	242.5	262	264	266	267.8	268.9	270
	ρ=2.2%	146.2	179	206.8	231.2	253.3	273.5	275.5	277.4	279	280.7	282

For any value of slab thickness shown in **table (8)**, the rate of increasing in punching strength of slab (SS1) with respect to punching strength of slab (SC1) is decreases with increasing the tension reinforcement ratio. For any value of tension reinforcement ratio shown in **table (8)**, the rate of increasing in punching strength of slab (SS1) with respect to punching strength of slab (SC1) is increases with increasing the slab thickness.



Figure(6): The relation between the calculated punching shear strength and the slab tensile reinforcement ratio for various concrete compressive strength values.

Table (7): Properties of slabs (SS1 and SC1).

	Slab (SS1)			Slab (SC1)		
Concrete compressive strength of slab (MPa)	20			20		
Tension reinforcement ratio for slab (%)	1	2	3	1	2	3
Slab thickness (mm)	Varies from75mm to 300mm	Varies from75mm to 300mm	Varies from75mm to 300mm	Varies from75mm to 300mm	Varies from75mm to 300mm	Varies from75mm to 300mm
Type and dimension of column	Square h=b= 117.81mm			Circular Diameter=150mm		

Table (8): Calculated punching shear strength value (kN) using proposed equation for reinforced concrete flat slabs (SS1 and SC1).

Slab thickness (mm)	Slab (SS1) Slab tension reinforcement ratio (%)			Slab (SC1) Slab tension reinforcement ratio (%)		
	1	2	3	1	2	3
75	98.8	101.8	112.1	88.05	98.5	111.4
100	140.27	151	164.7	129.35	143	160.5
125	194.5	207.8	225	176.61	193.75	215.5
150	256.5	272	293	229.85	250.5	276.5
175	325.5	344	368	289.05	313	343.5
200	402	423.7	451	354.25	381.6	416.5
250	578.75	605.5	640	502.5	536.75	580.5
300	785.75	818	859	674.5	715.75	768

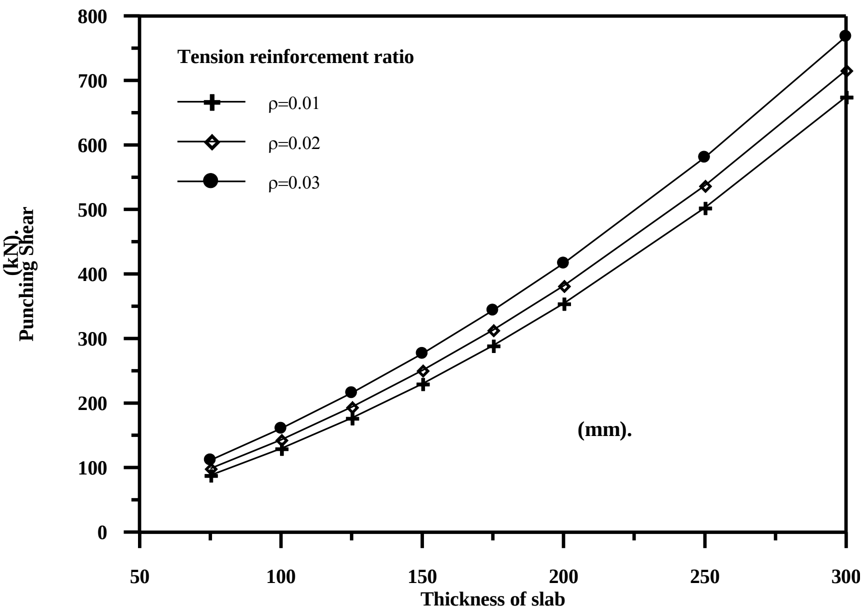


Figure (7): The relation between the calculated punching shear strength and the slab thickness for slab (SS1) with three values of tensile reinforcement ratio (0.01, 0.02, and 0.03).

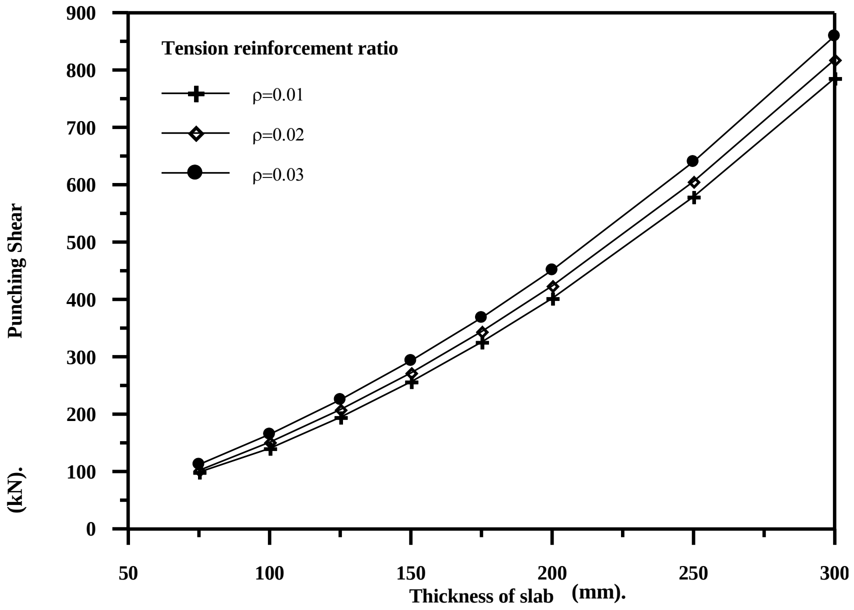


Figure (8): The relation between the calculated punching shear strength and the slab thickness for slab (SC1) with three values of tensile reinforcement ratio (0.01, 0.02, and 0.03)

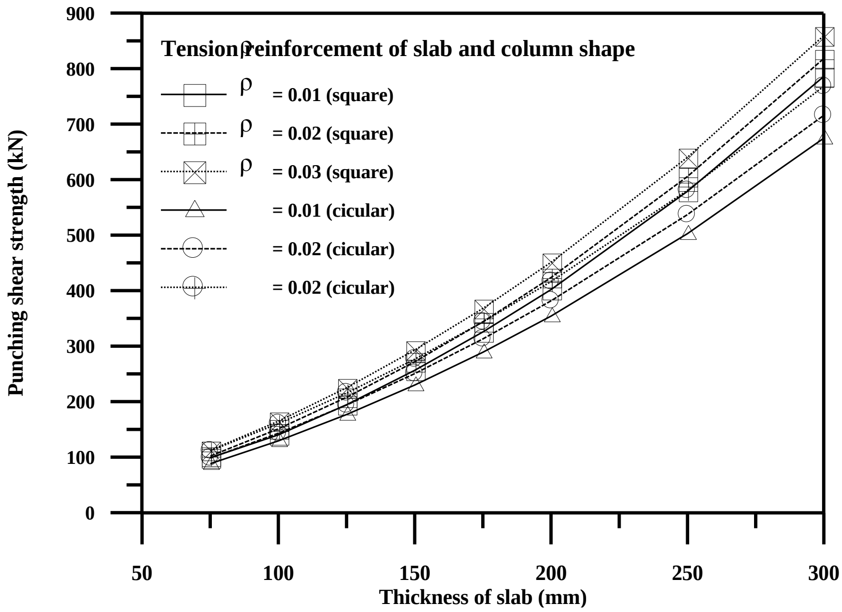


Figure (9): The relation between the calculated punching shear strength and the slab thickness for slabs (SS1 and SC1) with three values of tensile reinforcement ratio (0.01, 0.02, and 0.03).

Conclusions

Based on the analysis and discussion of the experimental and analytical results given above, the following conclusions can be drawn:

1. The proposed equation is a simple and accurate equation which can be used for calculation of normal and high strength concrete punching strength.
2. The increasing in concrete compressive strength cause increasing the concrete punching strength. But the rate of increasing in punching strength is decreases with increasing the compressive strength.
3. Increasing the slab tension reinforcement ratio has significant effects on increasing the punching shear capacity. The increase in tension reinforcement ratio from 0.6% to 2.2% cause increasing in punching shear strength about 17% for all values of concrete compressive strength.
4. The increasing in slab thickness cause increasing in punching strength for slab. The increasing in punching strength for slab are about (600%-700%) when the slab thickness increase from (75mm) to (300mm).
5. The punching shear strength of slab supported on square column is greater than punching shear strength of slab supported on circular column have same circumference of the square column by a ratio varies from (0.6%) to (16%) based on slab thickness and slab tension reinforcement ratio.
6. The rate of increasing in punching shear strength of slab supported on square column with respect to that for slab supported on circular column is decreases with increasing the tension reinforcement ratio of slab.
7. The rate of increasing in punching shear strength of slab supported on square column with respect to that for slab supported on circular column is increases with increasing the slab thickness.

References

[1]Ibrahim M. Metwally, Mohamed S. Issa, Sameh A. El – Betar," **Punching Shear Resistance of Normal and High – Strength Reinforced Concrete Flat Slabs**", Civil Engineering Research Magazine, Vol.30, No.3, pp.982 – 1004, Oct. 2008.

[2]Mahmoud Reda Taha1, Kyoung Kyu Choi, and Alaa Sherif," **Predicting The Punching Shear Strength of Interior Slab-Column Connections Using Fuzzy Systems"**, Joint International Conference on Computing and Decision Making in Civil and Building Engineering, pp.1312 - 1321, June 14-16, 2006 - Montréal, Canada.

[3]D. Tuan Ngo,**" Punching Shear Resistance of High-Strength Concrete Slabs"**, Electronic Journal of Structural Engineering, pp.52 – 59, 2001.

[4]ACI Committee 318, **"Building Code Requirements for Structural Concrete and Commentary"**, American Concrete Institute, 1999.

[5]Egyptian Code Committee 203, **"Egyptian Code of Practice for Design and Construction of Reinforced Concrete Structures"**, Housing and Building Research Centre, Cairo, 2007.

[6]British Standards Institution, **"Structural Use of Concrete, BS – 8110: Part 1 – Code of Practice for Design and Construction"**, London, 1997.

[7]CEB-FIP Model Code 1990. Thomas Telford Ltd., London, 1993.

[8]AS3600: Concrete Structures Standard. Standards Association of Australia, 1994.

[9]Ramdane, K.E. **,"Punching Shear of High Performance Concrete Slabs"**, 4th International Symposium on Utilization of High-strength/High-performance Concrete. Paris, pp. 1015-1026, 1996.

[10]Hallgren, M. and Kinnunen, S., **" Increase of Punching Shear Capacity by using High-Strength Concrete**", 4th International Symposium on Utilization of High-strength/High-performance Concrete, pp. 1037-1046, Paris, 1996.

[11]Marzouk, H. and Hussein, A. **"Experimental Investigation on the Behaviour of High-Strength Concrete Slabs**", ACI Structural Journal, V. 88, No. 6, pp. 701-713, Nov.-Dec., 1991.

[12]Tomaszewicz, A., **"High-strength Concrete SP2 - Plates and Shells. Report 2.3, Punching Shear Capacity of Reinforced Concrete Slabs**", Report No. STF70A93082, SINTEF, Trondheim, 1993.

[13]Abdel Hafez, A. M., **"Punching Shear Behavior of Normal and High Strength Concrete Slabs under Static Loading"**, Journal of Engineering Sciences, Assiut University, Vol.33, No.4, pp. 1215 – 1235, July 2005.