Eng. & Technology, Vol.24, No.9, 2005

Influence of High-Strength Concrete on Punching Shear in Slabs

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Received on: 25/8/2004
Accepted on: 28/11/2004

Abstract

This work studies punching shear resistance of slabs with normal strength concrete (NSC) and high strength concrete (HSC), with emphasis on HSC.

Test results of (47) reinforced concrete slabs, including (17) in NSC and (30) slabs in HSC available from existing research are studied in this paper. These (47) tests, covered a very wide range of concrete compressive strength (fc'), (fc' ranged between 14.4 MPa and 119.0 MPa), and all test specimens failed in punching shear.

Similar to other codes, the ACI code [1] limits the usefulness of concrete strength contribution to having $\sqrt{fc'} \leq 25/3$ MPa. This limits the usefulness of fc' to 69 MPa. The present development of concrete technology makes it possible to produce HSC with fc' much greater than this value .The present work attempts to bridge this gap. It is shown that the proposed equations in shear resistance give results that have good agreement with tests.

تأثير الخرسانة العالية المقاومة على القص المباشر(Punching Shear) في البلاطات الخرسانية

الخلاصة

يدرس هذا العمل مقاومة القص في البلاطات الخرسانية المسلحة ذات الخرسانة الاعتيادية والعالية المقاومة مع التركيز على الخرسانة العالية التحمل .

ولقد تم دراسة نتائج اختبار (47) بلاطة تتضمن (17) بلاطة ذات خرسانة اعتيادية التحمل و(30) بلاطة ذات خرسانة عالية التحمل.وهذه النماذج التي تم دراستها تغطي حيزا واسعا جدا لمقاومة الانضغاط للخرسانة حيث تتراوح بين (14.4) MPa و(119.0) MPa .كما ان هذه النماذج جميعا قد فشلت تحت تأثير قوى القص.

ان المواصفة الأمريكية (كذلك بعض المواصفات الأخرى) تضع حدا لمقاومة الانضغاط المسموح بها لحساب قوى القص بحيث لايتجاوز الجذر التربيعي لمقاومة الانضغاط (3\25) MPa ، اي ان لا تتجاوز مقاومة الانضغاط (69) MPa . ان التطور السريع الحاصل في تكنولوجيا الخرسانة جعل من الممكن انتاج خرسانة عالية التحمل تتجاوز الحدود التي تضعها المواصفات.ولذلك فان هذا العمل يحاول غلق هذه الفجوة واقتراح معادلات لحساب قوى القص بحيث تعطي نتائج تقترب بصورة افضل من النتائج العملية.

Notation

βc = is the ratio of the long side to short side of the column, concentrated load or reaction area .

bo = perimeter of critical section for slabs and footings, mm .

d= distance from extreme compression fiber to centroid of longitudinal tension reinforcement.

fc' = specified compressive strength of concrete ,MPa.

α_s = factor which equals 40 for interior columns, 30 for edge columns and 20 for corner columns.

Vc = nominal shear strength provided by concrete.

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

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https://doi.org/10.30684/etj.24.9A.6
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Acknowledgment

The researchers wish to thank the Building and Construction Engineering Department for support during this work.

Introduction

In a flat plate, inclined shear cracks usually form at load level of less than 70 percent of the ultimate load [2]. Although these cracks can completely surround the column, the slab is nevertheless stable, and can be unloaded and reloaded without any decrease of the ultimate load. It is therefore evident that the failure mechanism is not normally a pure "shear failure" governed by the diagonal tensile strength of the concrete. The solution to the punching shear problem must be found in properties of the uncracked compression zone of the slab in the vicinity of the column under consideration [2].

Recently, the use of HSC has been given considerable attention. Due to recent improvement in material technology, especially in the production of ready mixed concrete, concrete strength grades are now available with high fc′ values. HSC is used now in medium and long – span bridges, in some cases HSC may be used for durability especially bridge slabs.

HSC can be defined as concrete with compressive strength fc′ > 55 MPa [1].

The reinforced concrete flat slab system is a widely used structural system .Its formwork is very simple and therefore could be more economic, as no beams or drop panels are used. However, the catastrophic nature of the failure exhibited at the connection between the slab and the column has concerned engineers.

The area shown in Fig.1 (3) becomes the most critical area as far as the strength of flat slabs is concerned due to the concentration of high bending moments and shear forces. The failure load may be considerably lower than the unrestrained flexural capacity of the slab. A typical punching shear failure of bridge deck during testing is shown in Fig.2 (3). The use of HSC improves the punching shear resistance allowing higher forces to be transferred through the slab – column connection (3).

Research Significance

In the light of the recent increase in the concrete compressive strength fc′, this study aims at improving the relationship between test strength (P_{test}) and calculated resistance strength (P_r). By providing punching shear capacity design and analysis equations are presented for concrete slabs for HSC, as well as NSC.

Where the empirical expressions given in most design codes and researches have a limited value for concrete compressive strength fc′, this limit cannot express the influence of HSC. Hence it may be useful to provide new equations for punching shear design and analysis of slabs based on HSC.

Experimental Results From Existing Research

Experimental results of (47) reinforced concrete slabs have been taken from existing research. Some of these slabs are circular while the others are square or rectangular.

These (47) test results included both NSC and HSC.

These results covered a very wide range of concrete compressive strength fc' between 14.4 MPa to 119 MPa. All (47) specimens failed in punching shear.
Table (1) shows the details and test results of these concrete slabs.

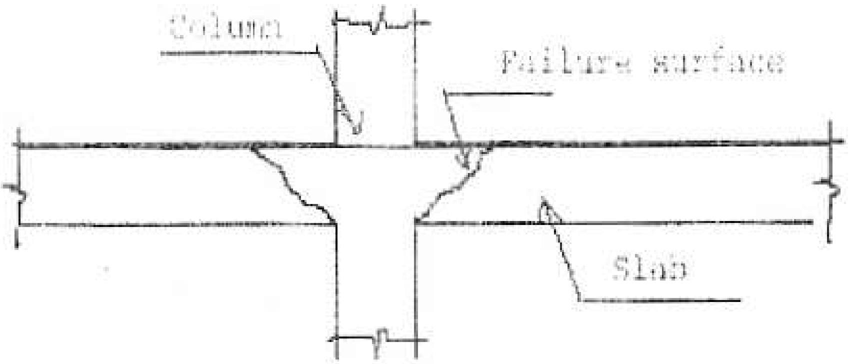

Fig. (1) Punching failure surfaces of flat slab.[3]

Fig.2 A typical punching shear failure of bridge deck.[3]

ACI -99 Code (1)

ACI code provisions for punching shear are based mainly on Moe's work mostly on NSC [4].

ACI –99 code expresses the resistance punching shear strength of concrete slabs by a set of equations, where the punching shear strength Vc is the least value between Eqs. (1-3).Critical section that must be investigated for shear is illustrated in Fig. 4,where the control perimeter must be taken at a distance of (d/2) from the face of column.

$$V_c = 0.85\left[1+\frac{2}{\beta_c}\right]\frac{\sqrt{f'_c}.b_o.d}{6} \qquad \ldots.1$$

$$V_c = 0.85\left[\frac{\alpha_s d}{b_o}\right]\frac{\sqrt{f'_c}.b_o.d}{12} \qquad \ldots.2$$

$$V_c = 0.85\,\frac{1}{3}\sqrt{f'_c}.b_o.d \qquad \ldots.3$$

where:

β_c = is the ratio of the long side to short side of the column, concentrated load or reaction area.

b_o = perimeter of critical section for slabs and footings, mm.

d= distance from extreme compression fiber to centroid of longitudinal tension reinforcement.

fc′ = specified compressive strength of concrete ,MPa .

α_s = factor which equals 40 for interior columns, 30 for edge columns and 20 for corner columns .

Vc = nominal shear strength provided by concrete.

This root ($\sqrt{fc'}$) has a limited value which shall not exceed 25/3 MPa (i.e. using an upper limit to fc′ of approximately 69 MPa).

The punching shear strength values vary with concrete compressive strength fc′. They are proportional to fc′. This square –root expression was adopted by Moe [4], who concluded that the shear failure is controlled primarily by the tensile – splitting strength, which is assumed proportional to $\sqrt{fc'}$.

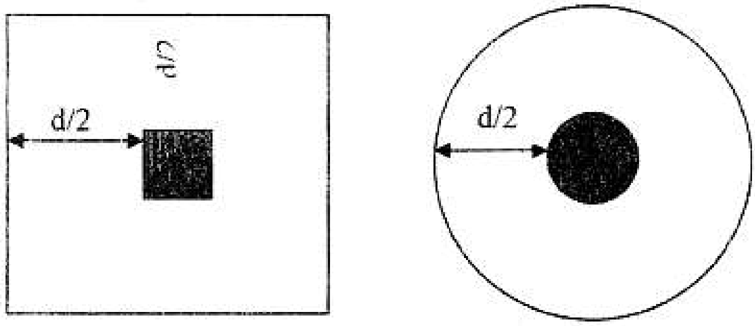

Fig. 3 perimeter b_o computation.

AS -94 Code (5)

In this code, the ultimate punching shear strength for slabs can be calculated from Eq. (4):

$$V_{uo} = b_o d\,(f_{cv}) \qquad \ldots 4$$

where:

b_o= length of the critical perimeter, taken at distance of d/2 from the column, mm . See Fig.3 .

Vuo = ultimate punching shear strength..

and (fcv) represents the punching shear strength, MPa ,see Eq. (5) :

$$f_{cv} = 0.17\left[1+\frac{2}{\beta_{\eta}}\right]\sqrt{f'_c} \quad \leq \quad 0.34\sqrt{f'_c} \qquad \ldots.5$$

where :

$\beta\eta$ = ratio of longest column dimension to shorter column dimension .

Also, the square –root of $\sqrt{fc'}$ is considered in this design approach , which is similar to ACI-99 code. But AS-94 gave an upper limit of 50 MPa for fc'

CAN – 84 Code (6)

The Canadian code design is considered in this work. In this code, the value of shear resistance can be computed from Eq.(6) .The critical section in this code is similar to the definition of the critical section that used in ACI -99 code, see Fig. (3)

$$V_c = \left[1+\frac{2}{\beta_c}\right]0.12 \quad \sqrt{f'_c} \quad b_o \quad d \qquad \ldots..6$$

But not greater than $0.24\sqrt{fc'}\ b_o\, d$

Proposed Method

As indicated in reference 1 most ACI code tests were based on specimens with fc' < 55 MPa - essentially NSC tests. In this work, with the availability of 30 tests of HSC (fc' > 55 MPa) a set of equations have been proposed based on regression analysis, to accommodate these HSC tests. The object of regression is to evaluate the coefficient of an equation relating the criterion variable to one or more other variables, which are called independent variables. This is a misnomer in that independent variables are usually neither of the other predictor variables.

After applying the statistical treatment for each analysis method and from the investigation of the validity of these methods, it has been found that the ACI code (and some other codes) cannot be adequate for HSC. This is because most ACI code design equations were based on NSC tests. Therefore, a set of empirical equations will be proposed and modified from the ACI-99 approach, for punching shear design and analysis. These equations are essentially derived to be more adequate for HSC.

Based on the regression analysis Eqs.(7-9) are proposed which are based on the cubic root of fc' ((fc')1/3).

$$V_c = 0.85\left[1+\frac{2}{\beta_c}\right]\frac{\sqrt[3]{f'_c}.b_o.d}{3} \quad \ldots.7$$

$$V_c = 0.85\left[\frac{\alpha_s d}{b_o}\right]\frac{\sqrt[3]{f'_c}.b_o.d}{6} \quad \ldots.8$$

$$V_c = 0.85\ \frac{2}{3}\sqrt[3]{f'_c}.b_o.d \qquad \ldots.9$$

Thus Eqs.(4-6) represent the results of regression based on 47 punching shear tests. Also, the length of the critical perimeter is taken at distance of d/2 from the column, mm. See Fig.3.

The results versus design methods

The (47) experimental results, which have been taken from existing research, are compared with predictions by ACI – 99, AS – 94 and CAN-84codes and the proposed method.

The results of these analysis are illustrated, where the relationship of $r_{test}/r_{calculated}$ versus concrete compressive strength (fc') are plotted to show the effect of this main variable on the safety of these methods, see Figs. (4-7).

Where, from these figures the ACI – 99 code, AS -94 code and CAN-84 code show that when (fc') increased the safety will have a very large decrease. While the proposed method has a slight rise in safety when (fc') increased.

Generally, in case of HSC the ACI - 99, AS – 94 and CAN-84 approaches tends to be very unconservative with the increase of fc'. In the other hand, the proposed method in this work will be more conservative in case of HSC.

Also, Table (2) gave the statistical results for all methods of analysis considered in this work. The table shows that the proposed method gives the better repreatation. The best COV. value (21.609 %), in compare with ACI - 99 , AS – 94 and CAN-84 approaches with COV. value of (23.958 %).This slight reduction in COV. value refers to the improvement (decrease) in the dispersion of the results.

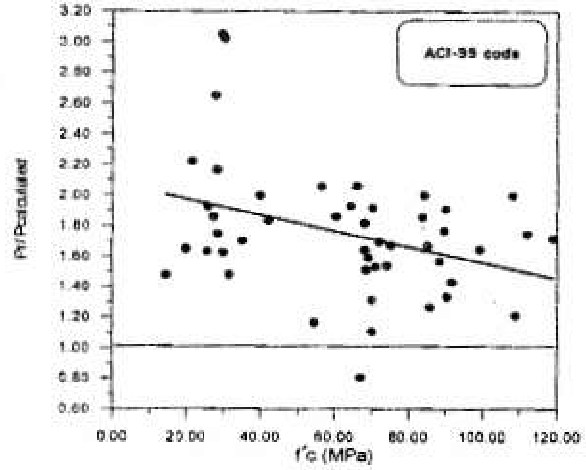

Fig.4 Concrete compressive strength versus strength ratio of ACI-99.

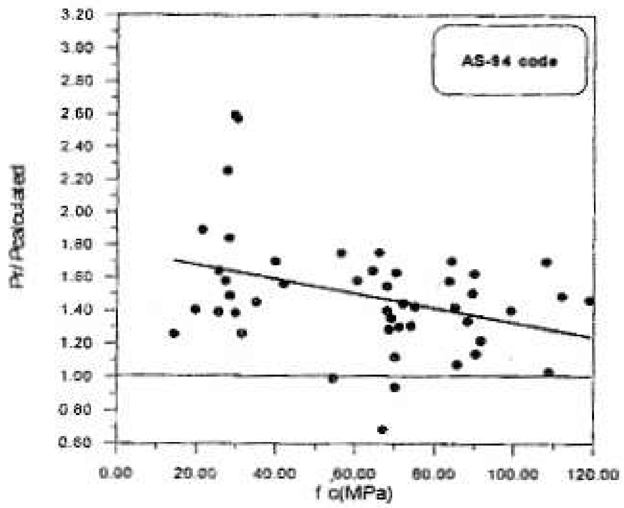

Fig.5 Concrete compressive strength versus strength ratio of AS-94 code

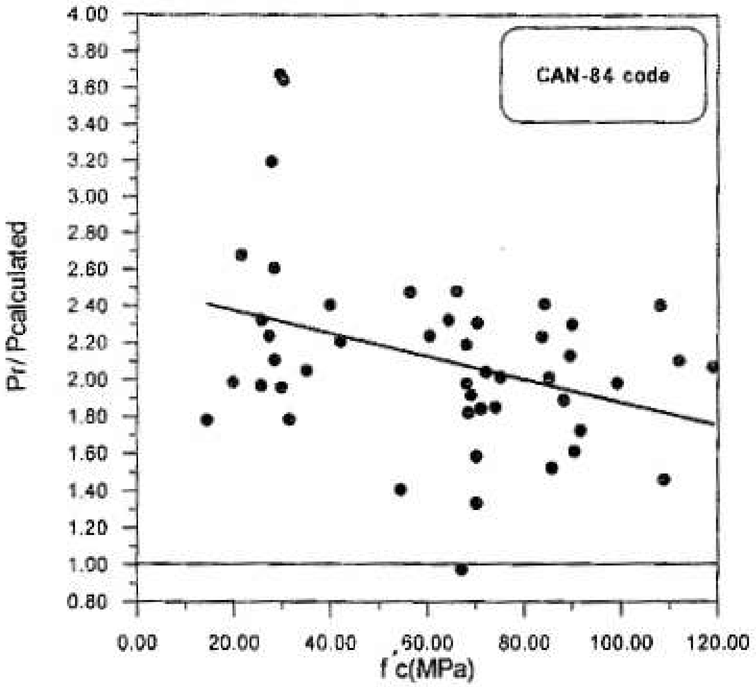

Fig.6 Concrete compressive strength versus strength ratio of CAN-84 code

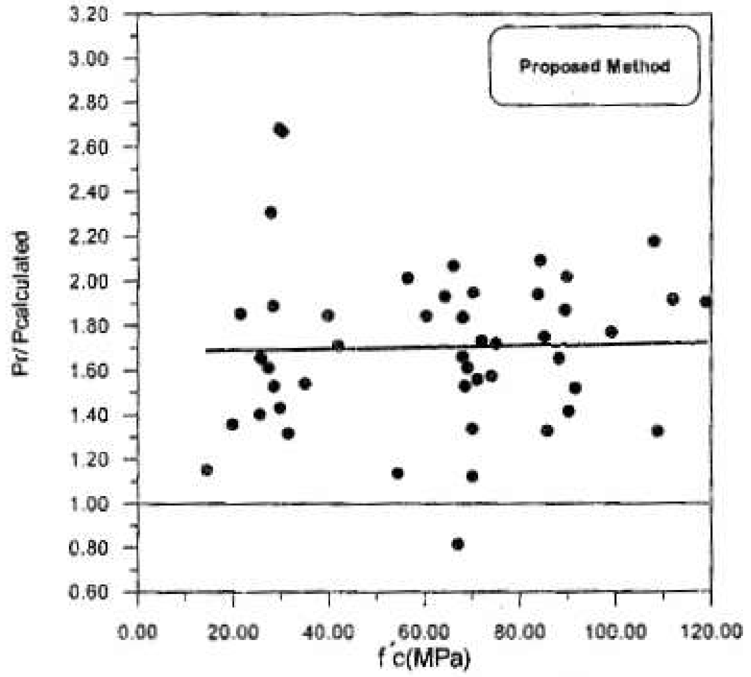

Fig.7 Concrete compressive strength versus strength ratio of proposed method.

Conclusions

The following conclusions can be derived from this work:

1. Generally, code provisions like ACI – 99 code (and some other methods) for punching shear, which are based on Moe's work, cannot be used to predict the punching shear capacity of HSC reinforced slabs. However Moe's equations were based on tests made using low concrete strength.
2. ACI – 99 code cannot be applicable for (fc') up to 69 MPa, where the term $\sqrt{fc'}$ is limited to 25/3 MPa. . Further, AS -94 code ,has an upper limit of 50 MPa for fc'.
3. The provision of ACI – 99 code (like other codes) tends to be very conservative with increasing of fc' (i.e. for HSC). In contrast, the proposed method leads to a slight rise in safety with increasing fc' , Figs. (4-7).
4. In general, the use of HSC improves the punching shear resistance allowing higher forces to be transferred through the slab – column connection.

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Table (1) Details of experimental concrete slabs

Slab No.	Slab Name	fc' MPa	b (mm)	h (mm)	D (mm)	Slab effective depth (d) (mm)	exp. (kN)	Ref.
1	Slab 5	54.4	-	-	150	98	190	2
2	Slab 12	60.4	-	-	150	98	319	2
3	Slab 15	68.4	-	-	150	98	276	2
4	Slab 16	99.2	-	-	150	98	362	2
5	Slab 22	84.2	-	-	150	98	405	2
6	Slab 23	56.4	-	-	150	98	341	2
7	HSC 0	90.3	-	-	250	190	965	2
8	HSC 2	85.7	-	-	250	190	889	2
9	HSC 4	91.6	-	-	250	190	1041	2
10	HSC 6	108.8	-	-	250	190	960	2
11	Nd65-1-1	64.3	200	200	-	253	2050	2
12	Nd95-1-1	85.7	200	200	-	253	2250	2
13	Nd95-1-3	89.9	200	200	-	253	2400	2
14	Nd115-1-1	112	200	200	-	253	2450	2
15	Nd65-2-1	70.2	150	150	-	190	1200	2
16	Nd95-2-1	88.2	150	150	-	190	1100	2
17	Nd95-2-3	89.5	150	150	-	190	1250	2
18	Nd115-2-1	119	150	150	-	190	1400	2
19	Nd115-2-3	108.1	150	150	-	190	1550	2
20	Nd-95-3-1	85.1	100	100	-	95	330	2
21	NS1	42	150	150	-	95	320	7
22	HS1	67	150	150	-	95	179	7
23	HS2	70	150	150	-	95	249	7
24	HS7	74	150	150	-	95	356	7
25	HS3	69	150	150	-	95	356	7
26	HS4	66	150	150	-	90	418	7
27	HS5	68	150	150	-	95	365	7
28	HS11	70	150	150	-	70	196	7
29	HS12	75	150	150	-	70	258	7
30	HS13	68	150	150	-	70	267	7
31	HS14	72	220	220	-	95	298	7
32	HS15	71	300	300	-	95	560	7
33	S1	39.84	-	-	250	242	1363	8
34	S2	28.4	-	-	250	243	1015	8
35	S3	29.76	-	-	250	250	1008	8
36	S4	25.68	-	-	250	232	992	8
37	S5	27.76	-	-	250	230	1401	8
38	S6	30.24	-	-	250	236	1732	8
39	S7	14.4	-	-	250	246	622	8
40	S8	31.44	-	-	250	245	915	8
41	S9	25.52	-	-	250	244	904	8
42	S10	29.52	-	-	250	232	1683	8
43	S11	28.24	-	-	250	235	1190	8
44	S12	27.28	-	-	250	242	1049	8
45	S13	19.76	-	-	250	244	803	8
46	S14	21.44	-	-	250	240	1100	8
47	POA	35	300	300	-	118.5	423	9

Table (2) Statistical results

NO.	Method	$\bar{X}$	COV. %	High	Low	NO.< 1
1	ACI-99 code	1.754	23.958	3.051	0.808	1
2	AS-94 code	1.491	23.958	2.593	0.687	3
3	CAN-84 code	2.112	23.958	3.674	0.973	1
4	Proposed method	1.704	21.609	2.682	0.814	1