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An Experimental Study on Punching Shear Behavior of Concrete Slabs

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Abstract: In determining the punching shear capacity of flat slabs, current codes of practice usually do not consider the effect of boundary restraint against rotation. The contribution of flexural steel reinforcement is ignored by some of the code provisions. Present paper is comprised of the test results of 15 model slabs in an effort to ascertain the influence of boundary restraint, the influence of flexural reinforcement and effect of thickness of the slabs on their structural behavior and punching load-carrying capacity. Cracking pattern and load-deflection behavior of the slabs tested have also been monitored closely. Significant effect of edge restraint on the punching failure load, resulting in an enhancing of the ultimate punching strength, and effect of flexural reinforcement on the punching failure load have been noticed. The code-specified strength of the specimens was calculated in accordance with the American, British, Canadian, European, and Australian codes. It has been understood that punching shear is not effectively estimated in some codes. Thus, inclusion of the findings of the study in the design codes is expected to result in a rational design of structural systems where punching phenomenon plays a vital role.

Key words: flat slab, punching shear, column, concrete, edge restraint, reinforcement.

1. INTRODUCTION

Present design rules for punching shear failure of reinforced concrete slabs, given in various codes of practice, are largely based on studies of the behavior and strength of simply-supported, conventional specimens extending to the nominal line of contraflexure (Alam 1997; Kuang and Morley 1992). The code provisions rely mostly on empirical methods derived from the test results on conventional (Selim and Sebastian 2003) and thin slab specimens (Lovrovich and McLean 1990). In continuous slab, all panel edges cannot rotate freely, in contrast to its simply supported counterpart. As a result, these codes may not properly mimic the punching shear behavior of continuous and actual slab construction.

Some of the present-day code provisions usually specify the punching shear strength as a function of compressive strength of concrete alone. Thus, these codes do not take adequate account of the possible role of specimen size and edge restraint. Some codes do not acknowledge the possible effect of flexural reinforcement on the punching shear behavior of reinforced concrete slabs. Design codes that were primarily based on the American code (ACI 318 2005), such as Canadian Standard (CSA-A23.3 2004), Australian code (AS 3600 1994), Bangladesh National Building code (BNBC 1993), do not reflect the influence of the flexural reinforcement ratio on the punching capacity of slab-column connections. British code (BS 8110 1997), European CEB-FIP (1990) code and German code (DIN 1045-1 2001) consider the effect of flexural reinforcement on the punching shear capacity of slabs. Some codes do not take adequate account of the possible role of specimen size and slab thickness (Lovrovich and McLean 1990; Mitchell *et al*. 2005).

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Table 1. Details of reinforced concrete slab specimens

Slab sample	Width of edge beam (b) mm	Slab thickness (h) mm	Reinforcement (ρ) %	Main bars in each direction No.—mm ϕ	Extra top bars in each direction no.—mm ϕ	Edge beam reinforcement no.—mm ϕ
SLAB1	245	80	0.5	15–6	15–6	4–16
SLAB2	245	80	1.0	30–6	30–6	4–16
SLAB3	245	80	1.5	16–10	16–10	4–16
SLAB4	245	60	0.5	11–6	11–6	4–16
SLAB5	245	60	1.0	22–6	22–6	4–16
SLAB6	245	60	1.5	33–6	33–6	4–16
SLAB7	175	80	1.0	30–6	30–6	4–16
SLAB8	175	60	0.5	11–6	11–6	4–16
SLAB9	175	60	1.0	22–6	22–6	4–16
SLAB10	105	80	1.0	30–6	30–6	4–16
SLAB11	105	60	0.5	11–6	11–6	4–16
SLAB12	105	60	1.0	22–6	22–6	4–16
SLAB13	0	80	1.0	30–6	30–6	*3–16
SLAB14	0	60	0.5	11–6	11–6	*3–16
SLAB15	0	60	1.0	22–6	22–6	*3–16

*These reinforcements were provided at the extended bottom section of slab.
All stirrups for edge beam were 6 mm ϕ @ 88 mm c/c., span = 1200 mm

Test results from simply supported slab specimens do not usually provide an accurate prediction of the ultimate load capacity of a slab having lateral restraint. When the slab is restrained against lateral deformation, this induces large restraining force within the slab and between the supports, thus membrane forces are developed (Selim and Sebastian 2003). The enhancement of punching shear capacity can be attributed to the presence of in-plane compressive membrane action in the slab (Kuang and Morley 1992; McLean *et al.* 1990; Selim and Sebastian 2003). The importance of compressive membrane stresses due to edge restraint was not incorporated into the code formulations, which results in conservative prediction.

Under the circumstances, the present study comprised of a planned series of tests on restrained as well as unrestrained slabs, variation of flexural reinforcement and slab thickness. Edge restraint was provided by means of edge beams of various dimensions to mimic the behavior of continuous slabs. The test results obtained from this study will be useful to evaluate an insight on the punching behavior of reinforced concrete slabs.

2. EXPERIMENTAL PROCEDURE

2.1. Specimen Details

A total of 15 square reinforced concrete slab specimens were constructed and tested in this study. Twelve of these slabs had edge restraints in the form of edge beam, whereas the other three samples were plain normal slabs having no edge beams. Width of edge beam, slab thickness and reinforcement ratio were test variable elements for different samples having one or more than one variability. Details of the slab samples are given in Table 1 and typical plan and sectional details of slabs with edge beam are shown in Figure 1. Photographs of slab sample with reinforcement can be seen in Figures 2 and 3.

2.2. Materials

The concrete used in the specimens consisted of ordinary Portland cement, natural sand and crushed stone aggregate with maximum size 10 mm. The water cement ratio for concrete was 0.45. Both 6 mm and 10 mm diameter steel bars having average yield strength of 421 MPa were used in the slab panels and stirrup of edge beams. Flexural reinforcement in the edge beam was provided by 16 mm diameter steel bars with average yield strength of 414 MPa. An average cylinder compressive strength of concrete of 36 MPa at the age of 28 days was obtained from trial mixes.

3. TESTING

The tests were designed to simulate conditions in actual structures. Each slab was subjected to concentrated loading at the geometric center using a universal testing machine. Four steel blocks were used at each corner of the slab as support. These blocks confirmed the clear span of 1200mm for all samples. During testing, corner

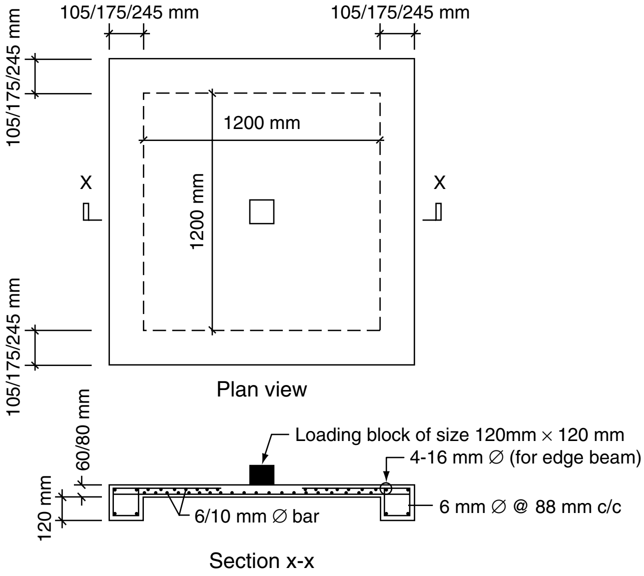

Figure 1. Details of a typical model slab with reinforcement

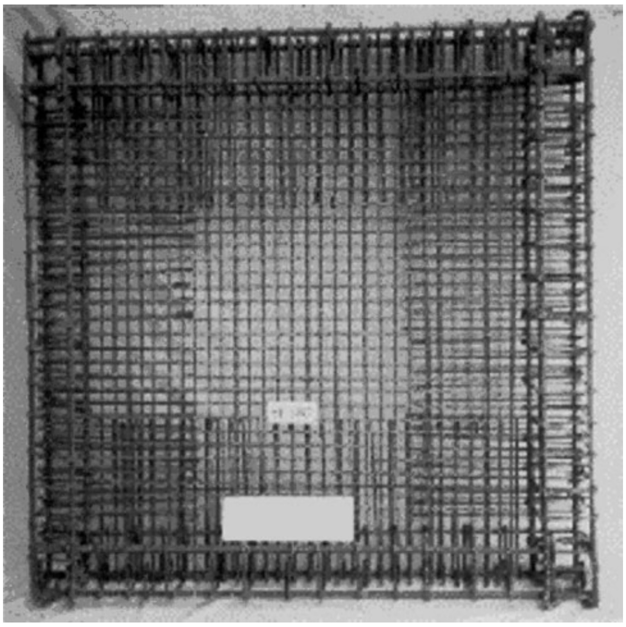

Figure 2. Photograph of typical model slab reinforcement with edge beam

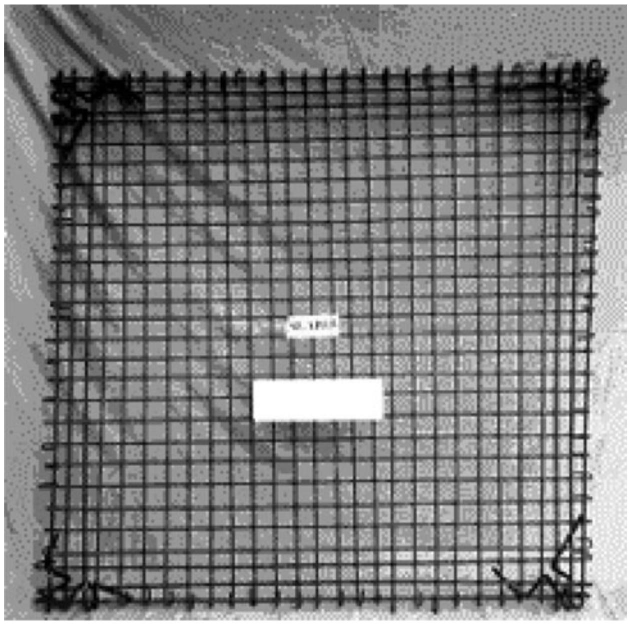

Figure 3. Photograph of typical model slab reinforcement without edge beam

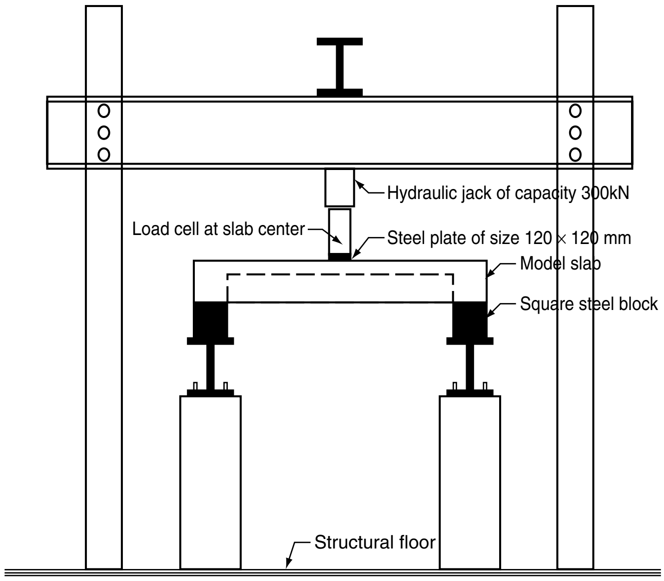

Figure 4. Testing set-up

sides of each sample were properly anchored by means of heavy joist, which was connected to structural floor. Loading was applied to specimen at an approximately constant rate up to the peak load; at the same time deflections were measured. Failure occurred abruptly in all specimens and loading was stopped after failure.

A test rig, consisting mainly of steel girder and 300 kN capacity hydraulic jack was used for the purpose of loading the slabs of various sizes under loading arrangements till failure. The load from the jack was applied to the model slabs at their geometric center through a 20 mm thick steel plate of 120mm × 120mm size, simulating a concentrated load. The applied load was measured using an accurately calibrated load cell. Loading was applied to the specimens in increments of 8.90 kN up to 71.17 kN and then in increments of 4.45 kN up to failure with measurements of deflections after each increment of loading. The testing set up and testing arrangement is shown in Figures 4 and 5.

There was one LVDT at the mid-span to measure the central slab deflection; one LVDT was placed at the middle span of one of the edge beams to measure

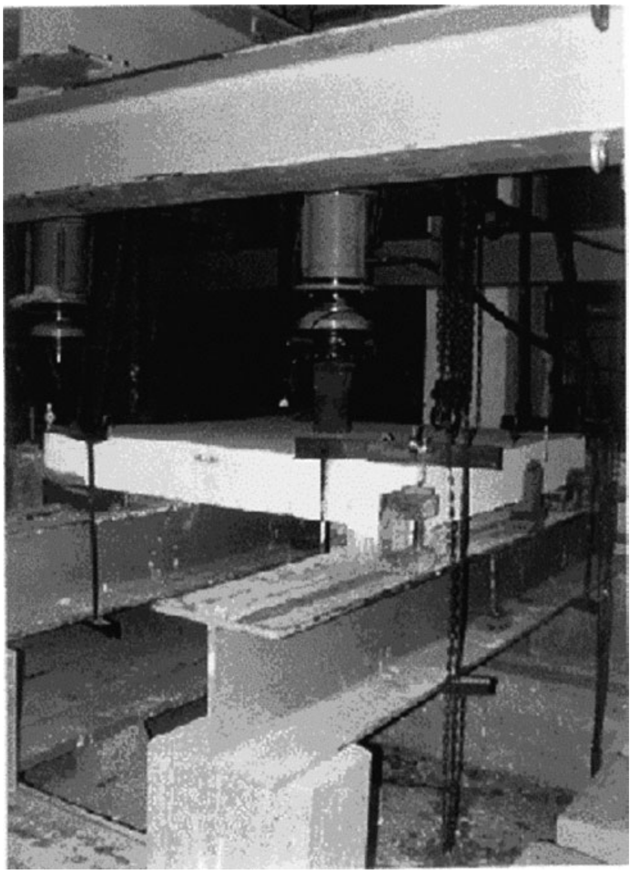

Figure 5. Test rig and testing arrangement

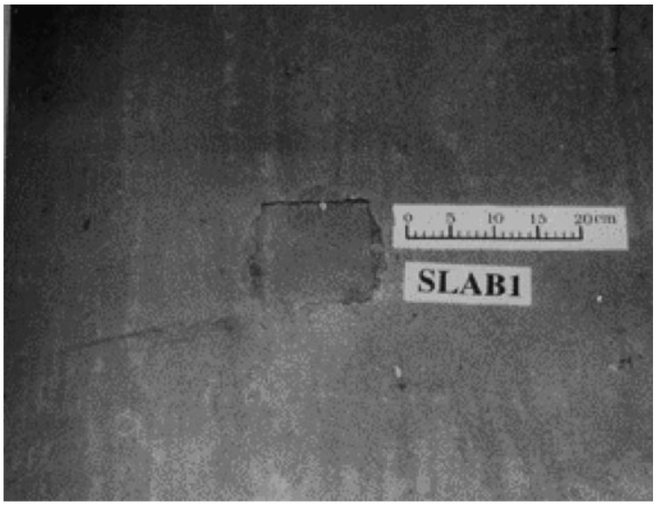

Figure 6. Typical cracking pattern on the top surface of a model slab

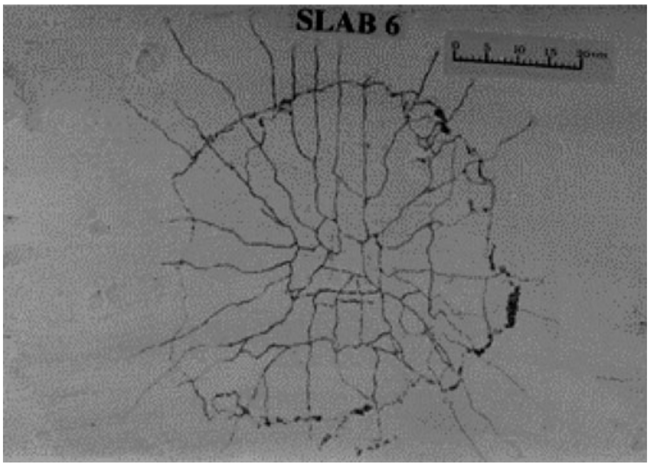

Figure 7. Typical cracking pattern on the bottom surface of a model slab

the central vertical deflection of the edge beam and four LVDTs were installed at the corner of edge beams to assess the performance of the supports. A scale was placed in each sample for the measurement of crack dimensions.

4. TEST RESULTS

All the models underwent punching type of failure with their inherent brittle characteristics and failed in a punching shear mode. Most of the slab samples failed at a load much higher than those predicted by the codes. The cracking pattern of the top surface of all the slabs were very much localized and approximately had a size of average 120mm x 120mm as shown in Figure 6. The cracking patterns at the bottom surface of slabs having low percentage of reinforcement were more severe than those having higher percentages of steel. It has been noticed that the surface area of cracked zone for the slabs having wider edge beams were more than those slabs having smaller edge beams. It has also been observed for all the samples that the deflection at support was negligible, pointing out to the fact that support fixity was ensured, albeit approximately, during the testing of the models. A typical crack pattern after failure on the bottom surface of slab model is shown in Figure 7.

5. DISCUSSIONS

Test results obtained from this study have been analyzed and shown in Table 2. It has been found that ultimate punching shear capacity and behavior of slab samples are dependent on restraining action of slab edges, flexural reinforcement ratio, slab thickness and span-to-depth ratio of the slab.

5.1. Deflection

The variation of slab deflection with applied load of all slabs is shown in Figure 8. It may be recalled that complete load-deflection curves of the entire slab tested could not be traced due to limitation of available instruments.

It is, however, clear from Figure 8 that central slab deflections were smaller for the slabs restrained by edge beams. The value of deflection decreased, in general, as

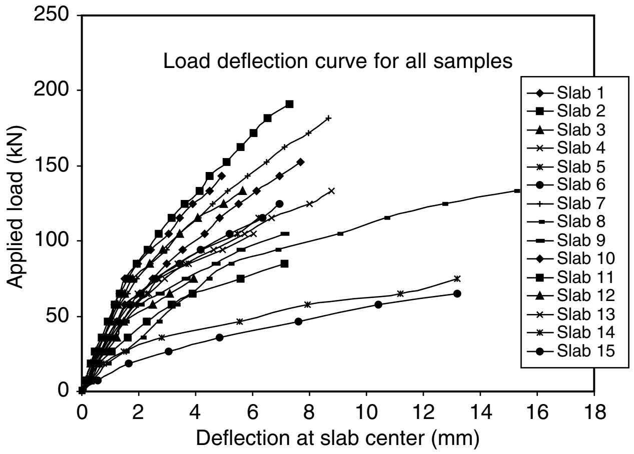

Figure 8. Deflection at slab center of all slabs under different loading

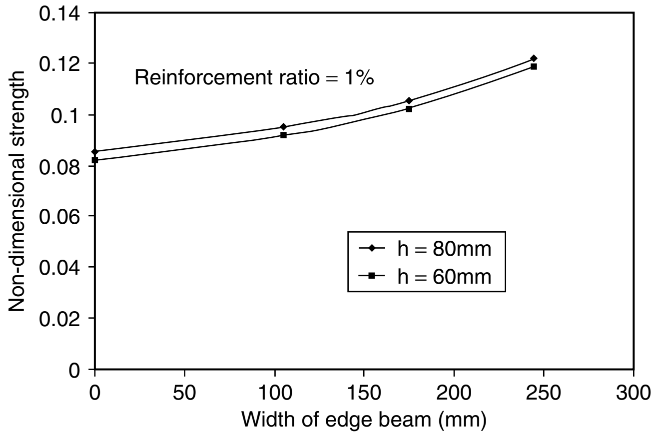

Figure 9. Effect of edge restraint for 1.0 percent reinforcement

Table 2. Test results, non-dimensional and normalized punching shear strength of reinforced concrete slabs

Slab sample	Slab thickness (h)	Reinforcement ratio (ρ)	Width of edge beam (b)	Experimental failure load (P_u)	Cylinder strength (f_c')	Non-dimensional strength	Normalized punching shear (strength
	mm	%	mm	kN	MPa	($P_u/f_c'b_0d$)	$P_u/\sqrt{f_c'}b_0d$)
SLAB1	80	0.5	245	225.16	38.51	0.1099	0.6820
SLAB2	80	1.0	245	242.09	37.42	0.1216	0.7439
SLAB3	80	1.5	245	142.95	28.19	0.0953	0.5061
SLAB4	60	0.5	245	138.12	38.24	0.1062	0.6569
SLAB5	60	1.0	245	147.59	36.60	0.1186	0.7175
SLAB6	60	1.5	245	130.51	41.95	0.0915	0.5927
SLAB7	80	1.0	175	181.64	32.45	0.1052	0.5994
SLAB8	60	0.5	175	133.27	41.30	0.0949	0.6099
SLAB9	60	1.0	175	115.51	33.14	0.1025	0.5902
SLAB10	80	1.0	105	188.89	37.45	0.0948	0.5802
SLAB11	60	0.5	105	112.88	40.43	0.0821	0.5221
SLAB12	60	1.0	105	115.73	37.04	0.0919	0.5593
SLAB13	80	1.0	0	171.96	37.72	0.0857	0.5263
SLAB14	60	0.5	0	84.73	34.71	0.0718	0.4230
SLAB15	60	1.0	0	91.76	33.03	0.0817	0.4696

the degree of edge restraint increased. Deflection is also very close in same thickness of slab with different reinforcement ratios. Although the higher the reinforcement, the smaller the deflection was observed for same loading as shown in these figures.

5.2. Ultimate Load Carrying Capacity

Analysis of test result as shown in Table 2, where non-dimensional punching shear strength $P_u/f_c'b_0d$, [where, d = effective depth of slab, $b_0 = 4 * (120 + d)$] and normalized punching shear strength $P_u/\sqrt{f_c'}\,b_0d$ of each specimen have been given. There is a general trend to increase the load carrying capacity of slabs with the increase of width of edge beam as well as flexural reinforcement of slab.

5.3. Effect of Edge Restraint

Table 2 shows that there was a definite increase in punching load of the slab panels as the degree of edge restraint increased. This trend is also evident in Figure 9, where punching shear capacity increased significantly with the increase in the width of edge beams up to 245 mm.

The enhancement in the punching load carrying capacity of slabs due to edge continuity may be attributed to the possible influence of in-plane restraint. Continuous slabs deflect less than similar simply

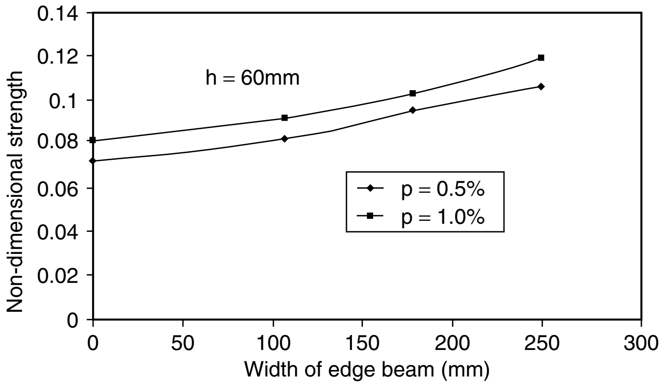

Figure 10. Effect of reinforcement for slab thickness of 60mm

supported slabs under the action of load. This helps the slabs having edge continuity to sustain more punching load (Alam 1997). Other researchers like Salim and Sebastian (2003), Kuang and Morley (1992), Lovrovich and McLean (1990), McLean *et al.* (1990) and Rankin and Long (1987) also advocated enhancement of punching shear capacity due to restraint action. Similar to the findings of other researchers, compressive membrane forces were, in fact, developed in the slabs due to edge restraints.

5.4. Effect of Steel Reinforcement

As shown in Figure 10, the load-carrying capacity of the test slab panels increased with the addition of flexural steel reinforcement.

Some other researchers such as Hallgren (1996), Marzouk and Hussein (1991), Vanderbilt (1972), Dilger *et al.* (2005), Gardner (2005) also advocated the increases in the punching load carrying capacity with the increase of flexural reinforcement of slab.

In the present study, non-dimensional strength of SLAB3 and SLAB6 having 1.50% flexural reinforcement are lower than similar type of other slabs. Excessive amount of reinforcement sometimes make structural concrete brittle as reported by Seraj et al. (1995). The decline in punching strength at higher level of reinforcement may also be due to such effects. However, additional tests are needed to investigate, in detail, the influence of the flexural reinforcement ratio on punching load capacity of concrete slabs.

5.5. Effect of Slab Thickness

As shown in Table 2, although the slab thickness is already in the denominator of the expression for dimensionless shear strength, it has been found that punching shear capacity of 80mm thick slabs having same edge restraint, clear span and reinforcement are higher than those of 60mm slabs. This is also evidenced in Figure 9.

5.6. Effect of Span to Depth Ratio

For smaller span to depth ratio of sample, the slab deflections at center were smaller than those of higher span to depth ratio. As shown in Table 2, slabs having same flexural reinforcement and edge restraint, non-dimensional strengths are higher for smaller span to depth ratio.

5.7. Cracks

During the tests, the development of cracking and the width of cracks were carefully observed and monitored at various load increments. Cracking on the underside of the slabs developed as a series of cracks radiating from the centrally loaded area. As the load increased, the widths of the cracks increased as expected. For lower level of reinforcement (ρ=0.5 percent), numbers of cracks were small and more spalling occurred than others. For higher level of flexural reinforcement (ρ=1.5 percent), cracks were concentrated in the middle portion of the slab.

Cracking pattern were fine and large in number in case of strongly restrained slabs, for moderately restrained slabs such cracks were found to be wider and fewer in number. In case of strongly restrained slabs, due to the presence of in-plane forces, the width of the cracks was less and consequently the total energy due to punching was distributed among a large number of fine cracks (Alam 1997; Kuang and Morley 1992). On the other hand, in slab having lesser amount of lateral restraint, initially produced cracks could widen and thereby, the total energy was distributed to lesser but wider cracks.

6. COMPARISON OF TEST RESULTS WITH DIFFERENT CODE PREDICTIONS

The load-carrying capacity of all the slab models as obtained from test results as well as from the predictions of ACI 318 (2005), BS 8110 (1997), CAN3-A23.3 (2004) and CEB-FIP (1990) is summarized in Table 3. Shear punching capacity by Rankin and Long's (Ranking and Long 1987) method is also included in Table 3. All terms related to various factor of safety have been put equal to 1.0. While calculating the predicted strength of slabs, actual compressive (cylinder) strength of concrete on the day of testing have been given as input, whereas compressive cube strength has been estimated to be 25 percent higher than its cylinder strength counterpart.

It is evident from Table 3, for both 80 mm and 60 mm thick slabs, that the experimental load carrying capacity is much higher than all the code predictions. American code (ACI 318 2005) has been found to be more conservative than the others codes while the European CEB-FIP (1990) code was the least

Table 3. Comparison of load carrying capacity with code predictions

Slab models	Experimental failure load in kN	Predicted ultimate load in kN: ACI 318	BS 8110	CAN3-A23.3	CEB-FIP	Rankin & long	Experimental failure load /Predicted Load: Expt. /ACI	Expt. /BS	Expt. /CAN	Expt. /CEB	Expt. /Rankin
SLAB1	225.2	108.9	104.8	132.1	139.2	115.2	2.07	2.15	1.70	1.62	1.95
SLAB2	242.1	107.3	132.0	130.2	153.0	135.1	2.25	1.83	1.87	1.59	1.79
SLAB3	143.0	93.2	144.9	113.0	126.7	129.7	1.53	0.99	1.27	1.12	1.10
SLAB4	138.1	69.4	66.6	84.1	89.7	73.4	1.99	2.07	1.64	1.54	1.88
SLAB5	147.6	67.9	83.9	82.3	97.6	85.4	2.17	1.76	1.79	1.51	1.73
SLAB6	130.5	72.7	96.1	88.1	106.9	101.1	1.80	1.36	1.48	1.22	1.29
SLAB7	181.6	100.0	132.0	121.2	139.1	125.8	1.82	1.38	1.50	1.31	1.44
SLAB8	133.3	72.1	66.6	87.4	94.5	76.3	1.85	2.00	1.52	1.41	1.75
SLAB9	115.5	64.6	83.9	78.3	91.3	81.2	1.79	1.38	1.48	1.26	1.42
SLAB10	188.9	107.4	132.0	130.2	153.1	135.1	1.76	1.43	1.45	1.23	1.40
SLAB11	112.9	71.3	66.6	86.5	93.1	75.4	1.58	1.69	1.31	1.21	1.50
SLAB12	115.7	68.3	83.9	82.8	98.4	85.9	1.69	1.38	1.40	1.18	1.35
SLAB13	172.0	107.8	132.0	130.7	158.8	135.6	1.59	1.30	1.32	1.08	1.27
SLAB14	84.7	66.1	66.6	88.1	84.1	69.9	1.28	1.27	0.96	1.01	1.21
SLAB15	91.8	64.5	83.9	78.2	91.1	81.1	1.42	1.09	1.17	1.01	1.13
						Average	1.77	1.54	1.46	1.29	1.48
						Coefficient of variation	0.148	0.224	0.157	0.153	0.180

conservative. The British code (BS 8110 1997) and the Canadian code (CAN3-23.3 2004) predictions fell in between the American and CEB-FIP (1990) codes. The trend of results calculated by Rankin and Long method (Rankin and Long 1987) are near to British and Canadian code.

It appears that for slab samples having 0.5 percent reinforcement, load carrying capacity predicted by the CEB-FIP (1990) and Canadian codes were closer to the experimental load carrying capacity for slabs having zero restraint. In this case, for restrained slabs, CEB-FIP (1990) code was, once again, found to be less conservative than all other codes. American and British codes, were most conservative in predicting the capacity of slabs having $\rho = 0.5$ percent. They also predicted similar conservative punching capacity.

It is also evident that the experimental load carrying capacity of the slabs increased with the increase in the degree of edge restraint provided by edge beams of larger widths. This restraining action of slabs has not been taken into consideration in any of the code provisions.

In view of the fact that ACI 318 (2005) is, perhaps, the most commonly used code in the world and also seems to form the basis of Bangladesh National Building Code (BNBC), the normalized punching shear strength using ACI code formula ($P_u/0.33\sqrt{f'_c}\, b_0 d$) for different edge restraints as well as reinforcement ratios are only 0.33 times $\sqrt{f'_c}\, b_0 d$, in reality as shown in Table 2, it may attain much higher values. Whereas, only further testing may lead to possible modifications in code provisions due to the dangerous nature of shear failure, CAN3-A23.3 (2004) already uses slightly higher values of 0.4 in a similar equation.

It is also shown in Table 3 that, experimental punching load carrying capacity of 1% flexural reinforcement is higher than all others of slabs of same thickness. Punching shear strength capacity with 1.5% flexural reinforcement as calculated by British, Canadian and CEB-FIP (1990) codes are close to the experimental load carrying capacity.

It is observed that punching shear capacity of slabs having 1.0 percent reinforcement and 80mm thickness, load carrying capacity in accordance with British and Canadian codes are very close. It appears that for slab samples having 0.5 percent reinforcement, load carrying capacity predicted by the European and Canadian codes were close and in SLAB14, this is very near to experimental punching capacity.

The coefficients of variation of test result with various codes or methods as shown in the Table 3 are within 14.8% to 22.4% and indicate the consistency of test results. According to the coefficient of variation, deviation from average value of the ratio of experimental load carrying capacity and predicted load capacity in accordance with American, Canadian and CEB are almost similar.

From the above discussion, it can be concluded that the present codes may not be capable of predicting the punching shear strength of reinforced concrete slabs satisfactorily taking into account the effect of edge restraint. For all the slabs tested, the prediction of ACI 318 (2005) is most conservative. On the other hand, although European CEB-FIP codes are very much on the conservative side, its prediction of punching failure load is better and more economical than the others.

7. CONCLUSIONS

Punching shear tests on fifteen reinforced concrete slabs have been reported in this paper. Twelve of these slabs were restrained at the edges to simulate continuous slab construction. The test results provided some basic experimental information on the behavior of restrained slabs subjected to concentrated loading. All the slabs failed in a punching mode when subjected to punching load at the slab centre. The following conclusions may be derived from the limited experimental work reported in this study:

a) Punching shear strengths observed from punching tests conducted on the restrained reinforced concrete slabs have been found to be higher than the predictions of present-day code provisions. Present code methods underestimate the punching load capacity of slabs as the code provisions are based on tests conducted on simply supported slabs with their edges unrestrained. The magnitude of the strength enhancement increases with the degree of edge restraint.

b) Whereas the level of flexural reinforcement may have a slightly negative or smaller effect on the ultimate punching shear capacity of the heavily reinforced slabs, it exerts a positive influence for those lightly reinforced. Although British, European CEB-FIP and German codes recognize the influence of percentages of steel, American, Australian and Canadian codes completely ignore the possible influence of the amount of flexural reinforcement in formulating its equations for punching shear capacity of slabs. The provisions of all these codes may, thus, be reviewed to accommodate the influence of flexural steel more rationally.

c) The outcome of the present series of tests may become useful for the development of a rational method of analysis. Further experimental research on a wide range of slabs is, of course, needed to consolidate the findings.

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NOTATION

b	width of edge beam
b_0	length of perimeter of critical section
d	effective depth of slab
h	slab thickness
P_u	experimental failure load
ρ	reinforcement ratio