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EFFECT OF EDGE RESTRAINT ON PUNCHING BEHAVIOUR OF SLABS

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SYNOPSIS

Punching shear is an important consideration in the design of flat plates, bridge decks and column footings. Present design rules for punching shear failure of reinforced concrete (RC) slabs, given in various codes of practice, are largely based on studies of the behaviour and strength of simply-supported, conventional specimens extending to the nominal line of contraflexure. As punching shear provisions incorporated in various Codes of practice are a direct result of the empirical procedures, they do not usually provide an accurate estimate of the ultimate load capacity of a slab with lateral restraint. This is because no direct account is taken of the possible enhancement due to the in-plane restraint in many types of reinforced concrete slab systems.

A total of 15 slabs have been tested in an effort to ascertain the influence of the degree of boundary restraint (provided by edge beams of various dimensions), percentage of steel reinforcement, and span-to-depth ratio of the slab specimens on their structural behaviour and punching load-carrying capacity. The significant positive effect of edge restraint on the punching failure load, resulting in enhancing the ultimate punching strength, has been noticed. The code-specified strength of the specimens was calculated in accordance with the American, British, Canadian and CEB-FIP codes. It became apparent that no code-specified method predicts an enhancement in the punching shear strength of a restrained concrete slab with an increase in the degree of such restraints. Present Codes do not recognize the role of percentage of longitudinal steel on the punching strength either. It has been understood that inclusion of the findings of the paper in the design Codes will result in an economic and rational design of structural systems where punching phenomenon plays a vital role.

INTRODUCTION

Columns tend to punch through the flat plates, flat slabs and footings because of the shear stresses which act around the perimeter of columns. At the same time the concentrated compression stresses from the column spread out into them (flat plates, flat slabs and footings) so that the concrete adjacent to the column remains in vertical or slightly inclined compression, in addition to shear. In consequence, if failure occurs, the failure surface takes the form of a truncated cone or pyramid with sides stippling outward at an angle approximately 45^0 around the reaction area. The punching shear provisions incorporated in various Codes of practices are deficient as they are usually based on tests conducted on simply supported slabs and, thus, fail to mimic the punching behaviour of continuous slab construction, whose all the panel edges can not rotate freely in contrast to its simply supported slab counterpart. Consequently, test results of simple slab specimens do not usually provide an accurate prediction of the ultimate load capacity of a slab having lateral restraint. It is the purpose of the present study to carry out a planned series of testing on restrained slabs in order to gather basic information on the real punching behaviour of RC slabs.

EXPERIMENTAL STUDY OF RC SLABS

Specimens details A total of 15 approximately one-fifth scale square reinforced concrete slab specimens were constructed and tested by Alam [1]. Twelve of these slabs had edge restraints in the form of beams, whereas the other three were normal slabs. In the model slabs, width of edge beam, slab thickness and reinforcement ratio were varied. The details of the slabs tested are given in Table 1 and Figure 1. The experimental model slabs with edge restraints (SLAB1-SLAB12) consist of a typical isolated slab-beam panel system, and the slab panel was supported and restrained on all four sides by edge beams. The edge beam was integrally connected with the slab, and the strength ratio of the beam to slab was such that the beam remain elastic until the failure of the slab. For all the specimens, the clear span of the slab panels was constant at 1200 mm, similarly to the slabs tested by Kuang and Morley [2]. The different span-to-depth ratios were achieved by varying the slab thickness, the chosen slab thickness being 80 mm and 60 mm, giving ratios of 15 and 20, respectively. Three levels of reinforcement (ρ = 0.5, 1.0 and 1.5 percent) in both the directions of the slabs were selected. The different degrees of edge restraint imposed at the slab surrounds were provided by having three different values of lateral rigidity of the edge beams, and the beam widths were 105, 175 and 245 mm. For the slabs having no edge restraints in the form of beams (SLAB13-SLAB15), slab thickness were 80 mm and 60 mm, and reinforcement ratio was 0.5 and 1.0 percent. During testing, although these slabs were provided with supports on all the four sides, absence of integrally constructed edge beams allowed them to rotate at the sides.

Table 1. Reinforced Concrete Slab Details

Slab	Width of edge beam	Slab thick-ness	Reinfor-cement ratio (ρ)	Main bars in each direction	Extra top bars in each direction	Edge beam reinfor-cement
	mm	mm	%	no-mm ϕ	no-mm ϕ	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	4-16
SLAB14	0	60	0.5	11-6	11-6	4-16
SLAB15	0	60	1.0	22-6	22-6	4-16

Materials The concrete used in the specimens consisted of ordinary Portland cement, sand and stone chips with maximum size 10 mm. The mix resulted in a cylindrical strength of approximately 36 MPa at an age of 28 days. Both 6 and 10 mm diameter plain steel bars, having an average yield strength of 414 MPa, were used in the slab panels. Flexural reinforcement in the edge beams were provided by 16 mm diameter deformed bar with a yield strength of 414 MPa.

Testing The specimen was put on four separate pedestals. To simulate continuos beam construction and prevent lifting of the other part of the specimen at the corners during testing, a channel was used at each corner, securely anchored to the structural floor by threaded rods, as shown in Figure 2. Linear variable displacement transducers (LVDTs) were used to record the central slab deflection and vertical deflection of the edge beams. The models were loaded at their geometric centre by a stiff screw jack with a capacity of 300 kN through a 120 mm square and 20 mm thick steel plate, simulating a concentrated load.

DISCUSSION OF RC SLAB TEST RESULTS

Ultimate load capacity All the slab panels, including those with low- (0.5 %) to high-percentage (1.5 %) of steel - with or without edge restraint - failed in a

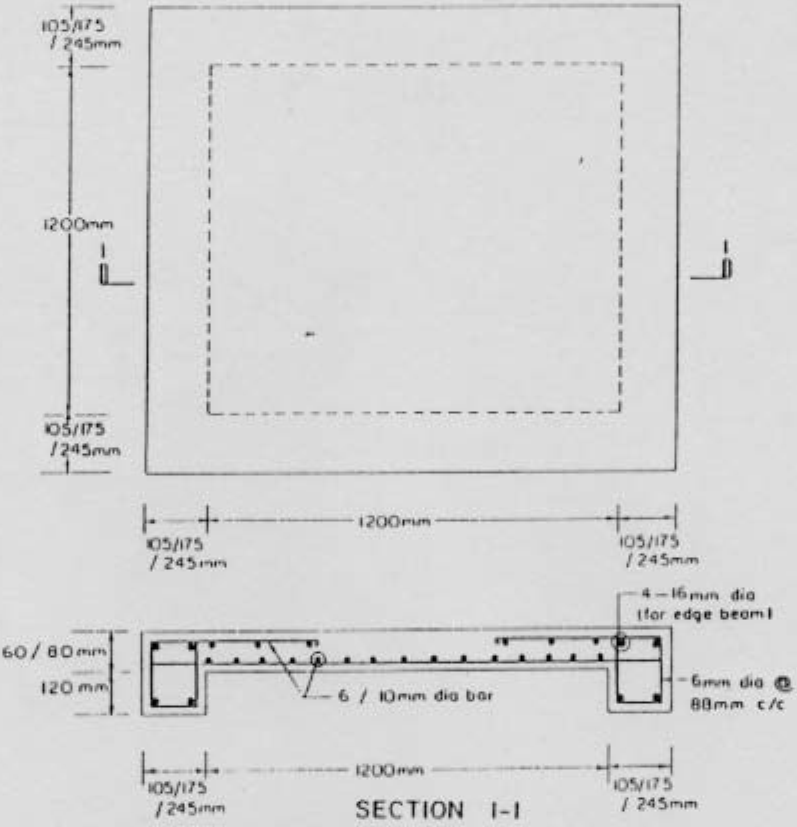


Figure 1: Dimensional, Cross-Sectional and Design Details of RC Slabs Tested

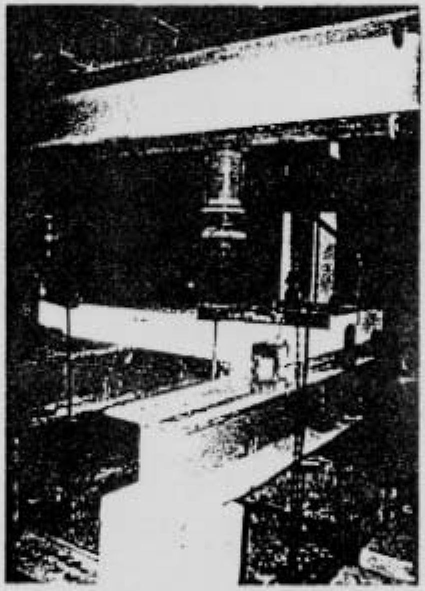


Figure 2: Testing Set-Up

punching shear mode. A summary of the test results is presented in Table 2, where non-dimensional punching shear strength ($P_u/b_o d f'_c$) of each specimen is also given, calculated by dividing the corresponding ultimate punching loads by the product of the compressive strength of concrete and the critical surface located at half the effective depth away from the perimeter of the load.

Effect of edge restraint Table 2 shows that there was a definite increase in ultimate punching load of the slab panels as the degree of edge restraint increased. This trend is very evident in Figure 3 from which it can be seen that the load-carrying capacity increased significantly with the increase in the width of edge beams from zero to 245 mm. Figure 3a shows the corresponding enhancements of ultimate non dimensional strength, for slabs having 1 percent steel, were approximately 45 percent for the thin slab (h = 60 mm) and 42 percent for slightly thicker slabs (h = 80 mm). Similar increases in strength were found in Figure 3b for RC slab panels irrespective of the level of reinforcement (ρ = 0.5 and 1.0 percent). Kuang and Morley [2], however, reported that for lightly reinforced slabs (ρ = 0.3 percent), such an increase in strength due edge restraint is less marked. This reveals that the edge restraint has a significant effect on the ultimate punching load of reinforced concrete slabs, resulting in a great increase in the shear resistance of the slabs and enhancing effectively the load-carrying capacity of the members subjected to punching load.

Table 2. Reinforced Concrete Slab Test Results

Slab	Effective depth (d)	b_o = 4(120+d)	Ultimate load (P_u)	Cylinder strength (f'_c)	Non-dimensional strength
	mm	mm	kN	MPa	
SLAB1	70	760	225.16	38.51	0.1099
SLAB2	70	760	242.09	37.42	0.1216
SLAB3	70	760	142.95	28.19	0.0953
SLAB4	50	680	138.12	38.24	0.1062
SLAB5	50	680	147.59	36.60	0.1186
SLAB6	50	680	130.51	41.95	0.0915
SLAB7	70	760	181.64	32.45	0.1052
SLAB8	50	680	133.27	41.30	0.0949
SLAB9	50	680	115.51	33.14	0.1025
SLAB10	70	760	188.89	37.45	0.0948
SLAB11	50	680	112.88	40.43	0.0821
SLAB12	50	680	115.73	37.04	0.0919
SLAB13	70	760	171.96	37.72	0.0857
SLAB14	50	680	84.73	34.71	0.0718
SLAB15	50	680	91.76	33.03	0.0817

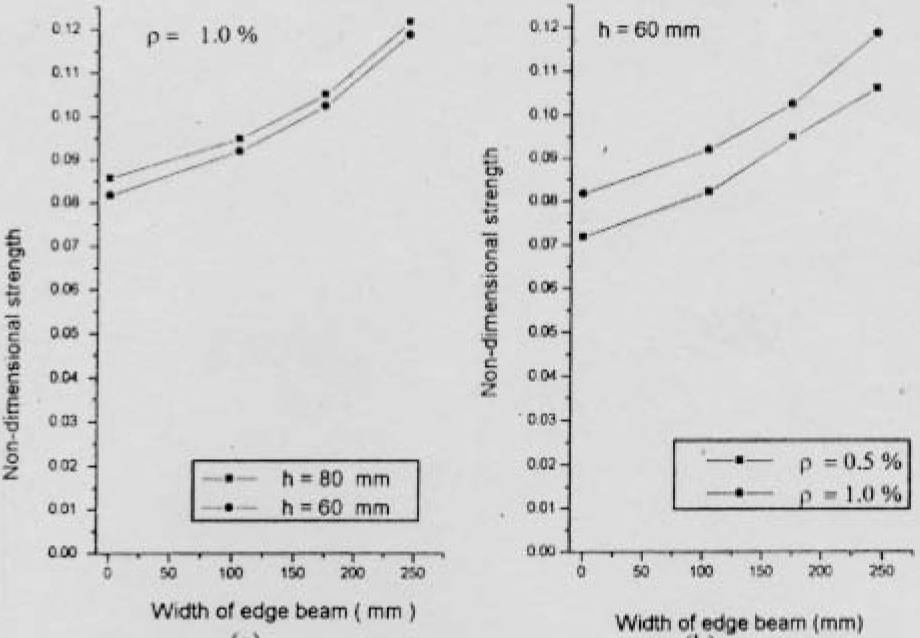
Influences of steel reinforcement and slab thickness The ultimate non-dimensional punching shear strengths are plotted in Figure 4 against the reinforcement ratio for the specimens having b equal to 245 mm. The load-carrying capacity of the test slab panels increased as the reinforcement ratio increased from 0.5 to 1 percent. The corresponding increases in the ultimate non-dimensional strength were 12 percent for the slabs with 60 mm thickness and 11 percent for those with 80 mm thickness. However, in contrast to the findings of Kuang and Morley [2], when the percentage of steel was over 1 percent, the non-dimensional punching shear strength decreased, by 14 percent for the slabs with 60 mm thickness and 13 percent for those with 80 mm thickness, with respect to similar slabs having 0.5 percent reinforcement. Kuang and Morley [2] reported virtually no change in non-dimensional punching shear strength in such cases. This indicates that whereas steel reinforcement has a positive effect on the punching shear strength for the lightly reinforced restrained slabs, for those that are heavily reinforced such effects may become negative. However, additional tests are needed to investigate, in detail, the influence of the reinforcement ratio on punching load capacity of restrained concrete slabs, especially for those with lower level of edge restraints.

Figure 4 also shows that the thicker the slabs, the higher the dimensionless punching shear strength, showing that the thickness is an important factor affecting the punching load capacity of a reinforced concrete slab with a given degree of restraint, despite the fact that thickness is already in the denominator of the expression for dimensionless shear strength.

Slab deflection The variation of central slab deflections of slabs with applied load revealed that the .deflections were smaller for the slabs restrained by edge beams. The value of deflection decreased as the degree of edge restraint increased. The heavily restrained slabs underwent less deflection, as expected.

Cracking During the tests, crack propagation was carefully monitored at various load increments. Cracking on the underside of the slabs developed as a series of cracks radiating from the central loaded area. The crack widths of normal to heavily reinforced (ρ = 1.0 to 1.5 percent) slabs were smaller than those of lightly reinforced slabs (ρ = 0.5 percent). Again, the crack were fine but large in number at the strongly restrained slab, whereas they were wider and fewer in number for weakly restrained slab. The crack pattern on the underside of some of the slabs tested to failure are shown in Figure 5. The discontinuity on the top of surface of the slabs after punching shear failure typically took the square geometry of the punching plate.

Comparison with design codes A comparison of the experimental failure loads and the punching shear strength predicted by various codes has been



(a) (b)

Figure 3: Effect of Edge Restraint on Punching Shear Capacity for (a) Different Slab Thickness and (b) Different Reinforcement Ratios

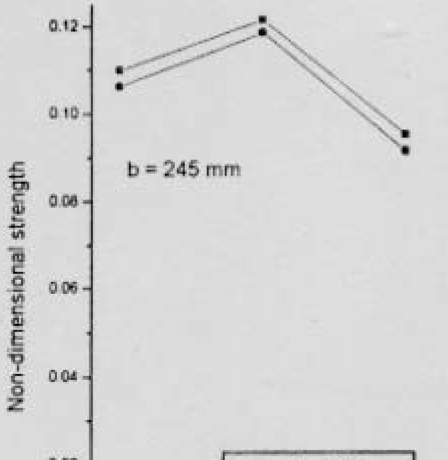


Figure 4: Influence of Reinforcement Ratio on Ultimate Punching Capacity

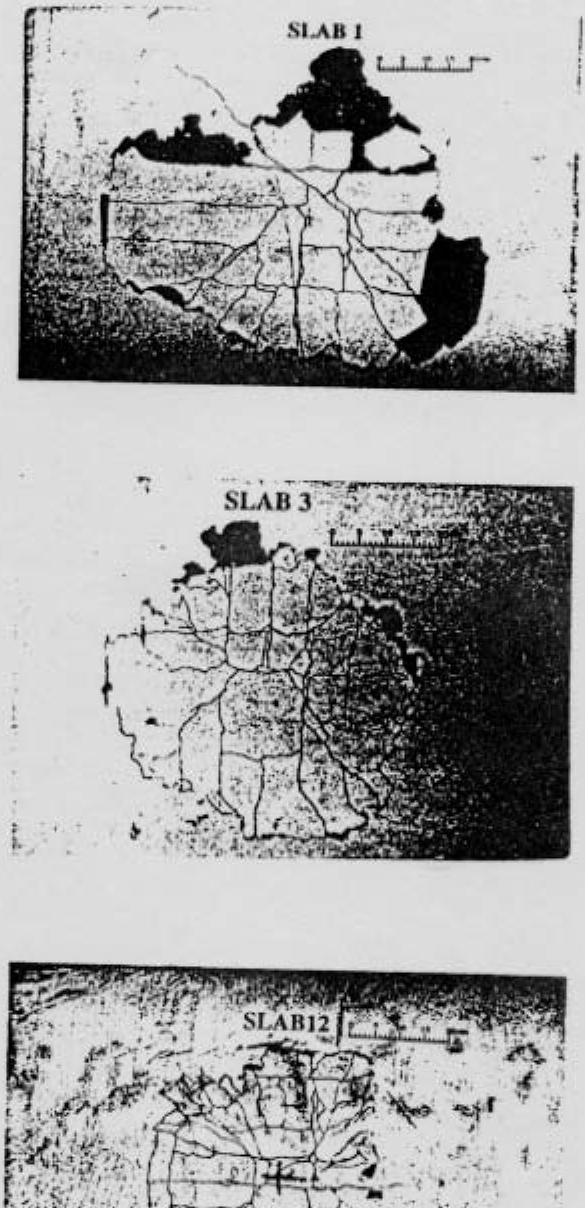


Figure 5: Crack Pattern on Bottom Surface of SLAB1, SLAB3 and SLAB12 Tested

made and shown in Figure 6. The code-predicted punching strengths of the specimens were calculated in accordance with ACI 318-89 [3], BS 8110 [4], CAN-A23.3-M84 [5] and CEB-FIP [6]. Partial safety factors, reduction factors, etc. have been removed in this exercise. Concrete cube strength has been taken as 25 percent higher than its cylinder strength counterpart on the day of testing the slabs. It is evident from the figure that the present codes are not capable of predicting the punching shear strength of RC slabs satisfactorily. For all the slabs tested, the prediction of ACI 318-89 was most conservative. On the other hand, although CEB-FIP code predictions were also very much on the conservative side, its predicted the failure load better that the others. In general, all the codes failed to cater for the beneficial effect of edge restraint.

CONCLUSIONS

The test results provided basic experimental information on the behaviour of restrained slabs subjected to concentrated loading. All the slabs failed in a punching shear mode when subjected to punching load at the slab centre.

- Punching shear strengths observed from punching tests conducted on restrained reinforced concrete slabs have been found to be much higher than the predictions of present-day design provisions. Present code methods under estimate the punching load capacity of the specimens, as the code expressions are based on tests on simply-supported slabs with their edges unrestrained. The magnitude of the strength enhancement increases with the degree of edge restraint. Whereas the level of steel reinforcement has negative effect on the ultimate punching shear capacity of the heavily reinforced specimens, it exerts a positive influence for those lightly reinforced.

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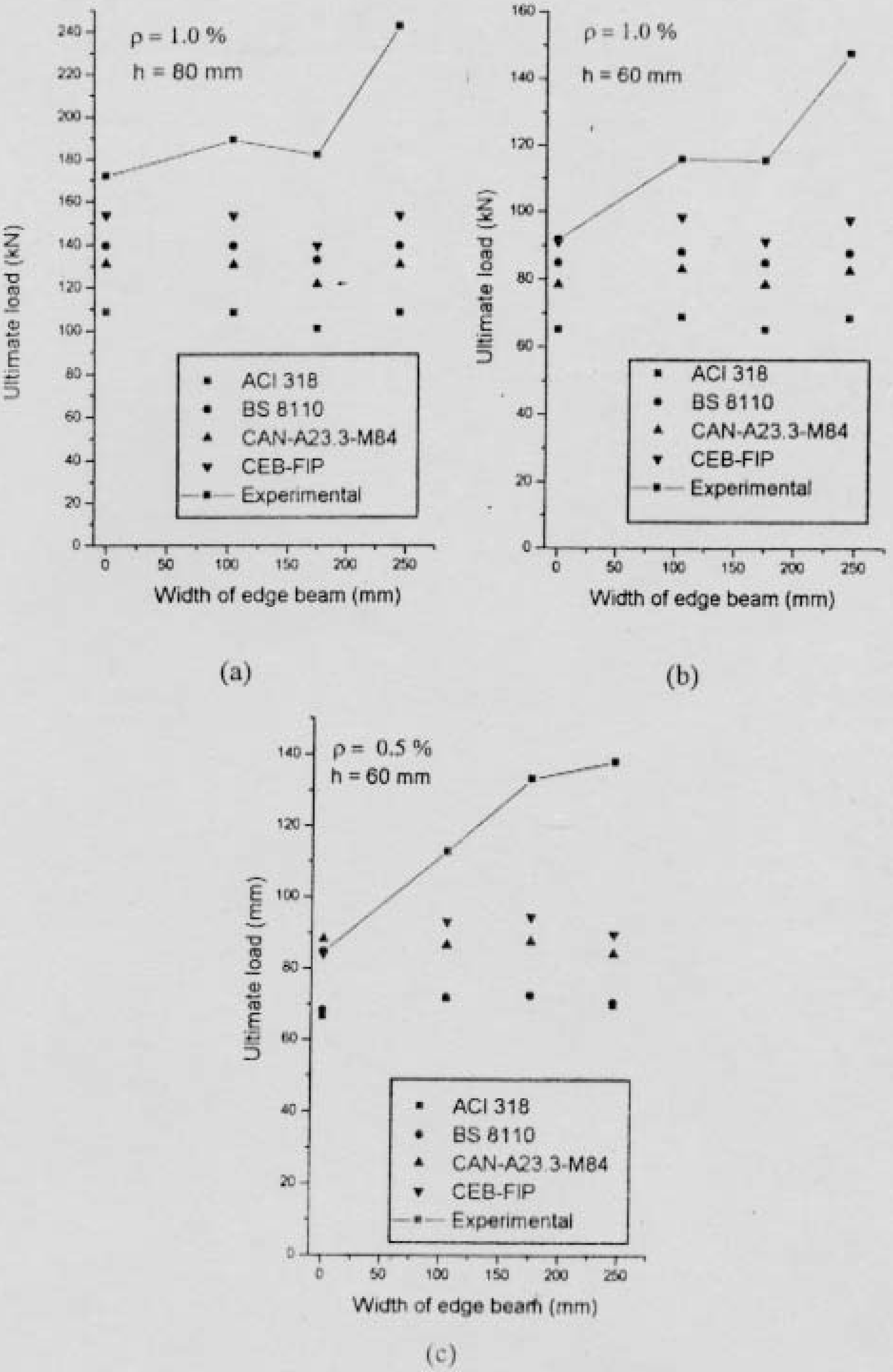

(a) (b)

(c)

Figure 6: Comparison of Test Results with Code Predictions