PUNCHING BEHAVIOUR OF FOOTINGS ON SAND

S. M. Seraj [1] and M. G. Mostafa [1]

[1] Department of Civil Engineering, Bangladesh University of Engineering & Technology, Dhaka 1000, Bangladesh

ABSTRACT

Present design codes indiscriminately use equations, based on punching tests conducted on simply-supported slabs, extending to the nominal line of contraflexure, for the design of footings. The present paper describes punching tests conducted on several reinforced concrete footings resting on sand. During tests, percentage of steel reinforcement, depth, size and concrete strength of specimen and punching are were varied. It became apparent that code-specified method do not address adequately the consequence of upward pressure and deformational characteristics of soil on the punching strength of footings. Present Codes do not recognize the role of percentage of longitudinal steel on the punching strength either. It appears that inclusion of the tenets of the paper in the design codes will result in an economic and rational design of footings where punching phenomenon plays a vital role.

KEYWORDS

Punching strength, Footing, Sand, Code, Deformation, Design parameters

INTRODUCTION

Punching shear is an important consideration in the design of reinforced concrete (RC) flat plates, bridge decks, column footings and mat foundations. Present design rules for the punching shear strength of RC slabs, footings, etc., 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 significant enhancement due to the in-plane restraint in many types of reinforced concrete slab systems. Again, present codes indiscriminately use equations, based on punching tests conducted on slabs, for the design of footings and mat foundations and, thus, fails to address the punching behaviour/strength pertaining to footings and mat foundations faithfully. Again, present codes usually represent punching shear strength merely as a function of concrete strength and ignores the possible effects of percentage of steel, span-to-depth ratio, etc. The present paper reports a planned series of testing on model footings resting on sand bed in order to gather basic information on the real punching behaviour of RC footings. The effect of various parameters has been studied by plotting them against the non-dimensional punching strength. The maximum sustained punching loads have been compared with their code counterparts, as well.

EXPERIMENTAL STUDY OF RC FOOTINGS

Footing Details

A series of square reinforced concrete footing specimens have been constructed and tested by Mostafa (1997). Findings pertaining to fifteen of such footings will be reported here. In the model footings, size of the footings, footing thickness (t), reinforcement ratio and concrete strength were varied. The details of the footings tested are given in Table 1. In Table 1, ρ stands for percentage of reinforcement in each direction and $f'c$ stands for uniaxial cylinder strength of concrete on the day of testing.

TABLE 1
REINFORCED CONCRETE SLAB DETAILS

Footing	Size B x B	t	ρ	f'c
	mm x mm	mm	%	MPa
FOOT1	750 x 750	55	0.40	33.74
FOOT2	750 x 750	55	0.65	33.74
FOOT3	750 x 750	55	0.85	33.74
FOOT4	600 x 600	55	0.40	33.74
FOOT5	900 x 900	55	0.40	33.74
FOOT6	750 x 750	65	0.55	33.74
FOOT7	750 x 750	75	0.48	33.74
FOOT8	900 x 900	55	0.40	38.80
FOOT9	900 x 900	55	0.40	29.32
FOOT10	750 x 750	55	0.40	33.74
FOOT11	750 x 750	55	0.40	33.74
FOOT12	600 x 600	55	0.65	33.74
FOOT13	900 x 900	55	0.65	33.74
FOOT14	600 x 600	55	0.40	29.32
FOOT15	600 x 600	55	0.40	38.80

Thus, while the size of the footings were varied in the range of 600 mm x 600 mm to 900 mm x 900 mm, the footing thickness chosen in the models were 55, 65 and 75 mm. Again, the level of reinforcement (ρ) in both the directions of the footings was kept approximately in the range of 0.4 to 0.85 percent. On the day of testing, at an age of about 150 days, the concrete strength varied approximately in the range of 29 to 39 MPa. While all but footings FOOT10 and FOOT11 were subjected to punching load over 100 mm x 100 mm area through 20 mm thick steel plates, FOOT10 and FOOT11 were loaded over 75 mm x 75 mm and 120 mm x 120 mm, respectively, in order to investigate the effect of punching area on the punching strength of RC footings.

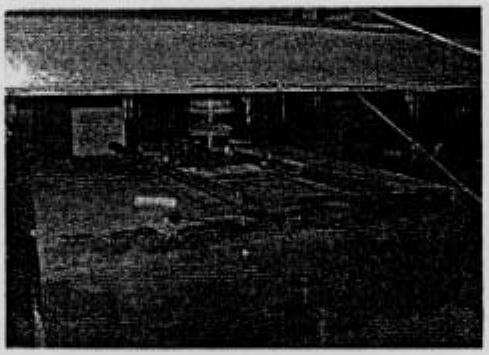
Materials

The concrete used in constructing the specimens consisted of ordinary Portland cement, sand and stone chips having maximum size 10 mm. Plain steel bars having a nominal bar diameter of 7 mm, having an average yield strength of 414 MPa, were used in the footing as longitudinal reinforcement.

Testing Rig and Testing Procedure

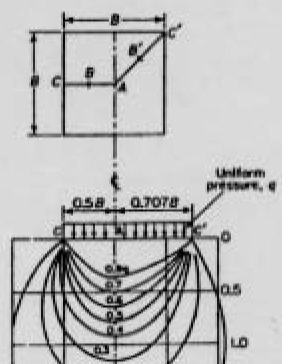
A testing rig was specially designed for testing the model footings (see Figure 1). The rig comprised of a testing tank filled with sand, loading jack and linear variable displacement transducers (LVDTs). In order to simulate the effect of infinitely extending soil surface, the inside dimensions of the tank was chosen as 2.1 m long, 2.1 mm wide and 2.2 m high, following the findings of Teng (1977). It is to be noted that Teng (1977) reported, based on Boussinesq's equation, that the vertical stresses under a square footing usually become less significant at a horizontal distance equal to B (i.e. the length or width of footing), from its centre and at a vertical distance of about twice the footing size (Figure 2). The tank was filled with compacted sand. Prior to each testing, samples were taken to measure the moisture content and unit weight of sand. On an average the sand below the footings had an unit weight of 1618 kg/m^3 and a moisture content of 3-3.5%. From direct shear test, the angle of internal friction was found to be about 27°. A total of six LVDTs were used to record the deflections of footing centre, four corners, as well as possible out of plane displacement of the walls of the testing tank. The models were loaded at their geometric centre by a stiff screw jack with a capacity of 300 kN simulating a concentrated load.

Figure 1



Testing set-up

Figure 2



Vertical stress under a square footing, Teng (1977)

DISCUSSION OF TEST RESULTS

Ultimate Load Capacity

All the footings, including those with low- (0.4%) to moderate-percentage (0.85 %) of steel failed in a 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 maximum sustained punching loads (P_u) by the product of the compressive strength of concrete and the critical surface located at half the effective depth (d) away from the perimeter of the load. During tests, after each load increment, load was kept constant for at least two minutes for stabilizing the whole system and monitoring the behaviour of test footings. Although the actual load at which punching failure took place was slightly above P_u, in the present study maximum sustained load (i.e. one load step prior to the actual failure load step) has been considered as the ultimate punching capacity. It is to be noted that the P_u values reported in Table 2 have been obtained after deducting appropriate soil reaction, within punching perimeter, from the load actually monitored during tests.

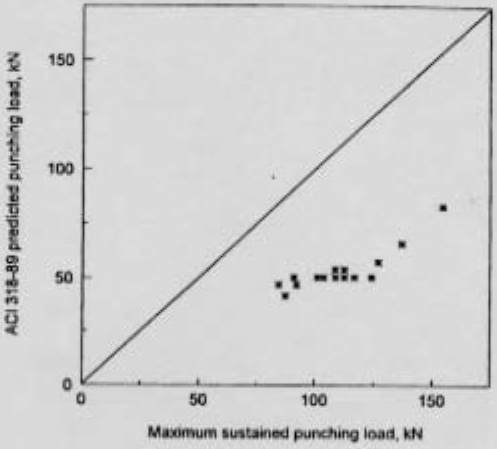
TABLE 2
RC FOOTING TEST RESULTS

Footing	d	Punching perimeter b_o	P_u	Non-dimen. strength
	mm	mm	kN	
FOOT1	45	580	90.95	0.103
FOOT2	45	580	101.07	0.114
FOOT3	45	580	124.01	0.140
FOOT4	45	580	103.80	0.117
FOOT5	45	580	112.52	0.127
FOOT6	55	620	136.84	0.118
FOOT7	65	660	154.45	0.107
FOOT8	45	580	112.52	0.111
FOOT9	45	580	92.02	0.120
FOOT10	45	580	87.31	0.119
FOOT11'	45	580	126.84	0.126
FOOT12	45	580	108.77	0.123
FOOT13	45	580	116.83	0.132
FOOT14	45	580	84.38	0.110
FOOT15	45	580	108.77	0.107

Comparison With ACI 318-89 Design Code

A comparison of the maximum sustained punching load during testing and the punching shear strength predicted by ACI 318-89 (1989) code has been made and shown in Figure 3. During the calculation of code-predicted punching strengths of the specimens, partial safety factors, reduction factors, etc. have been removed. It is evident from the figure that the ACI code is not capable of predicting the punching shear strength of RC footings satisfactorily. For all the footings tested, the prediction of ACI 318-89 was highly conservative; the actually sustained punching load being about twice the load predicted by ACI 318-89.

Figure 3



Comparison of ACI 318-89 predicted punching load with maximum sustained load during testing

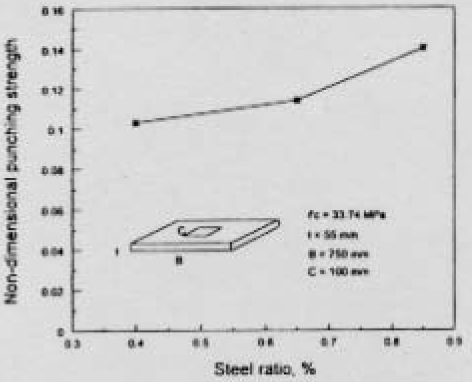
Effect of Reinforcement Ratio

The ultimate non-dimensional punching shear strengths are plotted in Figure 4 against the steel ratio. It is clear that the punching shear strength of footings on sand increases with a corresponding increase in the amount of steel ratio. Whereas such increase is of the order of 11% for an increase in ρ from 0.4% to 0.65%, when ρ changes from 0.65% to 0.85%, the punching shear strength increases by 23%. A total increase of about 36% in the amount of punching shear strength, due to an increase in ρ from 0.4% to 0.85%, clearly demonstrates the positive impact of the amount of steel reinforcement on the punching shear strength of footings. It is worth reiterating that almost all the major codes ignore the effect of quantity of steel on the punching shear strength of footings and mats.

Effect of Footing Size

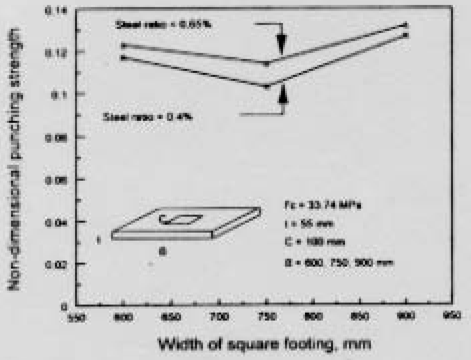
The non-dimensional punching strengths of various square footings have been plotted against footing size in Figure 5. For footings with 0.65% steel, as the width of footing increases from 600 mm to 750 mm, and then from 750 mm to 900 mm, the strength initially decreases by 8% and then increases by 16%. Thus, due to a change in footing area by 225%, the punching strength merely increases by 7%. Similar trend has been observed for footings with lighter reinforcements. Thus, it may be concluded that overall footing size has very little effect on the punching strength of footings.

Figure 4



Effect of reinforcement ratio on punching capacity

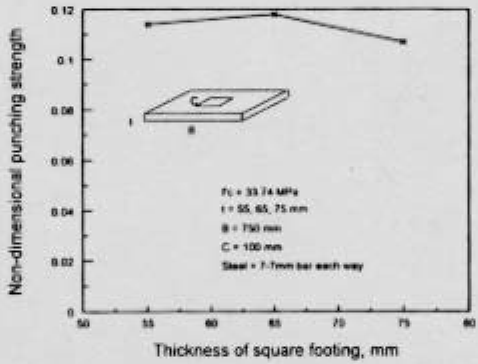
Figure 5



Effect of footing size on punching capacity

Effect of Footing Thickness
The non-dimensional punching shear strengths of footings have been plotted in Figure 6 by varying the thickness of footings. All other parameters have been kept constant. In all the footings, 7-7 mm ϕ bars have been used in both the directions. Thus, although the amount of steel in all the specimens was same, the percentage of steel actually decreased with an increase in the footing thickness. Figure 6 shows that whereas the initial portion of the curve is almost flat, with further increase in the thickness, the strength actually decreases slightly. This descending branch of the curve may be attributed to the decrease in the percentage of steel, as it has been demonstrated earlier that the amount of steel has a definite positive effect on punching strength. The presently adopted code methodology, where thickness has been considered to have a linear contribution towards the punching strength may, thus, be tentatively considered to be valid.

Figure 6

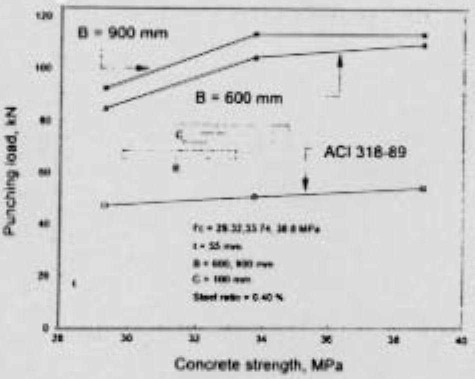


Effect of footing thickness on punching capacity

Effect of Concrete Strength
All the codes of practice give particular importance of the strength of concrete on the ultimate punching shear capacity. The punching load sustained by various footings of different sizes have been plotted against corresponding cylinder strength of concrete in Figure 7. The failure loads predicted by ACI 318-89 have also been included in the figure. The figure shows that concrete strength has, indeed, very positive influence on punching strength of footings. The inadequacy of ACI 318-89 is also evident. It is interesting to note that the effect of concrete strength becomes almost insignificant after f_c reaches 33.74 MPa. This finding is in-line with the recommendation of BS 8110 (1985), where concrete cube strengths above 40 MPa (equivalent to about 32 MPa cylinder strength) are not considered in calculating the beam and punching shear strength of various RC members.

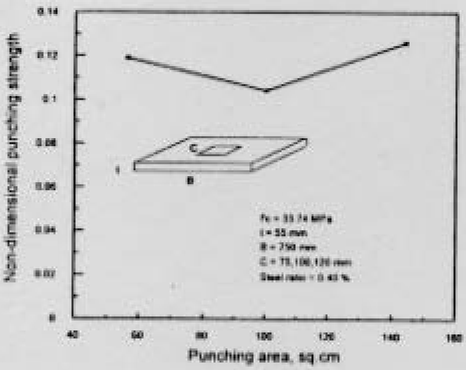
Effect of Punching Area
The non-dimensional punching shear strengths of footings have been plotted against punching area in Figure 8. Whereas a horizontal line would have validated the code methodology of considering punching shear strength proportional to the punching perimeter (b_0), the actual curve sheds slight doubt on the approach. In case of footings, the amount and profile of soil reaction is a vital factor and consideration of uniform soil pressure underneath the footing may lead to erroneous results. It is worth mentioning here that pressure distribution under a footing is expected to vary depending upon soil type (sand, clay, etc.) and code methods should address this issue faithfully to arrive at a realistic prognosis.

Figure 7



Effect of concrete strength on punching capacity

Figure 8



Effect of punching area on punching capacity

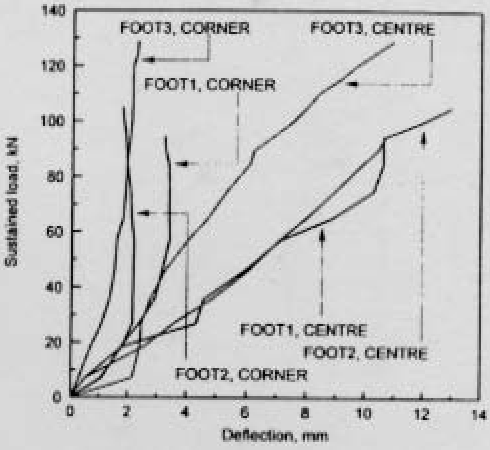
Footing Deflection

Whereas a detailed account of the load-deflection behaviour of all the footings tested is available elsewhere in Mostafa (1997), the variation of central as well as corner deflections of footings FOOT1, FOOT2 and FOOT3 are shown in Figure 9. Although there have been four LVDTs at each of the four corners, only one of them have been plotted as they recorded similar values. In Figure 9, deflections due to initial bedding-in effect have not been corrected. The total amount of central deflection with respect to edges, for all the footings, did not vary to a great extent. All the edges underwent slight uplift near failure loads.

Cracking Pattern

At the end of the tests, cracking pattern on both sides of the footings was carefully monitored. Cracking on the underside of the slabs developed as a series of cracks radiating from the central loaded area. The crack width and extent of various footings varied depending on the size and thickness of the footing, percentage of steel, concrete strength, etc. Again, a complete picture of the cracking patterns of all the specimens tested is available in Mostafa (1997). The discontinuity on the top of surface of the footings after punching shear failure typically took the square geometry of the punching plate (see Figure 10). Figure 11 shows the crack pattern on the underside of some of the footings loaded to punching failure in this study.

Figure 9



Load-deflection relationship of various footings

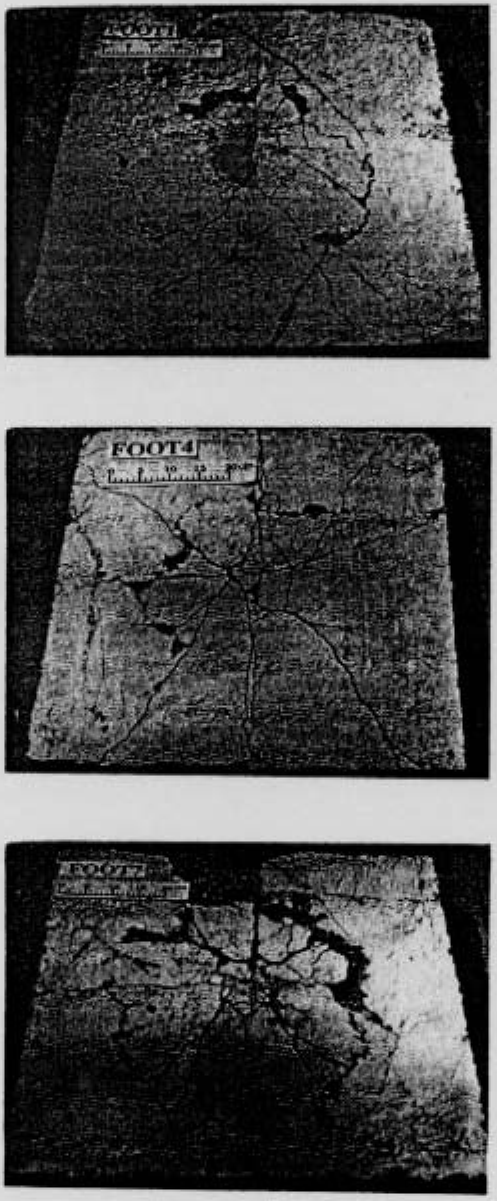
Figure 10

Crack pattern on top surface of FOOT1 tested

CONCLUSIONS

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

Figure 11



Crack pattern on underside of FOOT1, FOOT4 and FOOT7 tested

Punching shear strengths observed from punching tests conducted on reinforced concrete footings have been found to be much higher than the predictions of present-day design provisions. Present code methods grossly underestimate the punching load capacity of the footings, as the code expressions are based on tests on simply-supported slabs, not footings on sand or clay bed.

Percentage of longitudinal steel has been found to have a very positive influence on the punching strength of footings. The overall footing size has very little effect on the punching strength of footings. Since pressure distribution under a footing is expected to vary depending upon soil type, the code provisions for footings should address this issue faithfully to arrive at a realistic prognosis. Concrete strength has a very positive influence on punching strength of footings. The effect of concrete strength, however, becomes almost insignificant as the compressive strength of concrete reaches high values.

REFERENCES

ACI 318-89. (1989). *Building Code Requirements for Reinforced Concrete*, American Concrete Institute, Detroit.

BS 8110. (1985). *Structural Use of Concrete: Part 1: Code of Practice for Design and Construction*, British Standard Institution, London.

Mostafa, M. G. (1997). *Punching Behaviour of Footings*, M. Eng. thesis, BUET.

Teng, W. C. (1977). *Foundation Design*, Prentice-Hall International, New Delhi.