Alexandria Engineering Journal (2017) **xxx**, xxx–xxx

HOSTED BY
ELSEVIER

Alexandria University
Alexandria Engineering Journal
www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Effect of flexural and shear reinforcement on the punching behavior of reinforced concrete flat slabs

Rasha T.S. Mabrouk *, **Amr Bakr**, **Hany Abdalla**

Structural Engineering Department, Faculty of Engineering, Cairo University, Egypt

Received 15 April 2017; accepted 14 May 2017

KEYWORDS

Punching;
Flat slabs;
Flexural reinforcement;
Shear reinforcement;
Crack pattern;
Ductility

Abstract Punching is one of the most important phenomena to be considered during the design of reinforced concrete flat slabs. Three main factors affect the punching behavior. These factors are concrete compressive strength, horizontal flexural reinforcement, and vertical shear reinforcement in the form of stirrups, studs or other forms. This paper is part of an ongoing research program conducted at the concrete laboratory of the Faulty of Engineering, Cairo University to assess the contribution of horizontal flexural reinforcement and vertical shear reinforcement on the punching behavior of reinforced concrete flat slabs. In the current research, seven half scale specimens are cast and tested. The specimens had dimensions of 1050 × 1050 mm and a total thickness of 100 mm. All specimens were connected to a square column of dimensions 150 × 150 mm and loaded at the four corners with a span 950 mm. The parameters considered in this research included spacing between vertical stirrups, width of the stirrups, number of stirrups branches and the ratio of the horizontal flexural reinforcement. During testing, ultimate capacity, steel strain, cracking pattern and deformation were recorded. The experimental results were analyzed and compared against values estimated from different international design codes.

1. Introduction

Punching failure is a brittle failure caused by shear diagonal cracks developed through the full slab thickness forming a frustum pyramid in rectangular columns and a trenched cone in circular ones. Punching failure is a common failure that can be seen in reinforced concrete flat slabs as well as other structural elements such as foundations. Many factors affect the punching capacity of slabs such as concrete strength, column to slab aspect ratio, flexural reinforcement, shear reinforcement and boundary conditions. Design codes deal with the punching failure problem in different ways. For example, the current Egyptian Code of practice E.C.P. (203–2007) [1] highly underestimates the punching capacity by neglecting the contribution of the vertical and horizontal reinforcement in calculations. While, the American code ACI318-14 [2] neglects the effect of the horizontal reinforcement and the European code Euro-Code 2 [3] considers both of them. In addition, the location of the critical section of punching varies

---

* Corresponding author at: Concrete Laboratory, Faculty of Engineering, Cairo University, 48 Gezeeret El Arab, El mohandeseen, Giza, Egypt.
E-mail addresses: yrasha@yahoo.com (R.T.S. Mabrouk), amr_bakr@rocketmail.com (A. Bakr), habdalla5@yahoo.com (H. Abdalla).

Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2017.05.019
1110-0168

Please cite this article in press as: R.T.S. Mabrouk et al., Effect of flexural and shear reinforcement on the punching behavior of reinforced concrete flat slabs, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2017.05.019

Table 1 Reinforcement details of the experimental program [17,18].

Group I	S1-1	S1-2	S1-3
Top and bottom mesh	5 Ø10/m	7 Ø10/m	10 Ø10/m
Reinforcement ratio	0.40%	0.55%	0.785%
Group II	S2-1	S2-2	S2-3
Top and bottom mesh	5 Ø10/m	7 Ø10/m	10 Ø10/m
Vertical stirrups	Ø8@100 mm	Ø8@70 mm	Ø8@50 mm

among the design codes from half to double the effective slab depth measured from the column face.

Several analytical models were proposed over the past decade to simulate the punching behavior of concrete slabs. The first of these was the Kinnunen and Nylander model [4] which neglected the contribution of reinforcement to the punching capacity of concrete. Similar models were introduced [5,6]. In addition there are other models such as the plasticity approach [7], shear friction model [8], truss model [9] and yield line model [10]. Such models give an indication of the complexity of the punching problem in concrete slabs.

Increasing the punching capacity of RC slabs can be done using different methods such as drop panels, shear reinforcement in the form of studs or stirrups and bent up bars. Strengthening of existing slabs in punching can be performed using advanced composite materials such as carbon fiber reinforced polymers (CFRP), and glass fiber reinforced polymer (GFRP) [11]. Ebead [12] tested slab column connections strengthened with CFRP strips and GFRP laminates. Based on the test results, he concluded that the use of CFRP strips and GFRP laminates with the suggested dimensions was sufficient to achieve positive results for the flexural strengthened specimens. In addition, flexural strengthened specimens using CFRP strips showed an average gain in load capacity of 40% over that of the un-strengthened specimens. Moreover, flexural strengthened specimens using GFRP laminates showed an average increase in load carrying capacity of 31% compared to that of un-strengthened specimens. Megally [13] conducted a series of tests on slab column connections subjected to concentric and earthquake loads. He concluded that providing a slab column connection with drop panel increased the strength to the target value without significant improvement in ductility and energy absorption capacity. Megaily and Ghali [14,15] conducted a series of reversed cyclic tests

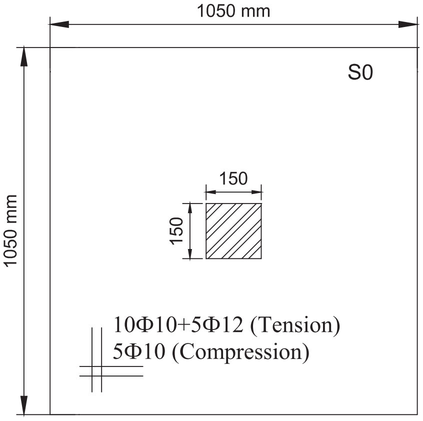

Figure 1 Reinforcement details of the control specimen (S0).

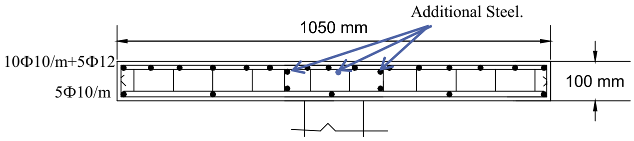

Figure 2 Typical cross section for specimens S1 to S6.

of edge slab column connections reinforced with stud shear reinforcement. The test variables were the provision of stud shear reinforcement, the spacing between shear studs, and the value of shearing force transferred between the column and the slab. They concluded that, without shear reinforcement, slab column connections subjected to earthquakes may fail in a brittle punching shear mode at relatively low drift ratios. In addition, provision of shear studs significantly enhances the ductility and maximum inter- story drift ratios that the connections can undergo without punching failure.

Broms [16] proposed a combination of bent bars and stirrups to be installed in the column vicinity in order to eliminate the brittle punching shear failure of slab column connections. In his research, the tested specimens were provided with bent bars as hangers into the column in combination with stirrup cages from welded wire fabric over a fairly large area around the column. This concept turned out to be very effective in creating an extremely ductile structural system.

Out of the above mentioned strengthening systems, using flexural reinforcement in addition to stirrups proves to be

Table 2 Details of the test specimens.

Slab No.	Tension side RFT		Compression side RFT	Stirrups			
	Main mesh	Additional RFT.	Main mesh	Diameter (mm)	Spacing (mm)	Width (mm)	No. of branches
S0	10 ϕ 10/m + 5 ϕ 12	–	5 ϕ 10/m	–	–	–	–
S1		–		8	100	250	2
S2		–		8	50	250	2
S3		3 Φ 12		8	100	250	2
S4		6 Φ 12		8	100	250	2
S5		–		8	100	350	2
S6		–		8	100	350	4

Please cite this article in press as: R.T.S. Mabrouk et al., Effect of flexural and shear reinforcement on the punching behavior of reinforced concrete flat slabs, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2017.05.019