Punching of reinforced concrete flat slabs with holes and shear reinforcement

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Abstract

Punching shear is a possible type of failure that occurs in reinforced concrete flat slabs, which can develop with an ultimate load below flexural capacity. Several researchers have studied the punching resistance of flat slabs over recent years. Although they have made great advances, there are codes that show different approaches to a singular design. Some codes show that there exist contradictions, even in the simplest situations, such as concentric loads. Most codes prescribe empirical expressions based in a theoretical model to analyze punching strength, but for flat slabs with holes around the column and shear reinforcement there are divergences between codes, justifying research in this area. This paper presents an experimental analysis of nine square reinforced concrete flat slabs under concentric loading (width: 1800 mm; thickness: 130 mm). The main variables used in the tests were: a) two square openings (150 mm) adjacent to the smallest side of the column and b) the use of shear reinforcement containing 3 layers, with 6 or 8 elements in each layer and radially distributed around the column. The research concludes that openings adjacent to the column affect punching shear strength, while the correct use of the shear reinforcement can minimize and even compensate this loss.

Keywords: punching, slabs, studs, holes.

1. Introduction

The conventional structure system (slab-beam-column), for some situations, has been substituted by the slab-column system in civil construction projects. The slab-column system does not have the support of the beams, where the slabs are supported directly onto the column. This structural concept brings advantages, such as facilitating the use of the formwork in order to reduce cuts influenced by beams. This produces greater agility in the construction process with a decrease in costs regarding material waste. The level of detail given to the reinforcement is simpler and consequently easier to execute, whereby there also exists the possibility of adapting the site for other ends due to the inexistence of beams.

On the other hand, this structure does have its disadvantages in using flat slabs. As beams do not exist, there may occur a reduction in the global stability of the structure, and as the flat slab is normally less rigid than a conventional slab (with beams), it is open to greater vertical displacements, when compared to conventional slabs.

According to code NBR6118:2014, a punching shear failure is an ultimate limit state near the concentrated forces, determined through reinforcement. Rupturing due to punching failure from a flat structural element such as a slab or foundation element can occur with the application of a concentrated force on a particular area of this element, producing an intense shear force in the region. The punching failure can occur in buildings in regions between the column and slab, where the column is supported on a slab. Another region that is also subject to damage through punching is the meeting point between the column and foundation. This damage may occur in an abrupt and fragile manner, without giving warning.

Holes adjacent to the columns for the passage of ducts used for electrical and hydraulic installarions can aggravate the rupture through punching shear. Research performed in Brazil and the exterior evaluated the use of stud type reinforcement to increase resistance to punching. The studies evaluate slabs with variable loads, holes and bending moment.

There have been research studies that resulted in some empirical formulations based on shear stress and control perimeter. A formulation is differentiated one from another basically in terms of position and form of the control perimeter. The first rational theory concerning punching was presented by KINNUNEN & NYLANDER (1960), based on circular slab trials without reinforcement.

Ha *et. al.* (2015) studied eight flat slabs with round holes, varying the amount and position of the hole. The authors concluded that the amount and position modifies the failure surface mode. Holes adjacent to the column reduce the shear strength of the slabs, and holes positioned at the column corner can result in further reduction.

In order to make the column/slab connection safer, an increase in the ductility and the resistance capacity of a flat slab's shear reinforcement is used to avoid punching. Research studies such as those by GOMES e REGAN (1999), ANDRADE (2000), SILVA (2003), SOUZA (2009) and BORGES (2013), FERREIRA (2010) e TRAUTWEIN (2011) demonstrate that the use of shear reinforcement can be extremely efficient in preventing punching failure, even to the point of changing the rupture due to flexure. This study aimed to provide increased punching resistance when using a shear reinforcement stud type, and when using an increased column perimeter.

2. Materials and methods

This paper shows a summary of the experimental results for nine square reinforced concrete flat slabs with the same dimensions, and flexural reinforcement with a load on their center. All of the slabs were square with side lengths of 1800 mm and a thickness of 130 mm (SILVA, 2003). A study is made of the central punching failure scenario, a common situation in the central columns of buildings with flat slabs, and with a symmetric load, which is transmitted to the slab without irregularity.

The slabs and the adopted test arrangement correspond to an area of negative bending on the column, approximately equal to 1/5 of the span in real scale and equivalent to a span of 4125 mm, considering a situation of internal column and symmetrical loading, as shown in Figure 1.

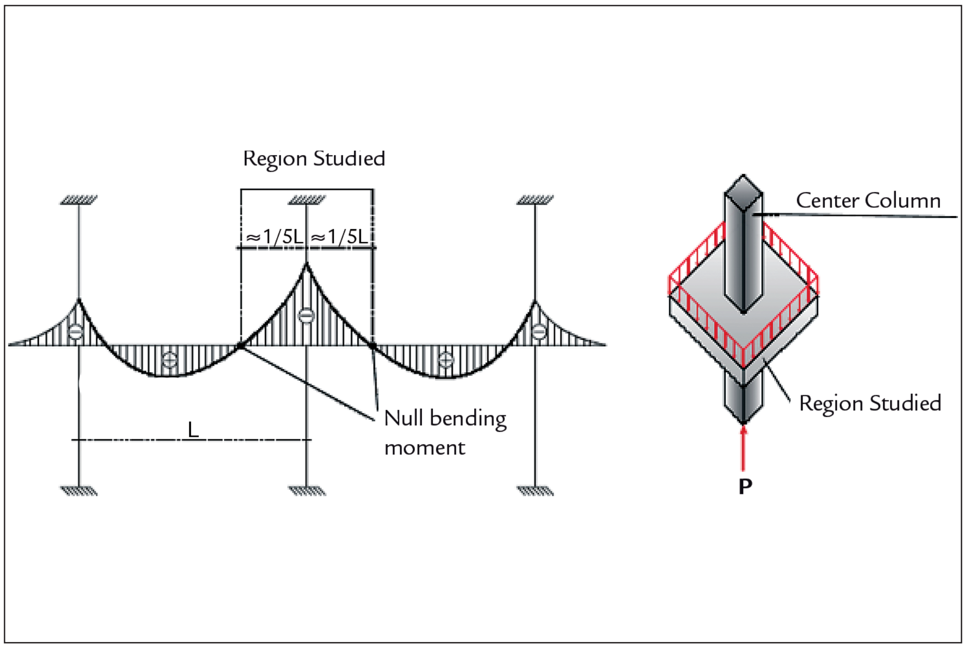

Figure 1
Hypothetical frame featuring
the region studied in ANDRADE (1999).

2.1 Characteristics of the trial slabs

The main characteristics of the slabs are: a) effective height of 90 mm, b) the existence of two holes of 150 mm x 150 mm arranged adjacent to the column, c) the use of shear reinforcement (SR) with a radial distribution in 3 layers and diameter ϕ = 8 mm, d) dimensions of the column with a constant side "a" equal to 150 mm and the other side "b" with values of 150 mm and 300 mm, as shown in Figure 2. The high ratio flexural reinforcements were adopted to avoid flexural failure. In the slabs without holes the ratio was 1.45 % and in the slabs with holes was 1.57 %. This difference is due to the addition of two perpendicular bars in the direction of the holes.

Slabs L1 and L2 are the reference slabs, without holes and shear reinforcement, slabs L3, L4, L7 and L8 have holes adjacent to the column, being that L7 and L8 are with shear reinforcement. Slabs L5 and L6 do not have holes but have shear reinforcement. Slab L9 has a circular section column without holes or shear reinforcement, Table 1.

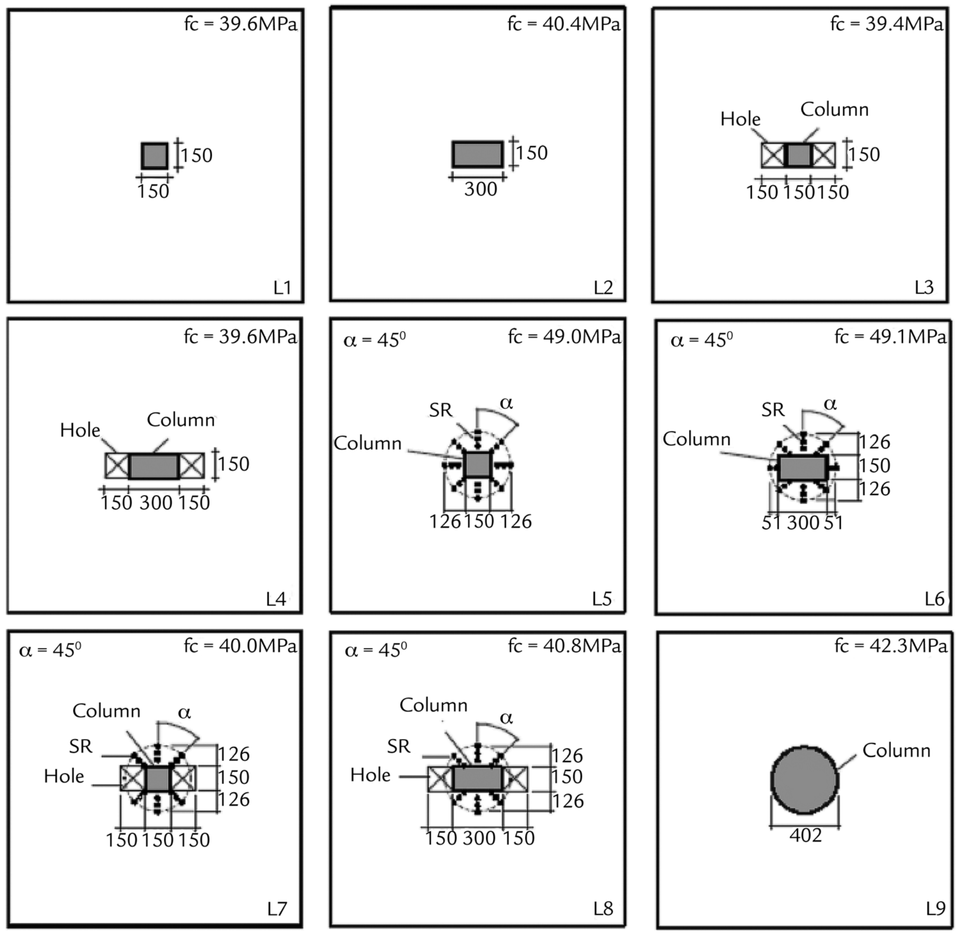

Figure 2
Main features of the slabs under study.
Source: Silva, 2003

Table 1
Slab features.

Slab	Dimensions of column		Effective height "d" (mm)	$\rho^{(1)}$ (%)	Hole	Shear Reinforcement (SR) "stud"
	a (mm)	b (mm)				
L1	150	150	90	1.45	no	no
L2	150	300	90	1.45	no	no
L3	150	150	90	1.57	yes	no
L4	150	300	90	1.57	yes	no
L5	150	150	90	1.45	no	yes(2)
L6	150	150	90	1.45	no	yes(2)
L7	150	150	90	1.57	yes	yes(3)
L8	150	300	90	1.57	yes	yes(3)
L9	-	-	90	1.45	no	no

(1) $\rho=\sqrt{(\rho_x \rho_y)}$, reinforcement rate, calculated with a width equal to 1034 mm; (2) 8 lines; (3) 6lines.

2.2 Test arrangement

The load was applied upward from a jack, with a capacity of 1500 kN, placed at the middle of the bottom face of the slab, and the reactions were provided by four ties fixed to the strong floor and through a set of steel beams (beams 1 and 2 of Figures 3 and 4) onto a reaction slab at each edge. This reaction was performed through 8 equidistant points positioned in a circumference with a radius equal to 825 mm.

2.3 Details of the tested models

The flexural reinforcement used on the slabs presents different details due to the holes and loading areas (columns). For the slabs without holes, the negative reinforcement (top) is composed of an orthogonal mesh of 19 bars of 12.5 mm in diameter (CA-50) in each direction. The positive reinforcement (bottom) is composed of an orthogonal mesh of 11 bars of 6.3 mm in diameter (CA-50 steel) in each direction. In the U-type form, 19 bars of 6.3 mm in diameter were added at both ends of each flexural reinforcement to help the anchorage and were fixed on each bar.

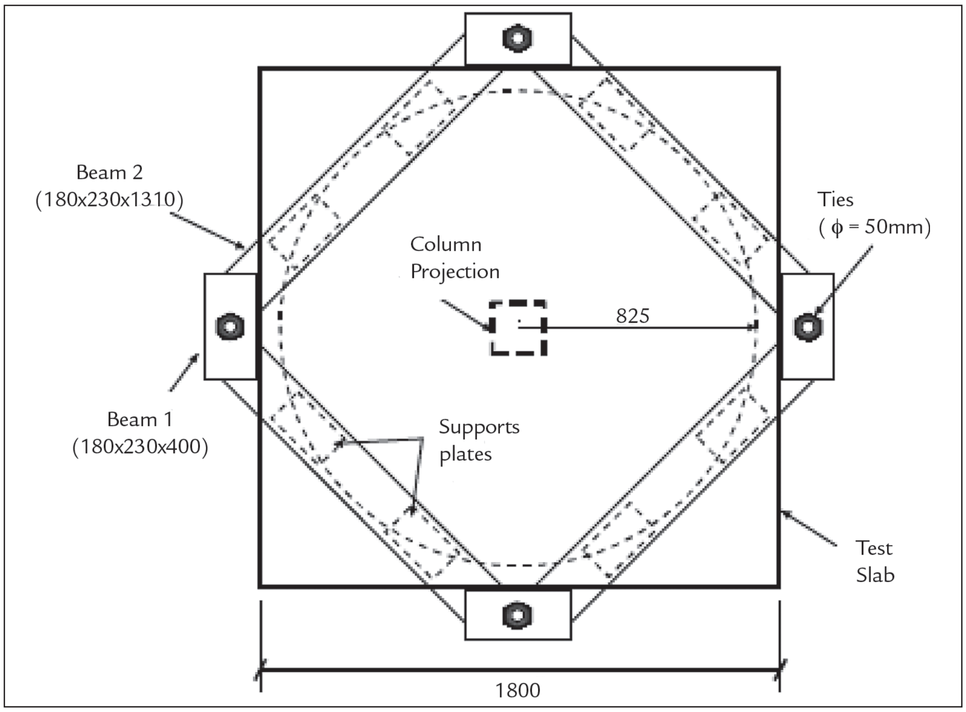

Figure 3
Test arrangement (Top view).
Source: Silva, 2003.

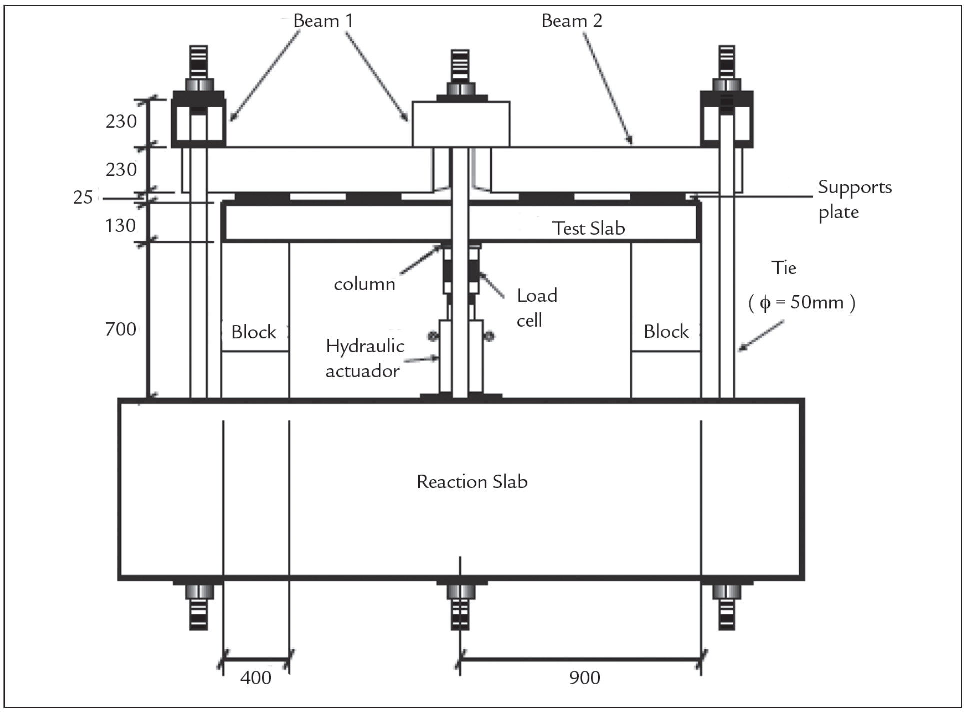

Figure 4
Test arrangement (side view).
Source: Silva, 2003.

Only slabs L5, L6, L7 and L8 used shear reinforcement (Table 1) of the stud type, where steel bars CA-50 (ϕ = 8 mm and a length of 105 mm) were welded at their extremities to steel plates of 30 mm in length and 100 mm in thickness. These studs were made through a manual welding process with a coated electrode of type “OK 48.04” of 3.5 mm from ESAB. Figure 5 shows a scheme with the dimensions of the shear reinforcement and a photograph that illustrated the positioning of the shear reinforcement in relation to the flexural reinforcement.

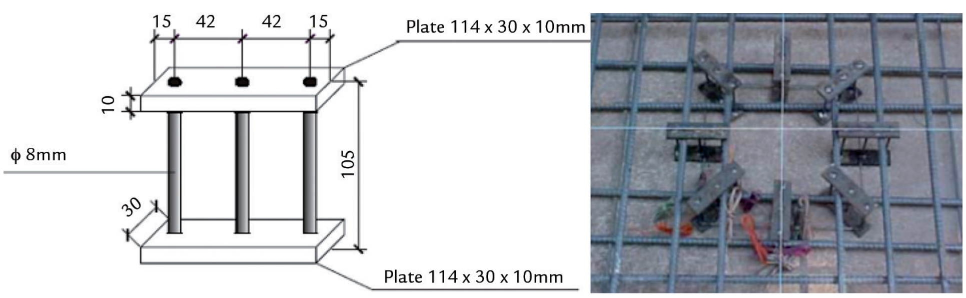

Figure 5
Shear Reinforcement.
Source: Silva, 2003.

In all slabs, the concrete had cylinder compressive strength between 39.4 MPa and 49.4 MPa. The mix proportion to weight ratio used to fabricate the concrete for all slabs was calculated by the company Betonmaster – Concrete and Artefacts from Cement Ltda. The superplasticizer additive was added minutes before concreting to improve the workability of the mixture.

3. Results and discussion

The experimental results included the ultimate load, mode of failure and cracking pattern.

3.1 Load and failure mode

The loads were applied in increments and tested up to failure for all slabs and had punching failure. The failure load adopted was the maximum value reached in the load cell, Table 2.

Slab	f_c (MPa)	Dimensions of column		$C^{(1)}$ (mm)	ρ (%)	Hole(2)	A.C.(3)	P_u (kN)
		a (mm)	b (mm)					
L1	39.6	150	150	600	1.45	no	no	273
L2	40.4	150	300	900	1.45	no	no	401
L3	39.4	150	150	600	1.57	yes	no	225
L4	39.6	150	300	900	1.57	yes	no	350
L5	49.0	150	150	600	1.45	no	yes(4)	420
L6	49.4	150	150	600	1.45	no	yes(4)	452
L7	40.0	150	150	600	1.57	yes	yes(5)	325
L8	40.8	150	300	900	1.57	yes	yes(5)	350
L9	42.3	402(6)		1262	1.45	no	no	525

(1) Perimeter of the column;

(2) Two holes of 150x150 mm placed adjacent to the side of the column;

(3) Shear reinforcement of the stud type, ϕ = 8mm, with 3 layers;

(4) 8 lines; (5) 6 lines;

(6) Circular column, value of diameter of the column.

Table 2
Slab Rupture Loads.

The failure load of the tested slabs obtained results depending on the perimeter of the column, and the number of holes with the use or not of shear reinforcement. The slabs with the same characteristics with higher perimeter and shear reinforcement increased the failure loads of the slabs.

For slabs L1, L2 and L9, without holes and shear reinforcement, a notable increase was observed in the failure load of slabs L2 of 46 % and L9 92 %, when compared to the rupture load of slab L1. This increase occurs, in all probability, because of the increase of the column perimeter on slab L5.

The strength drop due to the existence of the two holes arranged adjacent to the smaller sides of the column, in relation to the slabs without holes (L1-b/a = 1, L2-b/a = 2), was 48kN and 51kN, respectively. Note for these models that the load loss was practically constant for a "b/a" ratio of less than 2.

The reduced failure load due to the existence of holes placed adjacent to the column and without shear reinforcement, L3 and L4, were 18 % and 13 % respectively. However, when shear reinforcement is used, as with L7, the load increased by 16 % compared to the L1 reference slab. In terms of the slab without the hole but with shear reinforcement (L5), the increase of the failure load reached 35 %.

When comparing the failure loads of the slabs L8 (with two holes and shear reinforcement) and L4 (with two holes and without shear reinforcement), it was verified that the shear reinforcement adopted was ineffective, since it did not contribute any increase in the failure load.

Slabs L1, L2 and L12 showed signs of failure surface on the face of the column in two directions. The failure surface around the holes of slabs L3 and L4 initiated at the column face and extended to the other side of the hole. In the slabs that had shear reinforcement (L5, L6, L7 and L8), the failure surface initiated after the last layer of studs, constituting an external rupture.

3.2 Cracks

The first visually apparent cracks were radial and these occurred in all slabs for a load between 50 kN and 100 kN, as presented on Table 3. Noted here is that the first radial crack started between of 17 % to 19 % of the failure load for slabs without holes, and from 22 % to 24 % of the ultimate load for slabs with holes. Figure 6 presents the crack pattern after the failure of slabs L1, L3 and L4.

Slab	Pu (kN)	Pu'(1) (kN)	Pu'/Pu (%)
L1	273	50	18.3
L2	401	75	18.7
L3	225	50	22.2
L4	350	75	21.4
L5	420	75	17.6
L6	452	75	16.6
L7	325	75	23.1
L8	350	75	21.4
L9	525	100	19.0

(1) Load at the moment of the first visible radial crack

Table 3
Comparisons on the appearance of the first radial crack.

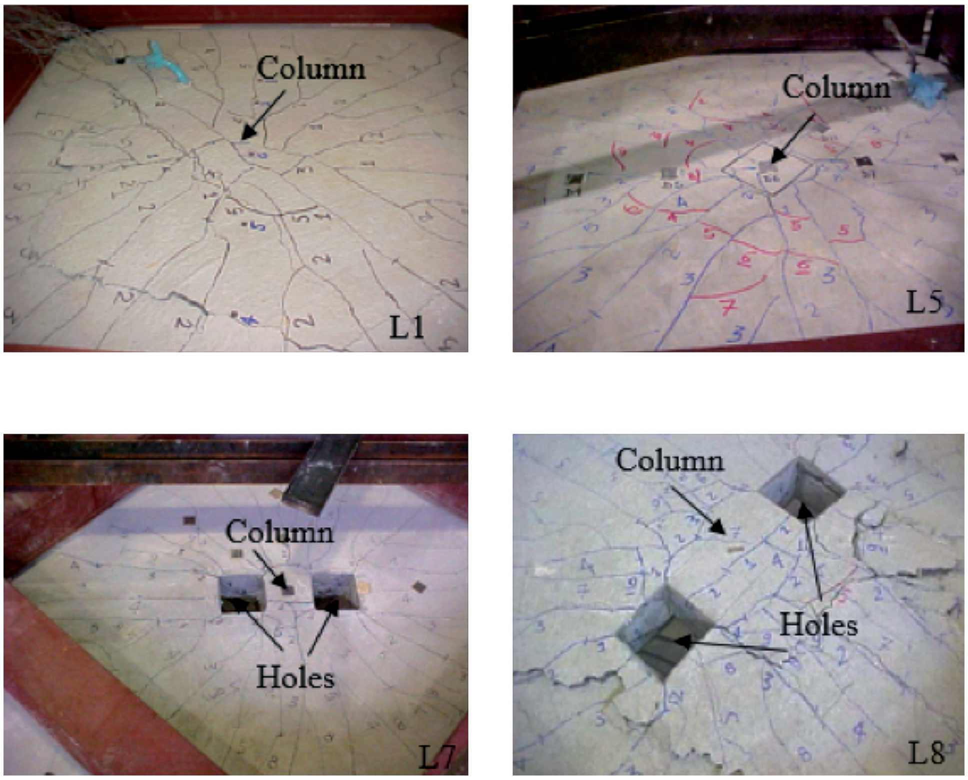

Figure 6
Crack pattern after the failure of slabs L1, L5, L7 and L8.
Source: Silva, 2003.

After the rupture, the slabs presented a similar development regarding radial cracks and with some difference in relation to the circumferential cracks. For slabs L3 and L6, the appearance of the circumferential cracks was considerable, practically surrounding the entire loading area and the radial cracks arrived near the supports.

4. Conclusions

The design of reinforced concrete flat slabs requires special care for punching shear, especially with the presence of holes near the column. The ultimate load at these columns supporting flat slabs may be distinctly below the flexural capacity and with a brittle failure. All the slabs tested had punching shear failure, and the research herein was directed to this failure mode. The slabs with shear reinforcement presented external failures, with the failure surface initiating after the last layer of the shear reinforcement.

The existence of holes adjacent to the column can affect the strength to the punching of flat slabs. Results show that the failure load decreased in up to 13%, when the strength portion of the concrete is reduced in the critical region, with two square holes of 150 mm side by side.

The process associated with the appearance of radial cracks and the development of circumferential cracks followed differentiated characteristics for slabs with and without holes and shear reinforcement. For slabs without shear reinforcement, the circumferential crack appeared at 26 % to 48 % of the failure load, and at 33 % to 86 % for the slabs with shear reinforcement.

The results also show that the use of this shear reinforcement can be a possibility to increase the punching strength in flat slabs with holes. This increase may even be higher when compared to slab without shear reinforcement and without holes (19 % - from slab L7 to L1).

The analyses performed in this study were limited by the slab dimensions (length and height) and by the size of the column. Different positions and dimensions of holes and shear reinforcement can contribute more towards understanding the problem of punching.

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