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Behavior of Flat Slabs Using Internal Studs as Shear Reinforcement

Comportamento de Lajes-Cogumelo com Armadura de Cisalhamento do Tipo "Stud" Interno




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Abstract

Six reinforced concrete flat slabs with shear reinforcement not embracing the flexural reinforcement were tested experimentally by a load on their centre through a square steel plate (200 x 200 x 50 mm). The main variables tested were the shear reinforcement diameter and the number of reinforcements layers in each slab. All slabs have rectangular shapes with dimensions of 200 mm in thickness and 3000 mm in side lengths. Results of failure load, failure surface, cracks, deflections and strain at shear reinforcement are described in this paper. The failure loads are compared to the ones obtained for similar slabs with standard shear reinforcement. This approach shows that the internal studs used as shear reinforcement may reach failure loads up to 1.75 higher than failure loads obtained in similar tests of slabs with no shear reinforcement.

Keywords: flat slabs, punching, shear reinforcement.

Resumo

Seis lajes de concreto armado com armadura de cisalhamento do tipo "stud" interno, posicionada entre as armaduras de flexão, submetidas a um carregamento aplicado no centro da laje através de uma placa metálica (200 x 200 x 50 mm) são analisadas experimentalmente. As principais variáveis dos ensaios são: o diâmetro da armadura de cisalhamento e o número de camadas utilizadas. As lajes têm dimensões de 3000 x 3000 mm de comprimento e uma altura nominal de 200 mm. São apresentados resultados de carga última, tipo de ruptura, fissuração, flecha e deformações da armadura de cisalhamento. As cargas de ruptura obtidas experimentalmente são comparadas com as de lajes similares, mas com armadura de cisalhamento ancorada na armadura de flexão. Os resultados mostraram que o uso deste tipo de armadura de cisalhamento colocada internamente à armadura de flexão proporcionou acréscimos de resistência à punção entre 48% e 75%, em relação às lajes sem armadura de cisalhamento.

Palavras-chave: lajes-cogumelo, punção e armadura de cisalhamento.

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Table 1 – Results of slabs tested by Gomes(1)

Slab	d (mm)	f_c (MPa)	$A_{sw}\,f_y$ /layer (kN)	Arrangement of shear reinforcement	Pu (kN)	Mode of failure
G1	159	40,24	-	-	560	-
G1A	159	41,12	-	-	587	-
G9	159	40,00	404,2	Radial	1227	Outside
G10	154	35,36	97,3	Radial	800	Within
G11	154	34,56	129,3	Radial	907	Within

d: effective depth;
A_{sw} – shear reinforcement;
Mode of failure:
Outside – Failure in the surface located in the region outside the shear reinforcement elements
Within – Failure in the surface crossing one or more layers of shear reinforcement

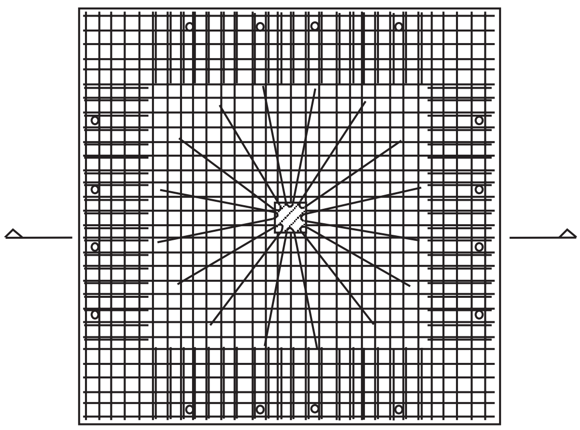
1 Introduction

This paper shows a summary of the experimental results obtained by some other researchers. All these results have been obtained for square flat slabs 200 mm high and 3000 mm wide.

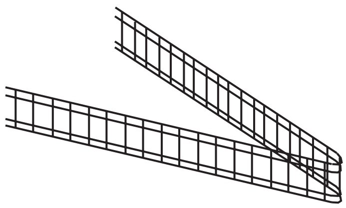
Gomes[1] tested twelve flat slabs, being two slabs without shear reinforcement. The shear reinforcement was made of I-beam cut-off sections embraced in the flexural reinforcement, with a thickness "s" in accordance to the required area. The slabs with this type of shear reinforcement reached ultimate loads up to 100% higher than the slabs without shear reinforcement. Table 1 presents the results of slabs G1 and G1A (without shear reinforcement), slab G9 (9 layers of shear reinforcement), and slabs G10 and G11 (5 layers of shear reinforcement).

Regan[2] analyzed shear reinforcement distributed in form of a star and positioned without embracing the flexural reinforcement, known as "RISS STAR". Figure 1 shows the details of analyzed shear reinforcement distributed in form of a star. Two slabs were tested; the first slab (RS1) had 16 layers of shear reinforcement with 6,0mm diameter, and the second slab (RS2) had 17 layers of 8,0mm. The spacing

Figure 1 – Slabs tested by Regan(2)

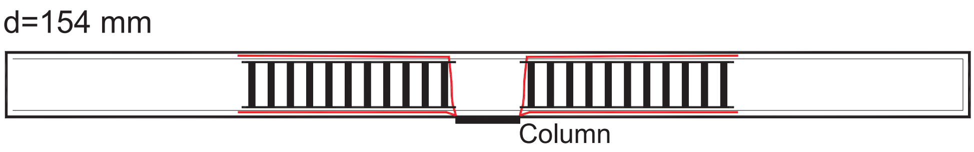


Radial distribution of shear elements



Details of shear reinforcement

Figure 2 – Horizontal cracks running over the planes of the top and bottom flexural reinforcements and over both edges of the shear reinforcement observed by Andrade(3)



between shear reinforcement was kept constant and equal to 50mm for all slabs. All slabs had punching failure with ultimate loads of 925 kN (RS1) and 950 kN (RS2). The enhancement of strength regarding punching shear of both slabs were about 67%, if compared to the results obtained for similar slabs without shear reinforcement.
Andrade[3] studied if punching shear reinforcement really needs to embrace the flexural reinforcement. Eight square reinforced concrete flat slabs of 3000 mm wide and 200 mm high with concrete strength nearly 40 MPa were tested. All slabs had punching shear failure with loads varying from 790 kN to 1090 kN. The obtained failure loads were about 90% higher than results obtained for similar slabs without shear reinforcement (Gomes[1] – Slabs G1 and

Figure 3 – Mode of failure and failure loads of all slabs observed by Trautwein (4)

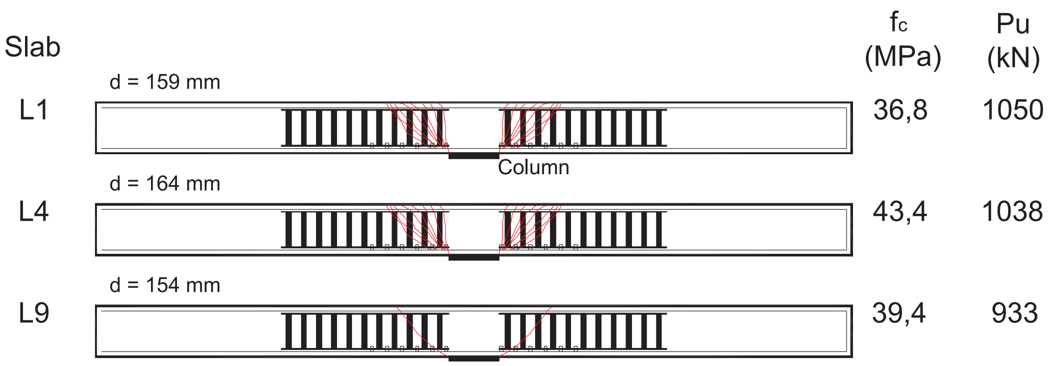
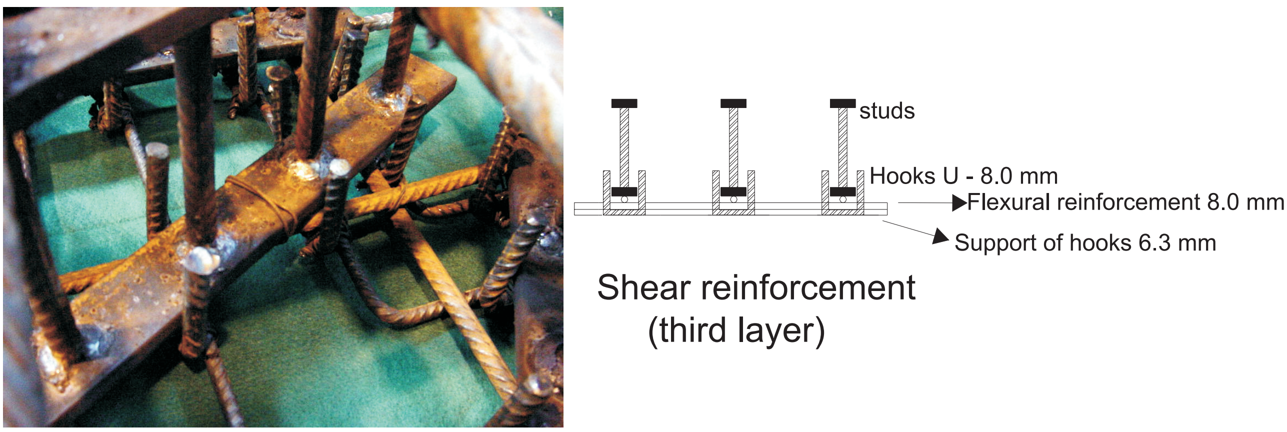
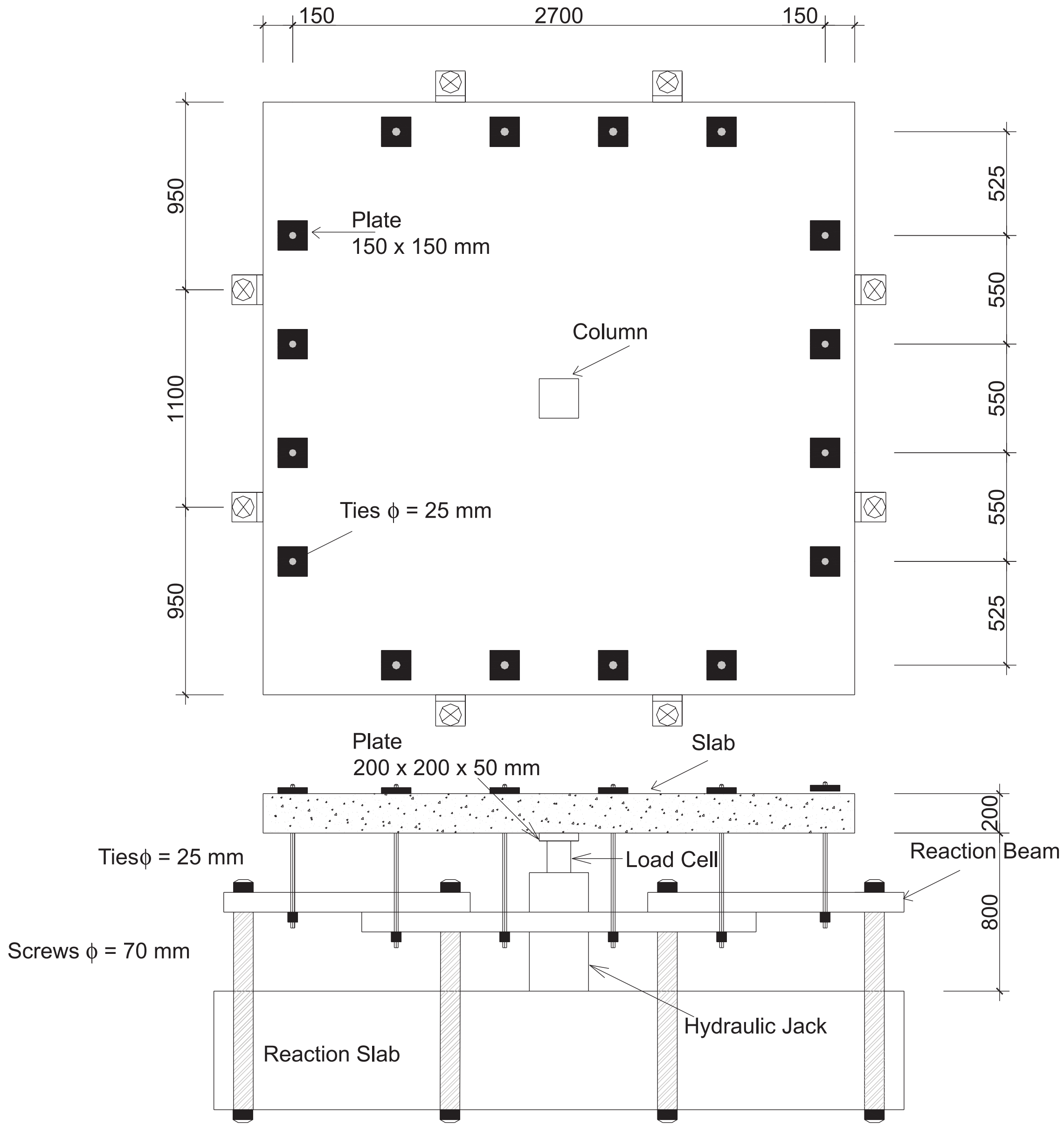


Figure 4 – Details of U hooks (Trautwein (5,6,7))



G1A). For slabs with shear reinforcement positioned internally, it could be observed cracks running over the planes of both top and bottom flexural reinforcement, and over both edges of the shear reinforcement (Figure 2).
Trautwein[4] continued the studies of Andrade[3] and tested more three slabs with shear reinforcement, internally located to the flexural reinforcement. The failure loads were 75% higher than loads obtained for similar slabs without shear reinforcement (Gomes[1] – Slabs G1 and G1A). All slabs had punching shear failure, however in two slabs could be observed a probable concrete crushing in the area of the shear reinforcement, as shown in Figure 3. The obtained results show that this type of shear reinforcement, located internally in relation to the flexural reinforcement, enhances the punching strength of flat slabs. However, Trautwein[4] recommended more tests in order to control all possible failure mechanisms and compare slabs with shear reinforcement involving flexural steel.
Trautwein[5,6,7] analyzed five square flat slabs, with the same characteristics of that ones previously tested by

Figure 5 – Test arrangements and dimensions (mm)



Trautwein [4]. This test was conducted in order to investigate the efficiency of shear reinforcement not embracing the flexural reinforcement in flat slabs. In all slabs, the concrete used had cylinder compressive strength between 36,9 MPa and 41,5 MPa. The position of "studs" and the number of U hooks which involved the bottom steel plate of shear reinforcement were the major variables in this study. The details of U hooks in relation to the shear and flexural reinforcement are illustrated in Figure 4. The objective of using U hooks was to prevent the horizontal cracks observed by Andrade[3] and Trautwein[5,6,7]. Results have shown that this new alternative of shear reinforcement with U hooks without embracing flexural reinforcement enhances the punching shear strength of flat slabs. When compared to results of slabs without shear reinforcement, an improvement between 65% and 104% was obtained.

Samadian[8] tested ten flat slabs with same dimensions and similar test arrangements to the other tests described in this paper. Five types of shear reinforcement were used and each type was used in each two slabs. The three first pairs of slabs had studs placed below or above the flexural reinforcement. Another groups of slabs had shear reinforcement similar to ladders and in shape of V in plane and was not embraced in the flexural reinforcement. The last group of slabs were reinforced with stirrups, which had 180º bends over the lower layer of the top of flexural reinforcement. All the slabs, except those with ladder reinforcement, had punching failure at an inclined surface crossing the region where the shear reinforcement were available. The two slabs with ladder shear reinforcement presented cracks running over the top and bottom flexural reinforcement plane. The horizontal cracks that appeared in this test were similar to those observed by Andrade[3] and Trautwein [5,6,7].

This paper aims to investigate the efficiency of the use of shear reinforcement that does not embrace the flexural reinforcement in flat slabs. The lack of embracement may facilitate the placement of such steel inside a reinforced concrete flat slab. The contributions of this internal shear reinforcement are analyzed in order to verify its influence on the failure behavior.

2 Experimental Program

The experimental program consisted of six square reinforced concrete flat slabs with the same dimensions, flexural reinforcement and loaded on their centre through a square steel plate (200 x 200 x 50 mm). The objective of this experimental program is to verify the behavior of flat slabs with shear reinforcement without involving the flexural reinforcement, when were calculated for a failure surface inside the region with shear reinforcement. Num-

Figure 6 – Test arrangements

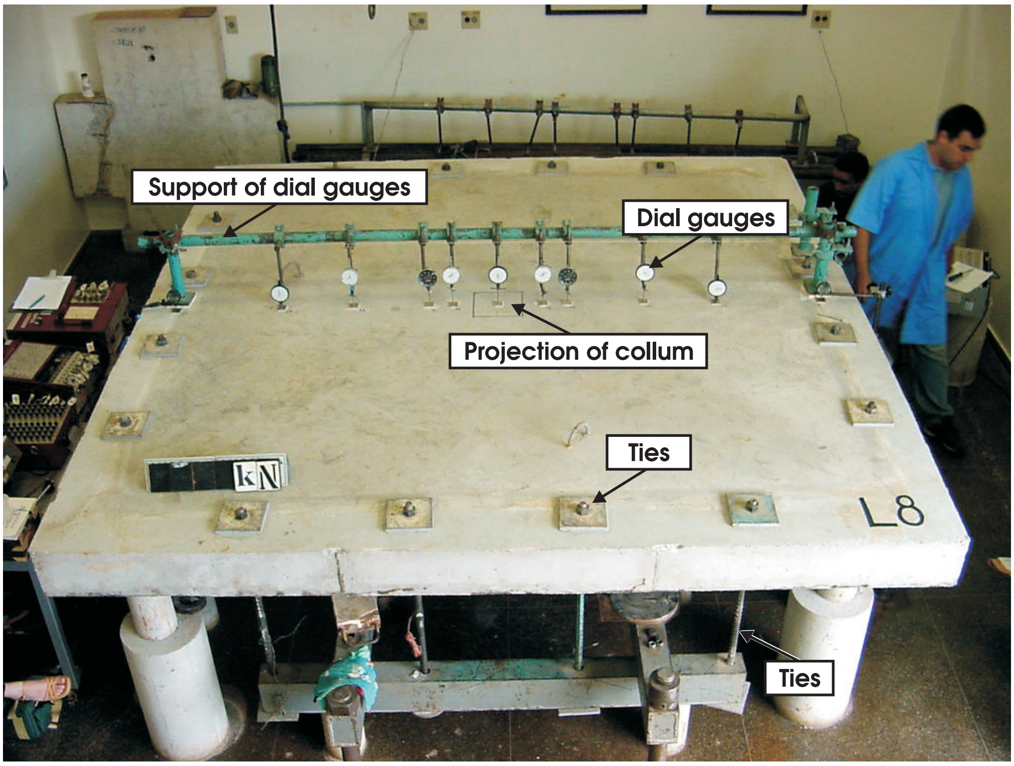
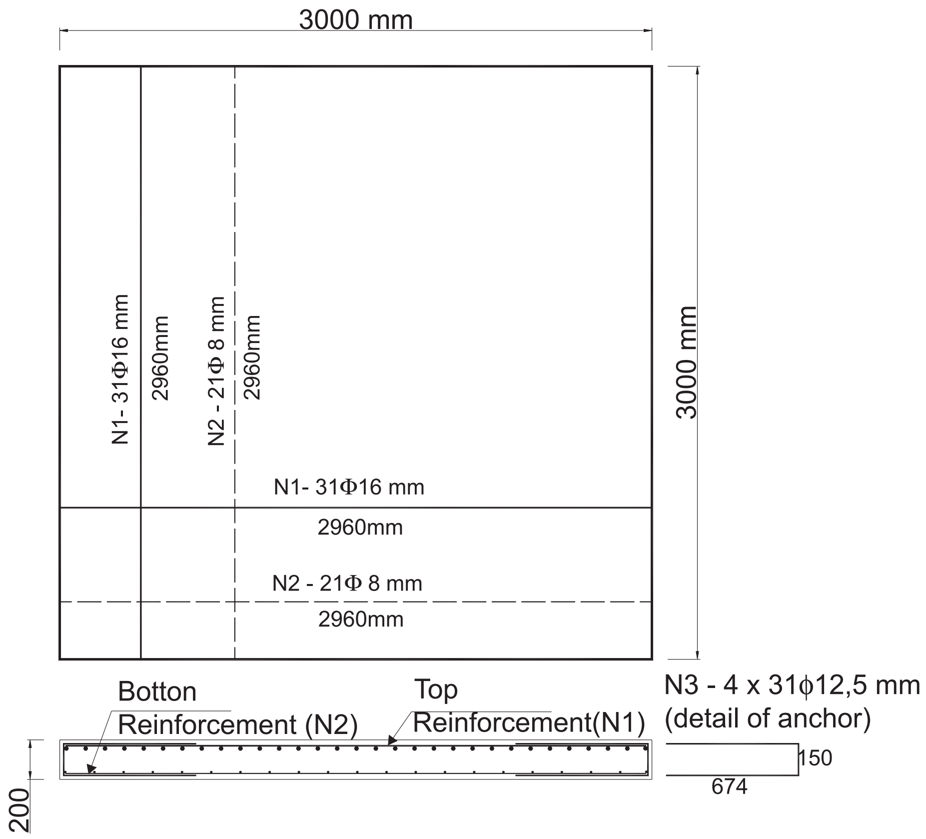


Figure 7 – Flexural reinforcement details



ber of layers, diameter and the radial spacing of shear reinforcement were the main variables of these tests.
Figures 5 and 6 show the test arrangements. The slabs were supported at the edges by 16 ties (φ= 25 mm) connected to spreader beams which transmitted the load to the strong floor. The load was applied upward from a jack at the centre acting on a square steel plate (200 x 200 x 50 mm), simulating a column with the same dimensions.
At the top, flexural reinforcement was spaced by 10 cm and composed by 31 bars of 16 mm diameter in each direction. At the bottom, flexural reinforcement was spaced by 15 cm and composed by 21 bars of 8 mm in each direction, 31 U-type bars of 12,5 were added at both ends of each flexural reinforcement to help the anchorage and were fixed on each side of the slab. Figure 7 presents the details of the flexural reinforcement used in all slabs. The measured mechanical properties are shown in Table 2.
Slabs I6, I7 and I8 had 11 layers of shear reinforcement, with a radial spacing ([1]S_r) of 60 mm and 8 layers of U hooks (φ=8,00 mm) in planar shape. The diameter of the used bars was 6.3 mm ([2]A_{sv}/cam = 249,25 mm^2) for slab I6; 10,0 mm ([2]A_{sv}/cam = 628,00 mm^2) for slab I7 and 8,0 mm ([2]A_{sv}/cam = 401,92 mm^2) for slab I8. Figure 8 shows the distribution of shear elements.

For the slabs I9, I10 and I11, five layers of shear reinforcement and U hooks in planar shape were used. The radial spacing ([1]Sr) and the distance from the first layer of shear reinforcement to the face of the column were 80 mm. The diameter of the shear reinforcement bars was 5,0 mm ([2]Asv/layer = 157,00 mm^2) for slab I9, 8,0 mm ([2]Asv/layer = 401,92 mm^2) for slab I10 and 6,3 mm ([2]Asv/layer = 249,25 mm^2) for slab I11. Figure 9 shows the distribution of shear reinforcement for slabs I9, I10 and I11.

3 Results

All models failed by punching shear with the failure surfaces crossing the shear reinforcement. The ultimate loads ranged between 853 kN (slab I9) and 978 kN (slab I7). The horizontal cracks at the bottom face of the slabs were not observed after the failure. Table 3 summarizes the modes and failure loads of all six slabs and their main characteristics. Figure 10 presents the failure surfaces of the tested slabs.
For the slabs I6, I7 and I8, with 60 mm of radial spacing, the shear reinforcement bars broke up only after the failure of the slab. These three slabs (I6, I7, and I8) had failure surfaces crossing the three reinforcement layers in-

[1]S_r – *radial spacing*
[2]A_{sv}/cam – *area of shear reinforcement per layer*

Table 2 – Material properties of the slabs

Steel						
ϕ (mm)	**f_y (MPa)**			**f_u (MPa)**		
5,0	770,0			887,0		
6,3	594,0			714,0		
8,0	615,0			723,0		
10,0	578,0			716,0		
12,5	542,7			694,3		
16,0	600,0			704,0		
Concrete						
Slabs	**I6**	**I7**	**I8**	**I9**	**I10**	**I11**
f_c (MPa)	39,1	39,6	35,4	43,6	44,4	41,4
f_{ct} (MPa)	3,7	3,4	2,6	4,0	3,2	3,7
E_c (MPa)	23,6	22,7	26,1	25,0	27,1	26,8

corpos-de-prova cilíndricos 150x300 mm
2 corpos-de-prova: resistência do concreto à compressão simples;
2 corpos-de-prova: módulo de elasticidade e tração por compressão diametral.

nermost to the column. For the slabs I9, I10 and I11, with 80mm of radial spacing, the failure surface has crossed the first three layers of shear reinforcement for slab I9 and the first two reinforcement layers innermost to the column for slabs I10 and I11.
The deflection of each slab was measured by means of dial gauges located on the top surface. Figure 11 shows the deflection of each slab up to at least 85% of the failure load. The deflection profiles of all slabs were almost symmetric. The deflections of the tested slabs varied from 14,41 mm (slab I8) to 20,20 mm (slab I11).
For 30% and 40% of the failure loads, all the slabs presented almost the same radial cracks and deflections. For the slabs I9, I10 and I11, with 80mm of radial spacing, the central deflections ranged between 2,77 mm to 2,86 mm. For 85% of the failure loads, only slab I6 presented a higher deflection than the others slabs. Figure 12 presents the comparison of deflections for all slabs.
Strains for the shear reinforcement of all slabs are given in Figure 13. For the slabs I6, I7, and I8, with radial spacing equal to 60 mm, only the slab I7 had its shear reinforcement yielded. However, the strain gages 13, 14 and 15 from slab I6 showed that the shear reinforcement yielded at the moment of the failure. The last measure of strains was made at 90% of the ultimate load. For the slabs I9, I10 and I11, with radial spacing equal to 80 mm, the first two layers have been most requested. Some bars of the slab I10 yielded before failure (gages 27 and 37). Probably some bars in the slab I9 (gages 16, 17 e 32) also yielded before failure.
The monitored U hooks on the slabs I6, I7 and I8 have shown strains inferior to yield strain of steel. For the slabs I6 and I7, the highest strains occurred at the first layer ($1{,}95 \times 10^{-3}$ – slab I6 and $2{,}06 \times 10^{-3}$ – slab I7). Slab I8 has shown strains below $1{,}0 \times 10^{-3}$. The strains obtained for all U hooks in the slabs I9, I10 and I11 were very shorter and below to $1{,}0 \times 10^{-3}$.

4 Discussion

The experimental results, including the ultimate load, maximum deflection and cracks pattern, are presented. The obtained results are then compared with results of others tests. Both steel and concrete contribution are considered in order to analyze the punching shear strength of slabs.

4.1 Ultimate Load

In order to verify the improvement of punching strength in flat slabs with shear reinforcement without involving flexural reinforcement, the results are compared with slab G1 of Gomes[1], with the same dimensions, concrete strengths of the slabs studied in this paper and with out shear reinforcement. Slab G1 failed by punching and the failure load was 560 kN.
Table 4 compares the failure loads of all slabs with similar tests without shear reinforcement, Slabs G1 (Gomes[1]). The failure loads increased from 48% to 75% in relation to the failure load of slab G1, indicating the potentiality of this type of shear reinforcement. It is important to remember that the objective of these slabs was not to reach a higher load, but to evaluate the behavior of slab with this kind of shear steel, (failure surface inside the region with shear reinforcement). Slab I7 with the greatest area of steel per layer obtained the highest improvement of punching strength (75%).
Table 5 presents a comparison between the results of this work with experimental results of similar slabs with different types of shear reinforcement. The presented results have been obtained from slabs with the same dimensions and mechanical properties of the slabs tested in this research.
The results of slabs G10 and G11 (Gomes [1]) can be compared with the slabs I9, I10 and I11, with similar radial spacing and steel area per layer. Analyzing these five slabs, the failure loads had small variations. This fact proves that the use of shear reinforcement without involving flexural reinforcement with the U hooks, did not reduce the punching strength. The failure load of slab I11 (A_{sv}/layer = 249,00 mm^2) has improved the punching strength by 18% and 5%, if compared with slabs G10 (A_{sv}/layer =226,00 mm^2) and slab G11 (A_{sv}/layer =300,80 mm^2),

Figure 8 – Details of slabs I6, I7 and I8

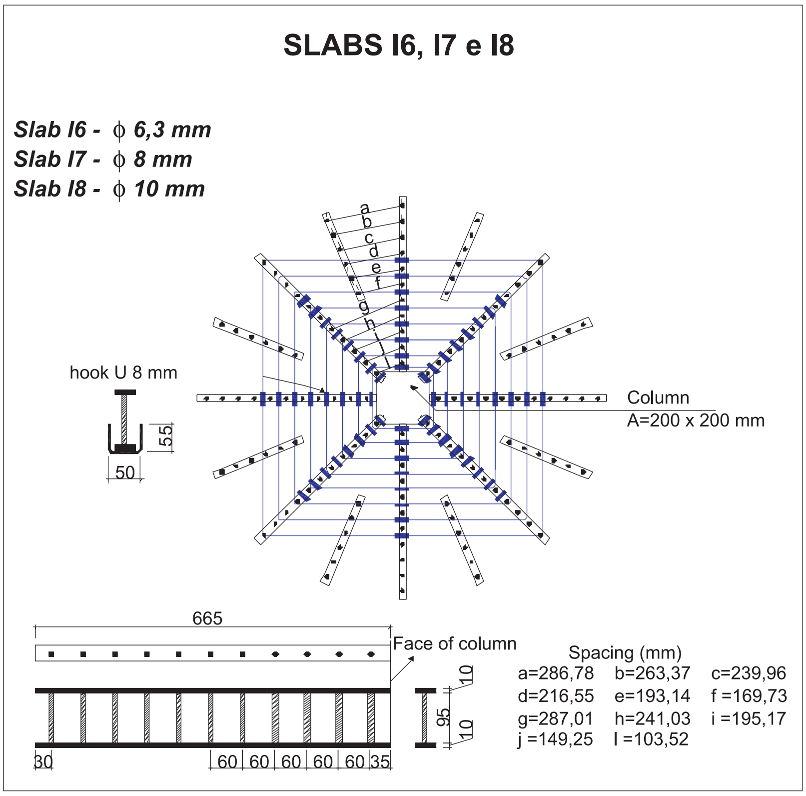
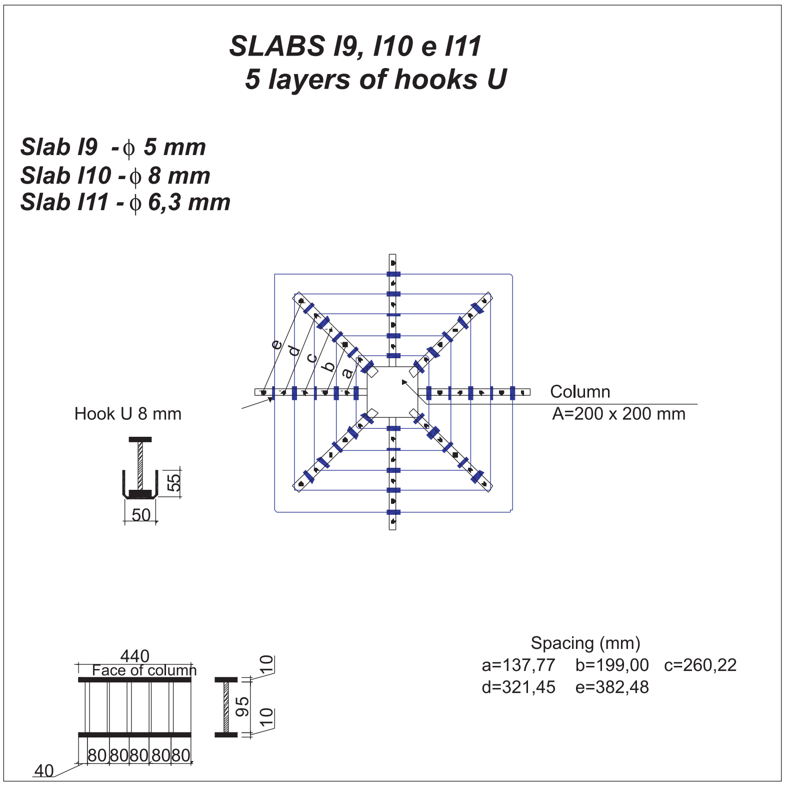


Figure 9 – Details of slabs I9, I10 and I11



respectively. Slab I9 had a steel area per layer lower than slab G11 (Gomes [1]), showing a reasonable improvement of the punching strength (approximately 7%).

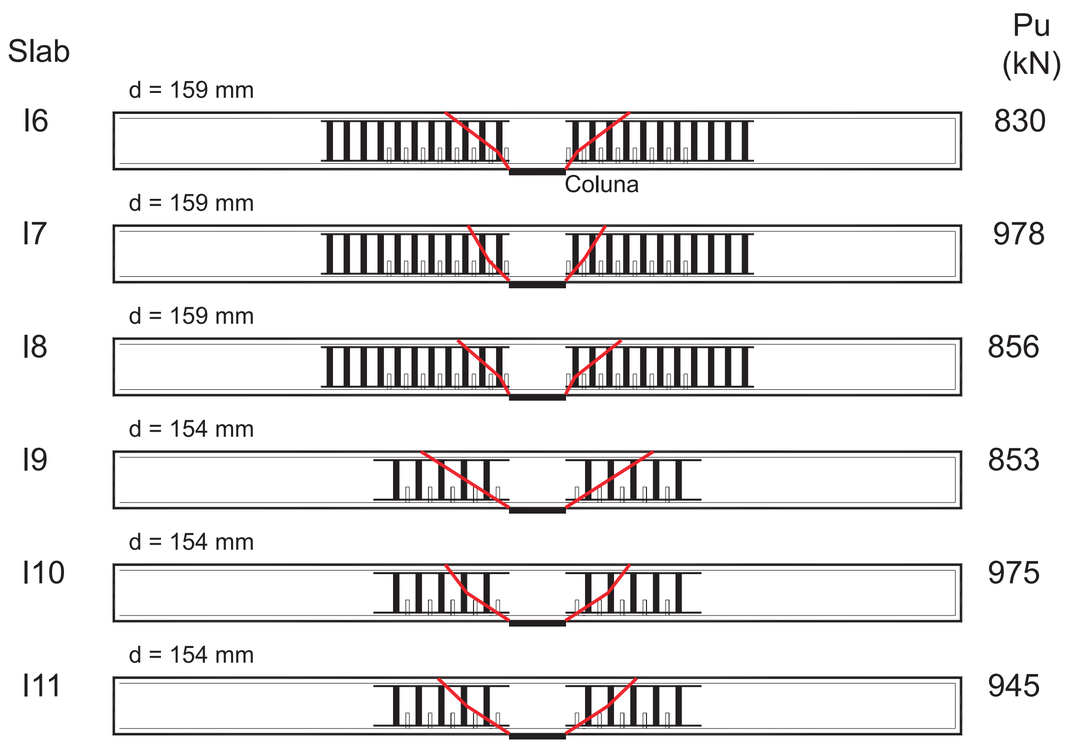
Slab I7 had the same characteristics of slab A305 (Andrade [3]) and TL9 (Trautwein [4]) in therms of type, the area of steel per layer and radial spacing. The punching

Table 3 – Failure loads of the slabs

Slabs	f_c(MPa)	d (mm)	Number of layers (A_{sw})	Layers of Hooks U (ϕ=8.0mm)	S_r (mm)	A_{sw} / S_r (mm²/mm)	P_u (kN)
I6	39,1	159	11	8	60	4,2	830
I7	39,6	159	11	8	60	10,7	978
I8	35,4	159	11	8	60	6,7	856
I9	43,6	161	5	5	80	2,0	853
I10	44,4	161	5	5	80	5,0	975
I11	41,4	161	5	5	80	3,2	945

d: effective depth;
A_{sw} – shear reinforcement;
S_r – radial spacing of shear reinforcement

Figure 10 – Failure mode and loads for all slabs tested



strength of slab I7 was approximately 20% higher then slab A305 and 5% higher then slab TL9. The maximum failure loads reached by Andrade[3] and Trautwein[4], with this type of internal shear reinforcement, were 1020 kN (slab A308) and 1050 kN (slab TL1), respectively. It is important to remember that horizontal cracks observed by Andrade[3] were not observed in the slabs analyzed in this paper.
Slab SRS1 and SRS2 with shear reinforcement "Riss Star", placed below or above the flexural reinforcement, reached failure loads of 925 kN and 950 kN, respectively. The shear steel of this slabs had 16 layers and a radial spacing equal to 50 mm. Slab I8 is similar to slab SRS1 and slab I7 is similar to slab SRS2. The relation between the failure load of slab SRS1 and the slab I8 was of 1,08, while the relation between of slab SRS2 and the I7 slab was 0,97. The relation between the failure loads of slab SRS1 and slab I8 was 1,08, and between slab SRS2 to slab I7 was 0,97.

4.2 Deflection

Figure 14 presents load vs. deflection curves for the central measured point for all slabs. The deflections at earlier load stages increase similarly for all slabs and increase together the load. The slopes of the curves modify only after the first radial cracks. From this limit the increase of deflection were higher for the same gain of load. Beyond 600 kN only a small gain of load is achieved for a considerable increase of deflection.

Figure 11 – Slabs deflections

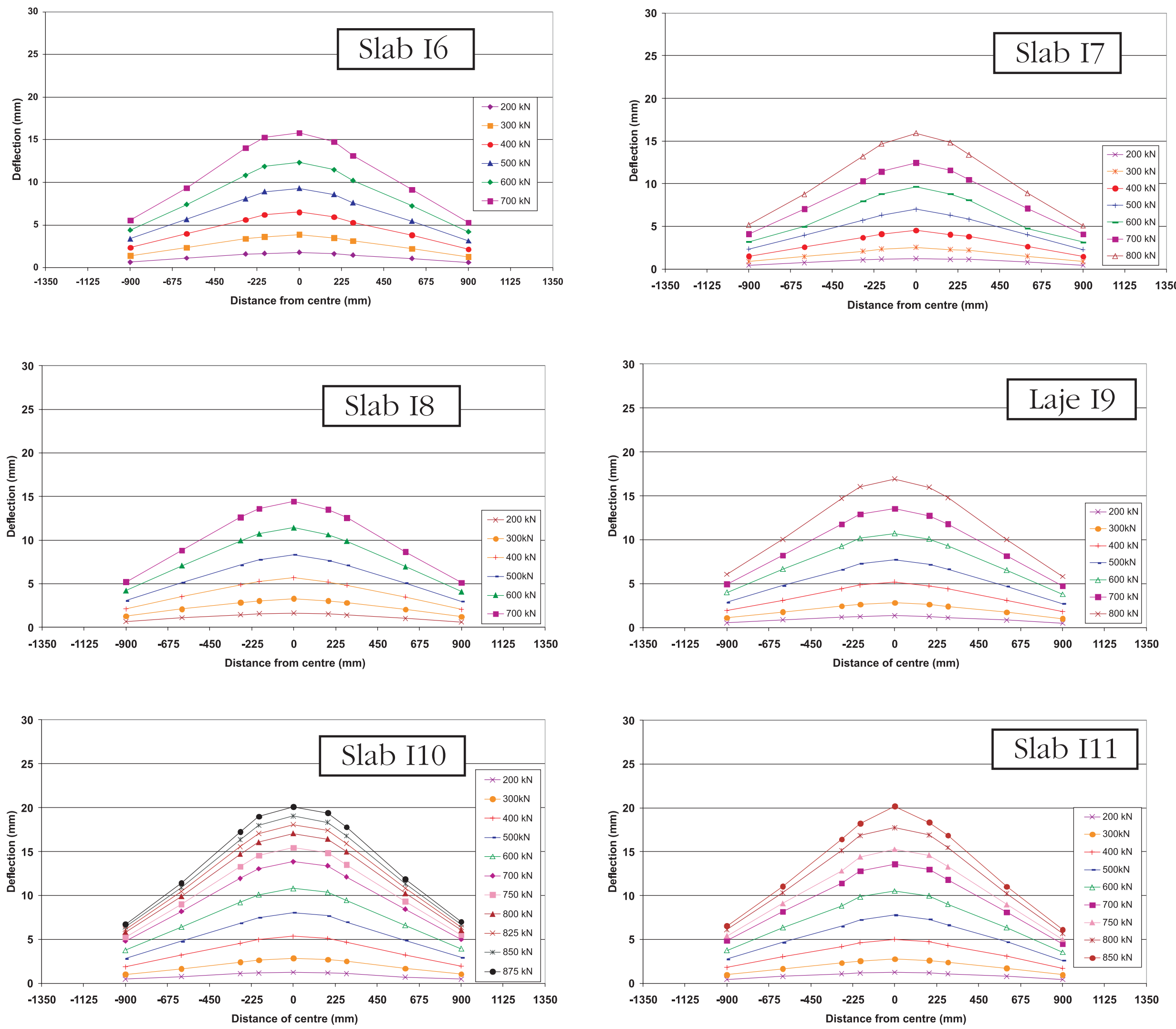


Figure 12 – Comparison of slabs deflections

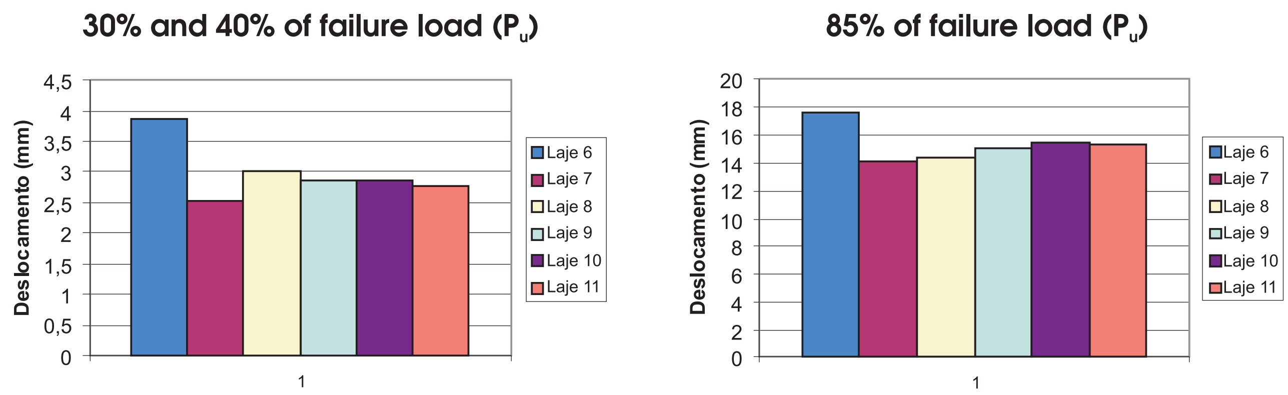


Figure 13 – Shear reinforcement strain curves of slabs I6, I7, I8, I9, I10 and I11

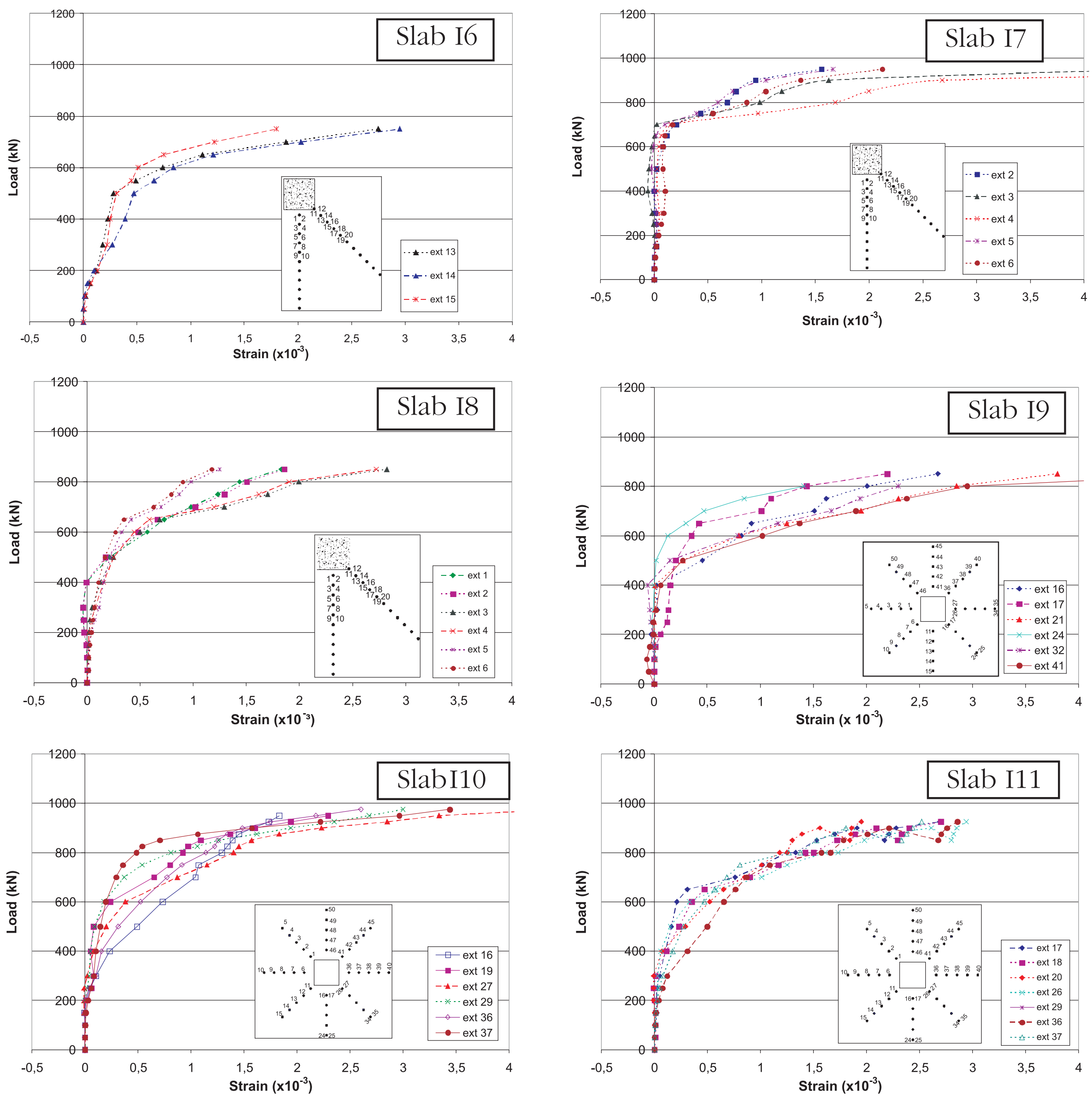


Table 4 – Comparison between failure loads of this paper and slab G1 of Gomes (1) without shear reinforcement

Slab	f_c (MPa)	d (mm)	Number of layers (A_{sw})	ϕA_{sw} (mm)	P_u (kN)	P_u /560	A_{sw} / S_r (mm²/mm)
Gomes (1991)							
G1	40,2	159	-	-	560	-	-
I6	39,1	159	11	6,3	830	1,48	4,2
I7	39,6	159	11	10,0	978	1,75	10,7
I8	35,4	159	11	8,0	856	1,53	6,7
I9	43,6	161	5	5,0	853	1,52	2,0
I10	44,4	161	5	8,0	975	1,74	5,0
I11	41,4	161	5	6,3	945	1,69	3,2

d: effective depth;
A_{sw} – shear reinforcement;
S_r – radial spacing of shear reinforcement;
P_u – Failure load of the slabs

Table 5 – Comparison between failure loads of this paper and slabs with different types of shear reinforcement

Slab	f_c (MPa)	d (mm)	S_r (mm)	ϕA_{sw} (mm)	A_{sw}/cam (mm²)	$A_{sw.fy}$ (kN)	P_u (kN)	A_{sw} / S_r (mm²/mm)
I6	39,1	159	60	6,3	249,3	149,9	830	4,2
I7	39,6	159	60	10	628,00	361,3	978	10,7
I8	35,4	159	60	8	401,9	233,3	856	6,7
I9	43,6	161	80	5	157, 0	105,9	853	2,0
I10	44,4	161	80	8	401,9	233,3	975	5,0
I11	41,4	161	80	6,3	249,3	149,9	945	3,2
G10	35,4	154	80	6	226,4	97,3	800	2,8
G11	34,6	154	80	6,9	300,8	129,3	907	3,8
A301	37,8	164	80	10	628,0	378,1	830	7,9
A305	29,3	154	60	10	628,0	378,1	785	10,5
A308	31,5	154	60	12,5	981,3	665,3	1020	16,4
SRS1	35,4	-	50	6,0	452,2	235,1	925	9,0
SRS2	33,8	-	50	8,0	803,8	417,9	950	16,1
TL1	36,8	159	60	12,5	981,3	645,7	1050	16,4
TL3	45,7	164	60	8,0	401,9	247,6	999	6,7
TL8	40,6	154	60	5,0	314,0	249,3	970	5,2
TL9	39,4	154	60	10	628,0	362,4	950	10,5

d: effective depth;
A_{sw} – shear reinforcement
S_r – radial spacing of shear reinforcement;
P_u – Failure load of the slabs.

Slab I7 with the most shear reinforcement present a rigid behavior in comparison to the other slabs. The behavior of slabs I6 and I8, with 60mm of radial spacing, was more ductile if compared with slabs I11 and I10, with 80mm of radial spacing.

The deflections of slab I8 and I10 were respectively 65% and 131% higher than slab G1 (Gomes [1]) without shear reinforcement. For slabs with 60mm of radial spacing (slabs I6, I7 and I8) the final deflections were smaller than to slabs with 80mm of radial spacing (slabs I9, I10 and I11).

The number of layers and radial spacing of shear reinforcement for slabs I9, I10 and I11 are similar to slabs G10 and G11 (Gomes [1]). The diameter of each shear element for slabs I9, I10 and I11 were respectively 5,0mm, 8,0mm

Figure 14 – Load-deflection curves (Slabs I6, I7, I8, I9, I10 and I11)

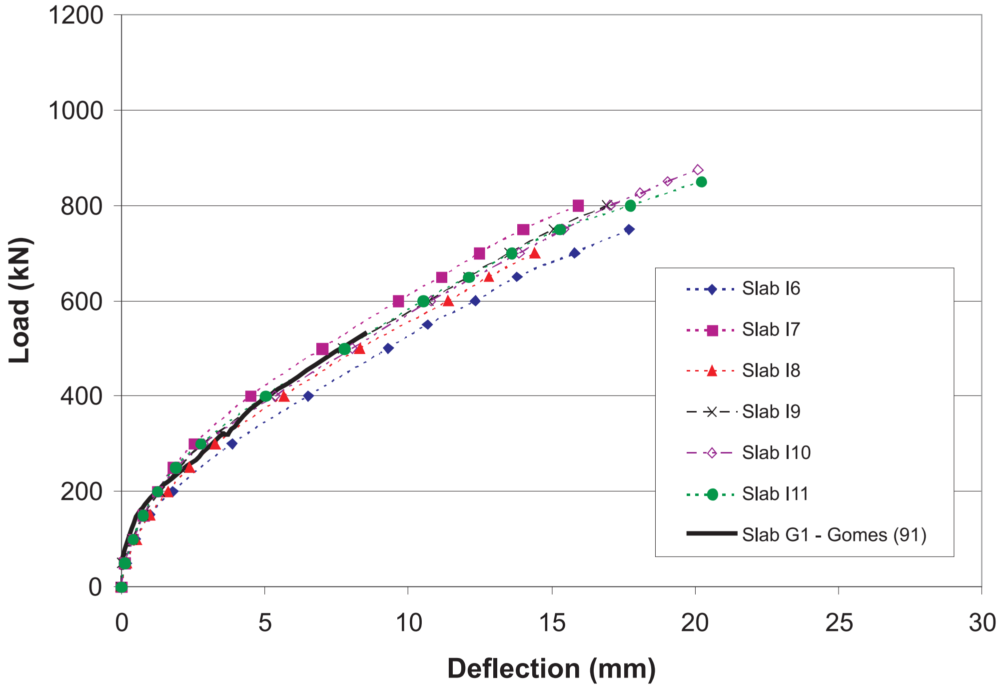
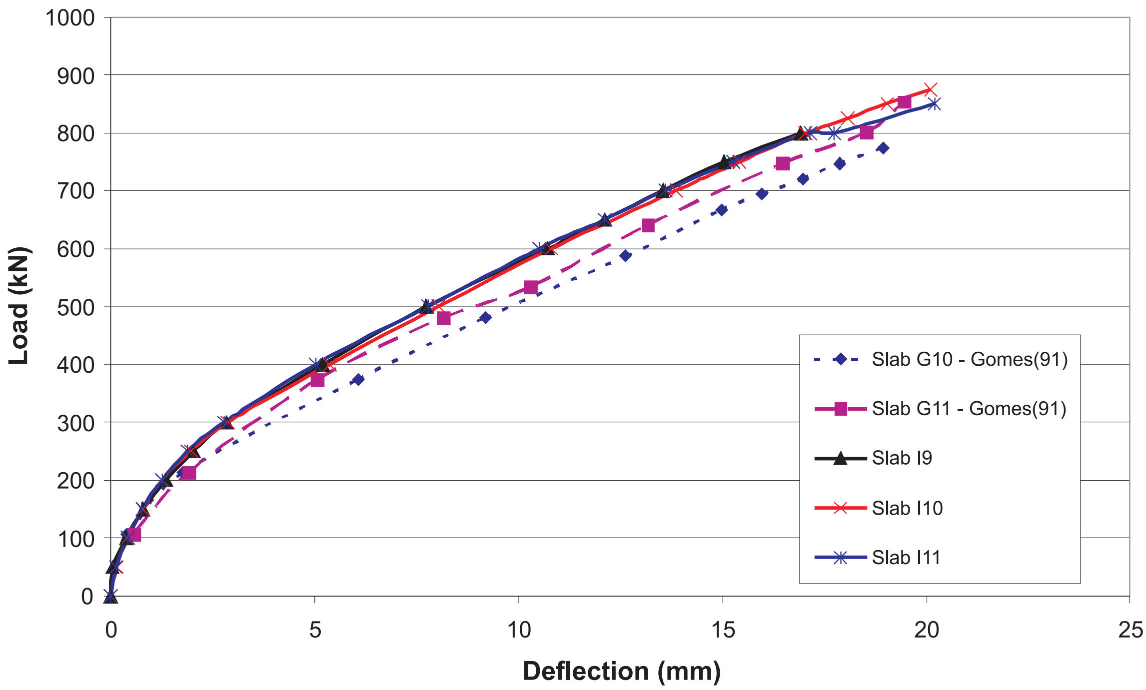


Figure 15 – Comparison of slabs I9, I10 and I11 with slabs G10 and G11 of Gomes(1)



and 6,3mm and for slabs G10 and G11 were 6,0mm and 6,9mm. Figure 15 presents the curves load vs. deflection of slabs I9, I10 and I11 compared to slab G1 (Gomes[1]). From these test results the deflections at the same level of loading were smaller than slab G1. The final deflection of slabs I9, I10 and I11 had a considerable increase if compared to slab G1 (Gomes [1]).

4.3 Crack Pattern

Cracking started with formation of radial cracks in all slabs, for a load ranging between 150kN and 250kN. At the moment the first radial crack appeared, the central displacement increased rapidly for the same load increment.
The first radial cracks started in the range between 20% to 26% of the ultimate load, and vertical displacement was always smaller than 2 mm. The first circumferential crack appeared between 250kN and 400kN. The shear reinforcement strains increased rapidly after the appearance of circumferential cracks and the first circumferential crack appeared in the range of 30% and 42% of ultimate load. At the moment of appearance of the first circumferential crack, the central deflection was smaller than 6mm.

4.4 Shear Steel and Concrete Contributions to the Ultimate Load

The punching shear strength of flat slabs with shear reinforcement is provided by a combination of both steel and concrete strengths. The shear contribution, provided by steel and concrete to the ultimate load, have been argued by many researchers and there are considerable differences between codes. Regan[9] observed that a flat slab without shear reinforcement has a failure surface around 25º. If the first layer of shear reinforcement is positioned in a distance from the column that could be change the inclination of failure surface, the concrete contribution in the ultimate load should be increased. This increase should be higher when the inclination of failure surface is higher than 45º.
Regan[9] suggested that steel contribution should be the sum of the forces in shear reinforcement crossing a 45º failure surface while the concrete contribution should be taken as 75% of the shear resistance of a slab without shear reinforcement.
In this work all the slabs failed by punching. The failure surface was in the region within shear reinforcement. An analysis of both steel and concrete contribution is presented in Table 6. The value of potential concrete contribution is taken equal (V_{ck}), calculated according to EC2/2001[10].
If only 75% of possible concrete contribution is considered, it can be seen that all six slabs should have needed at least one more layer of shear reinforcement to have attained their actual failure loads. When considering a full concrete contribution term, it seems that the numbers of shear reinforcement layers influence was closer to what occurred in tests. The failure surface of slab I6 crossed two shear reinforcement layers, and the analysis considering a full concrete contribution, suggested that 1,93 layers cooperate to steel contribution.
The last column of Table 6 show the comparison of expected failure loads calculated with the full concrete contribution and shear reinforcement resistance with the experi-

Table 6 – Shear steel and concrete contributions to the ultimate load

Slab	d (mm)	S_r (mm)	V_{ck} (kN)	V_u (kN)	$A_{sw}.f_y$ (kN)	$\frac{V_u - 0,75V_{ck}}{A_{sw}f_y}$	$\frac{V_u - V_{ck}}{A_{sw}f_y}$	$\frac{nA_{sw}f_y + V_{ck}}{V_u}$
I6	159	60	543	830	149,87	2,82	1,92	1,01
I7	159	60	547	978	361,28	1,57	1,19	1,29
I8	159	60	508	856	233,25	2,03	1,49	1,13
I9	154	80	584	853	105,87	3,91	2,54	1,05
I10	154	80	591	975	233,25	2,27	1,64	1,08
I11	154	80	564	945	149,87	2,82	2,54	1,07

d: effective depth
A_{sw} – shear reinforcement
S_r – radial spacing of shear reinforcement
n – number of layers
n = 2 (slabs 6, 7, 8, 10 e 11)
n = 3 (slab 9)
V_u – Experimental failure load of the slabs
$V_{ck} = 0,18.k.(100.\rho.f_c)^{1/3}.d.u_1$.......... (EC2/2001)

mental failure load (Vu). Slab I7 gives the highest ratio, because the failure surface could be crossed only the top of second layer and the analysis considered the full contribution of this shear reinforcement bar.

5 Conclusions

The objective of these tests was to verify the behavior of flat slabs with shear reinforcement not embracing the flexural reinforcement with U hooks. The failure surface expected for all slabs was inside the area of shear reinforcement, considering the reinforcement diameter, number of bars and spacing between layers.
The displacements for all tested slabs were very similar: the slab I11 had the higher vertical displacement (20,20 mm) and slab I7 had the displacements smaller than the others at the same loads.
For slabs I6, I7 and I8 shear reinforcement bars did not reach the corresponding deformation of yielding. For slabs I9, I10 and I11 some bars have yielded with inferior load to the one of rupture and others had probably also reached the tension of yielding at the moment of the rupture. The layers most requested in the six slabs of this group had always been the first three near the column.
Cracks running over the plane of the bottom flexural reinforcement and the shear reinforcement were not observed. The failure loads showed a reasonable improvement of the punching strength with the use of shear steel, on average 62% higher, compared to the punching strength of a slab without shear reinforcement.
The results of the tests show that internal studs without embracement in the flexural reinforcement can be effective as shear reinforcement of flat slabs and can improve the punching strength of reinforced concrete flat slabs.

6 Acknowledgments

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