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Punching shear in concrete reinforced flat slabs with steel fibers and shear reinforcement

Punção em lajes lisas de concreto armado com fibras de aço e armadura de cisalhamento





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Abstract

Steel fibers in reinforced concrete increase the performance of slab-column connection once they increase ductility and energy absorption capacity of the concrete. The use of fibers in flat slabs may increase strength and change the mode of failure. The objective of this work is to present an experimental evaluation of punching shear strength of reinforced concrete flat slab with steel fibers and punching shear reinforcement. Eight square slabs, size 1800 mm by 1800 mm by 130mm, were loaded until failure by punching shear around the column. The models were divided in two groups, depending on the type of the concrete used (with or without steel fibers). The steel fiber volume used in the slabs of second group was of 0.9%. Each group was composed of four slabs: one without shear reinforcement and three with shear reinforcement (studs) distributed radially around the column. The use of steel fibers increased the ultimate strength of all flat slabs. In one of the slabs, the association of steel fibers with shear reinforcement changed the failure surface from outside to inside the punching shear reinforcement region.

Keywords: reinforced concrete, flat slabs, punching, shear, fibers.

Resumo

A inclusão de fibras de aço em sistemas de ligações laje-pilar se torna interessante uma vez que as fibras podem melhorar a ductilidade e capacidade de absorção de energia do concreto. O uso das fibras melhora o desempenho dessas lajes, seja pelo aumento da resistência, seja pela modificação do modo de ruptura. O objetivo deste trabalho é apresentar uma análise experimental para avaliação do efeito da punção em lajes lisas de concreto armado com adição de fibras de aço e armaduras de cisalhamento. Para isso, oito lajes quadradas, 1800 mm por 1800 mm por 130 mm, foram carregadas axialmente até a ruptura. Os modelos foram divididos em dois grupos, dependendo do tipo de concreto utilizado (com ou sem fibras de aço). O volume de fibra de aço utilizado nas lajes do segundo grupo foi de 0,9%. Cada grupo foi composto por quatro modelos: um sem armadura de cisalhamento e três com armadura de cisalhamento (studs) distribuídos radialmente em torno do pilar. O uso de fibras de aço aumentou a capacidade resistente das lajes lisas em todos os modelos testados. Em um dos modelos, a associação de fibras de aço com armadura de cisalhamento alterou o modo de ruptura da laje de externo às armaduras de cisalhamento para ruptura interna à região armada.

Palavras-chave: concreto armado, lajes lisas, punção, fibras.

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1. Introduction

Flat slabs, also called flat plates, are structurally reinforced or prestressed concrete slabs supported directly by the columns, without the existence of beams (NBR 6118:2014). Their use has been common for decades, mostly due to the simplicity of the structural system, construction costs and execution time, and flexibility of construction space (Albuquerque, 2010; Nguyen-Minh et al. 2011). According to Lima Neto (2012), the main disadvantages of flat slabs are: greater vertical displacements, larger moments at the column connection, less stability due to horizontal forces and possible failure by punching shear at the slab-column connection.

Punching shear failure may occur in thin slabs under concentrated loads leading to high shear stresses in small regions around the columns Albuquerque, 2010; Nguyen-Minh et al. 2011). According to Trautwein (2011), a punching shear failure may lead to progressive collapse if the structure does not have enough load redistribution capacity.

Several variables influence punching shear in flat slab design such as the use of high strength concrete, column geometry at the slab interface, slab depth and use of reinforcement to improve shear strength as shown in previous research done by Gomes and Regan (1999), Borges, Melo and Gomes (2013) and Silva et al. (2017).

According to Maghsoudi and Sharifi (2009), self-compacting concrete (SSC) improves the punching shear strength of slabs although they present less ductility then conventional concrete and a smoother failure surface thus decreasing the contribution of aggregate interlock. Choi et al. (2007) state it is evident that shear reinforcement contributes to increase punching shear strength. However, the authors observe that the type and distribution of shear reinforcement around the column can make placement of flexural reinforcement difficult.

Recently the use of fibers to increase shear strength of reinforced concrete has been widely studied as shown in research done by Choi et al. (2007), Hanai and Holanda (2008), Cheng and Parra-Montesinos (2010), Maya et al. (2012) and Gouveia et al. (2014).

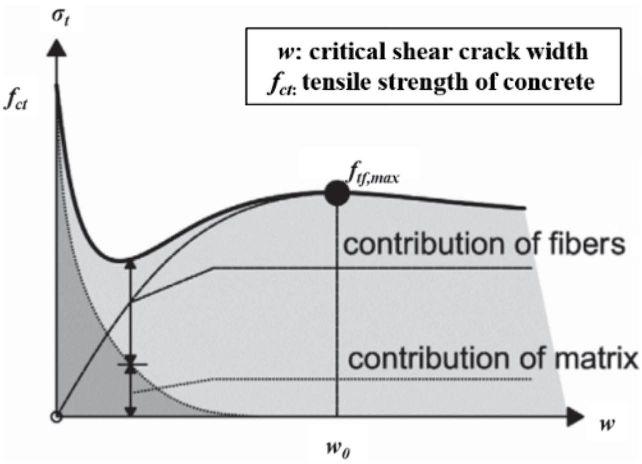


Figure 1
Post cracking behaviour of fiber reinforced concrete – matrix and fiber contributions

These studies have concluded that the use of steel fibers in slab-column connections significantly improves ductility and energy absorption capacity of the concrete. Such an increase in ductility comes from the tie action of fibers after cracking of the concrete matrix (Figure 1). The use of fibers may increase the performance of such slabs by increasing their strength or by changing to a more ductile mode of failure. Also, fibers reduce stress concentrations at ends of flexure and shear cracks, controlling crack propagation, according to Figueiredo (2011) and Moraes Neto, Barros and Melo (2013).

The objective of this article is to evaluate the possibility of increasing punching shear strength of reinforced concrete flat slabs with the use of studs as shear reinforcement and of steel fiber reinforced concrete. Tests were done on reinforced concrete flat slabs subjected to concentric column loading.

2. Materials and experimental program

This work covers punching shear in reinforced concrete building with flat slabs subjected to symmetrical vertical loading without moment transfer at the slab-column connection. The slab and the experimental setup simulated a negative moment region limited by the slab's inflection points with a length of approximately two fifths of the total span (4500 mm) as shown in Figure 2.

Eight square reinforced concrete slabs were tested until failure. The slabs were 1800mm long with a thickness of 130 mm. The most important variables used were: existence and amount of shear reinforcement, and use of reinforced concrete with the addition of steel fibers. Other parameters such as loading position, concrete compressive strength and slab size remained unchanged.

All slab testing was done at the Structures Laboratory of the School of Civil Engineering of the Federal University of Goiás. Material property tests were done at the laboratories of Carlos Campos Consulting and the Concrete Laboratory of the Center of Engineering Technology of Furnas Centrais Elétricas S.A. All these facilities are located at the metropolitan area of Goiânia, Goiás.

2.1 Slab characteristics

The slabs were divided into two groups: Group 1 – slabs cast with conventional concrete (named L1, L2, L3 and L4) and

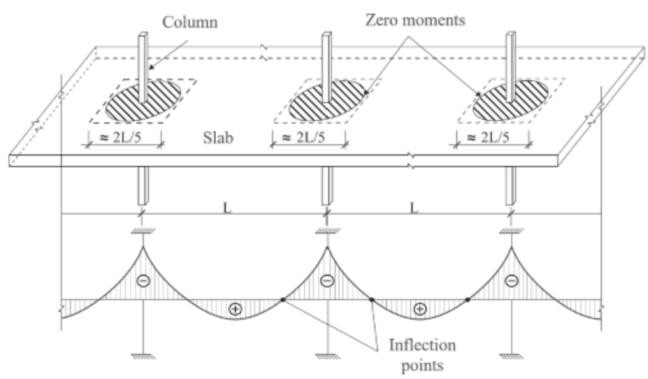


Figure 2
Idealized interior panel characterizing the situation studied

Table 1
Slab characteristics

Group	Slab	Fibers	Shear reinforcement			
			φ (mm)	# of layers	S_0 (mm)	S′ (mm)
1	L1	No	–	–	–	–
	L2		10	3	42	42
	L3		10	5	42	63
	L4		5	7	42	42
2	LF1	Yes	–	–	–	–
	LF2		10	3	42	42
	LF3		10	5	42	63
	LF4		5	7	42	42

φ = rebar diameter; S_0 = distance from the column face to the innermost stud placed at a line perpendicular to the column face; S′ = stud spacing.

Group 2 – slabs cast concrete with steel fibers (named LF1, LF2, LF3 and LF4). The steel fibers had a circular cross section and hooks at the ends for anchorage. The fiber percentage used was 0.9%, which is equivalent to 70.6 kg of fibers per cubic meter of concrete.
To achieve a desired punching shear failure, a high flexural horizontal steel ratio of 1.38% was used. The presence, quantity and spacing of shear reinforcement (steel studs) varied for each slab. All studs were radially distributed around the column.
The first two slabs in each group (slabs L1 and LF1) were taken as reference slabs and had no shear reinforcement. Three equally spaced layers of shear studs (diameter of 10 mm) were placed at every 42 mm for slabs L2 and LF2. The same diameter studs were used in slabs L3 and LF3, but the number of layers was increased to five and spacing was also increased to 63 mm. A 42 mm spacing stud distribution was used in slabs L4 and LF4 but they reached the same outside radius as the studs in slabs L3 and LF3 so two extra layers were used. Stud diameter was reduced to 5 mm in slabs L4 and LF4. These slab parameters are shown in Table 1 and in Figure 3 for all slabs.

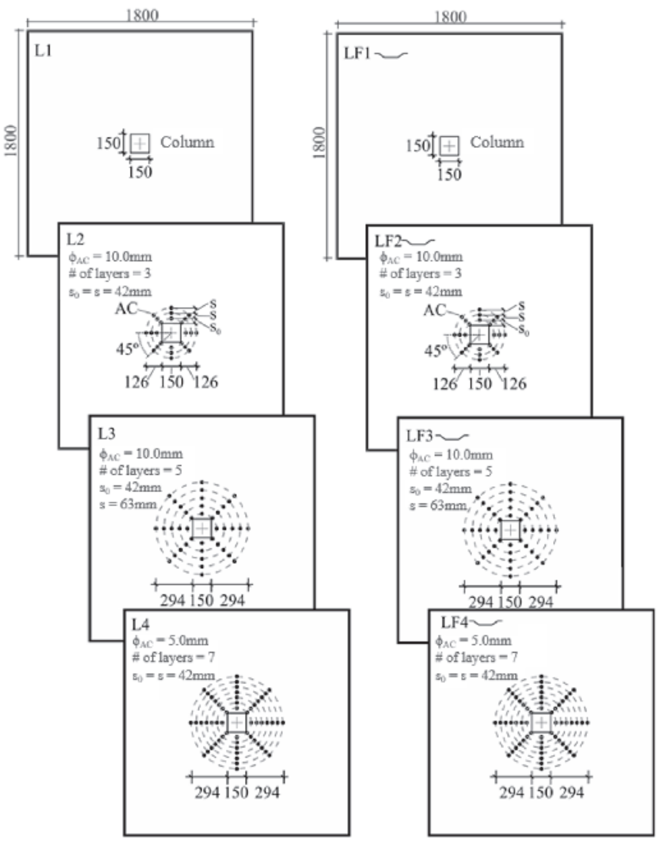


Figure 3
Slab characteristics (units in mm)

2.2 Test setup

The load was applied upward with a 1500 kN capacity hydraulic jack (Yellow Power model) placed at the bottom of the slab's centre. The slabs were tied to the strong floor through a set of 4 steel beams placed at each slab edge and 4 steel rods as shown in Figure 4. Eight small 120 mm by 200 mm by 25 mm thick steel plates were placed between the slab's top surface and the steel beams, at a radial distance of 825 mm from the slab's center.
This setup was used to obtain a similar force distribution of an interior column without moment transfer. The eight small plates served as the slab's reaction points. Figure 4 shows the drawings and photographs of the setup ready for testing.

2.3 Details on models tested

All slabs had the same flexural reinforcement as described below and detailed in Figure 5.

- Top reinforcement: nineteen 12.5 mm diameter rebars both ways (yield strength f_y of 508 MPa e yielding strain e_y of 2.83 mm/m);
- Bottom reinforcement: eleven 6.3 mm diameter rebars both ways (yield strength f_y of 558 MPa e yielding strain e_y of 3.06 mm/m);
- To assure anchorage of the top flexural reinforcement, nineteen 6.3 mm diameter "U" shaped horizontal hooks were added at each side of the slab (yield strength f_y of 558 MPa e yielding strain e_y of 3.06 mm/m).

Only slabs L1 and LF1 did not have shear reinforcement. All other slabs had stud type shear reinforcement built with steel rebars welded to 40 mm wide by 10 mm thick steel plates. Studs were 10 mm diameter rebars in slabs L2, L3, LF2 and LF3, with yield strength f_y of 839 MPa and yield strain e_y of 4.18 mm/m; and 5 mm diameter rebars in slabs L4 and LF4, with yield strength f_y = 624 MPa and yield strain e_y of 3.41 mm/m. Studs were manually welded to the steel plates using a 3.5 mm diameter ESAB electrode.
Figure 6 shows the studs and their sizes. The size of the stud's steel plates was chosen such that anchorage of the studs was guaranteed during testing. The top flexural rebars were placed below the top steel plates and bottom flexural rebars were placed above the bottom steel plates as shown in Figure 7. This figure also shows all vertical dimensions used for steel positioning.
Figure 8 shows the shear reinforcement distribution, the distance S_0 from the column face to the innermost stud placed at a line perpendicular to the column face, stud spacing S' and the angle α between lines of studs. Shear reinforcement and flexural

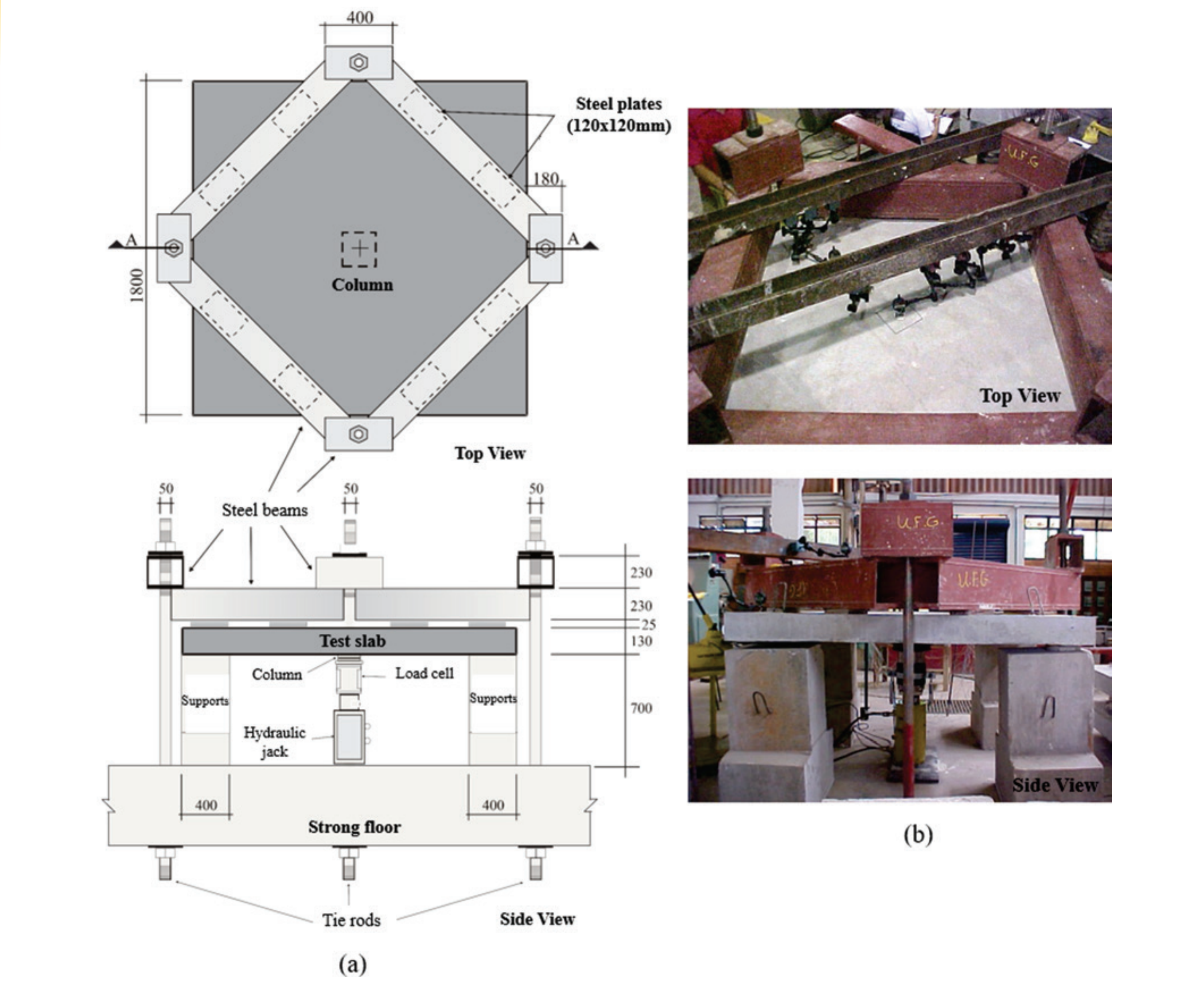


Figure 4
Test setup – (a) top and side view; (b) photo of setup (units in mm)

reinforcement of slabs L2 and LF2 is shown in the photo of Figure 9. The distance S_0 was 42 mm in all slabs. Stud spacing S' was 42 mm for slabs L2, LF2, L4 and LF4, and 63 mm for slabs L3 e LF3. Radial distribution of the shear reinforcement was done in 3 layers in slabs L2 and LF2, 5 layers in slabs L3 and LF3 and seven layers in slabs L4 and LF4. All slabs had eight lines of reinforcement placed radially equidistant, forming an angle of 45º between them. Slabs were designed for a punching shear failure but with different failure surfaces. Failures surface crossed the shear reinforcement for slabs L4 and LF4 and failure surfaces were outside the shear reinforcement region for slabs L2, LF2, L3 e LF3. Hence, the

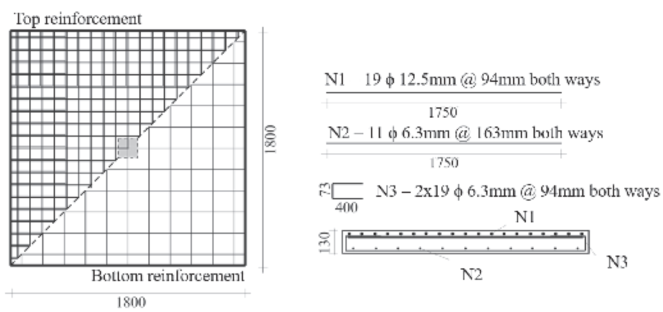


Figure 5
Slab flexural reinforcement (units in mm)

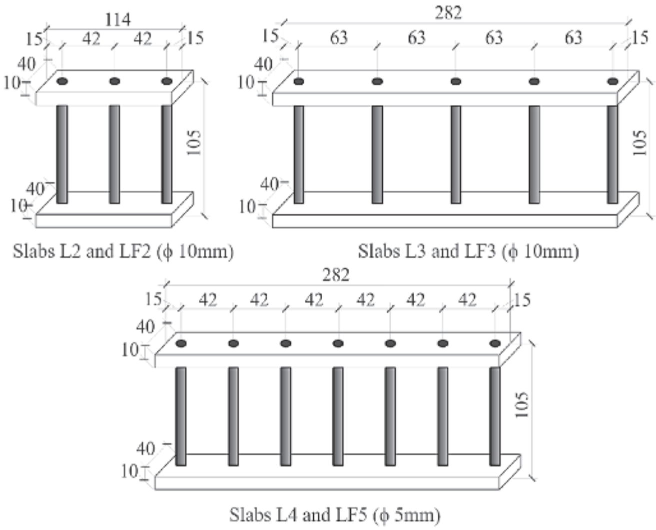


Figure 6
Shear reinforcement (units in mm)

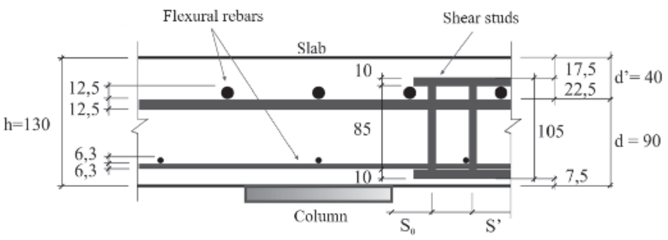


Figure 7
Positions of shear and flexural reinforment (units in mm)

distance from the column face to the outermost stud is the same (294 mm) for slabs L3, LF3, L4 and LF4 but the number of layers (five for slabs L3 and LF3, and seven for slabs L4 e LF4), stud spacing (63 mm for slabs L3 and LF3, and 42 mm for slabs L4 and LF4) and stud diameter (10 mm for slabs L3 and LF3, and 5 mm for slabs L4 e LF4) were different.

DRAMIX RC 80/60 BN steel fibers manufactured by Bekaert were used. Fibers were 60 mm long, had a nominal diameter of 0.75 mm and a size factor (diameter/length ratio) of 80. These fibers had hooks at both ends and were glued to each other but fell apart during concrete mixing due to the presence of water.

Concrete mix design aimed for a 28-day compressive strength of 35 MPa. Concrete was mixed and delivered by a local concrete supplier called Realmix Concrete S.A. Both concrete with and without steel fibers had the same mix design. Fibers were added after mixing the aggregates and before mixing all the water and cement. Superplasticizer was added to the concrete minutes before initiating casting.

Casting of the eight slabs was divided into the two groups. First, the four slabs of conventional concrete were cast (named Goup 1) and then the other four slabs (named Group 2) were cast with

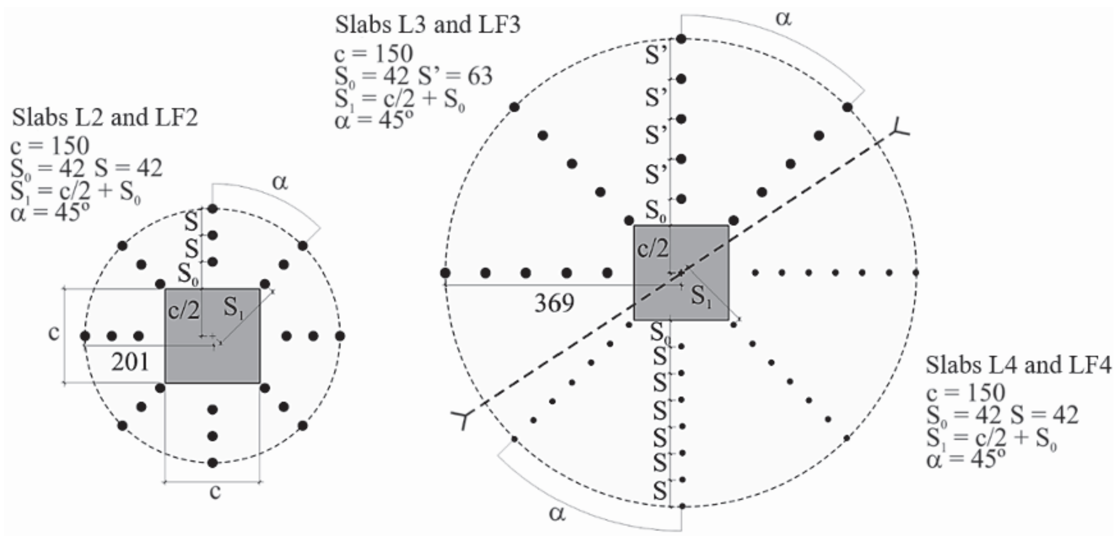


Figure 8
Distribution of shear reinforcement (units in mm)

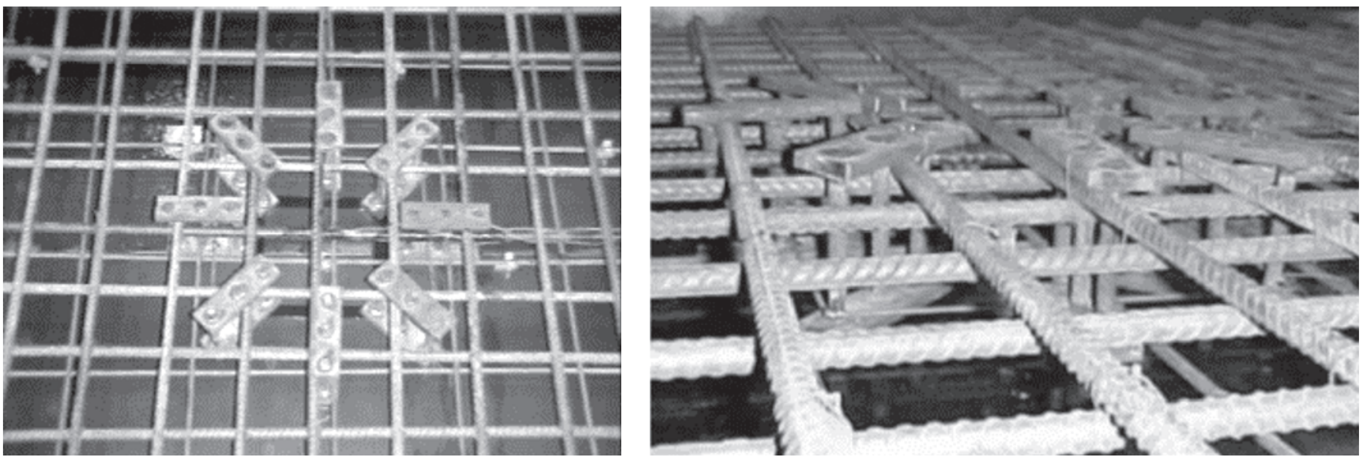


Figure 9
Shear and flexural reinforcement in slabs L2 and LF2

Table 2
Composition by m³ of concrete
(provided by Realmix Concrete S.A.)

Materials	Quantity per m³
Aggregate n° 0 (kg)	1048
Aggregate n° 1 (kg)	3468
Natural sand (kg)	415
Artificial sand (kg)	637
Cement Goiás CP II F 32 (kg)	440
CSF Silmix – Camargo Corrêa (kg)	41.8
Retarding admixture 390 MB – MBT (l)	2.64
Water (l)	172
Steel fiber (kg)	70.6
Ratio water/ (cement + CSF)	0.36

CFS = Condensed silica fume

fibers in the concrete. The concrete mix proportions are reported in Table 2.

The mechanical properties of concrete (compressive strength, splitting tensilest and modulus of elasticity) were conducted using 150 x 300 mm cylindrical specimens. These properties can be seen in Table 3.

3. Results and discussion

3.1 Ultimate loads and mode of failure

All slabs failed in punching shear. For flat slabs without shear reinforcement and fibers, with a flexural reinforcement ratio around 1.2%, the flexural strength is approximately double that of the punching shear strength. All slabs with shear reinforcement had a failure surface outside the shear reinforced region except for slab LF4. Slab LF4 from Group 2 had a different failure surface than its counterpart L4 from Group 1. The failure surface started at one of the column faces, at the bottom surface of the slab, and crossed the two innermost layers of shear reinforcement before reaching the top surface of the slab. Thus, the presence of fibers in slab LF4 modified the failure surface from outside the shear reinforced region to inside the shear reinforced region. Figure 10 shows the cross section of the slab indicating the failure surface.

The slabs were loaded in steps of 50 kN until failure. Ultimate load was the maximum load obtained from the load cell recorder. The slab´s self-weight and the steel beams are not considered in the ultimate load. Table 3 presents the most important slab characteristics and compares their ultimate loads. Concrete compressive strength in slabs without fibers was 42 MPa and compressive strength for slabs with fibers was 36 MPa on testing day. Concrete tensile strength ranged from 3.7 MPa to 4.0 MPa. To evaluate fiber influence on punching shear, ultimate loads from slabs with fibers (loads V_{uLFi}) were compared to ultimate loads from similar slabs without fibers (loads V_{uLi}), as for example, slabs LF1 and L1 (ratio V_{uLF1}/V_{uL1}). The ultimate loads from each slab were compared to the group's reference slab without shear reinforcement (loads V_{uL1} and V_{uLF1} for reference slabs L1 and LF1, respectively). These comparisons are shown in Table 3 as ratios V_{uLi}/V_{uL1} for Group 1 and as ratios V_{uLFi}/V_{uLF1} for Group2.

Assuming all slabs without fibers had the same compressive strength and practically the same effective depth (no more than a 2% difference), results in Table 3 show slabs L2, L3 and L4 had ultimate loads about 50 % higher than their reference slab L1 as shown by the ratio V_{uLi}/V_{uL1}. Slabs with fibers and shear reinforcement (Group 2) had ultimate loads averaging 33% higher than their reference slab LF1 as expressed by the ratio V_{uLFi}/Vu_{LF1}. In this case, effective depth varied about 7%.

Evidently, shear reinforcement increased punching shear strength in all slabs. This increase was higher in slabs without fibers. For example, ultimate loads were 49% higher for slab L2 compared to slab L1; both slabs without fibers. But ultimate loads were 33% higher for slab LF2 compared to slab LF1; both slabs with fibers. Also, slab L3 had an ultimate load 53% higher than the ultimate load of slab L1 and 14% higher than when similar slabs with fibers LF3 and LF1 are compared. This difference was highest (28%) when slabs L4 and LF4 are compared to their respective reference slabs.

Slabs L3 and L4 had different layers of shear reinforcement, different stud spacing and diameter, but the perimeter of the shear reinforcement region was the same with a radius of 369 mm. Both slabs had practically the same ultimate loads (472 kN for slab L3 and 467 kN for slab L4) and the failure surface was external to the shear reinforcement in both cases.

Table 3
Main slab characteristics and ultimate load comparisons

Group	Slab	d (±2mm)	f_c (MPa)	f_t (MPa)	E_c (GPa)	Shear reinforcement	V_u (kN)	V_{uLFi} / V_{uLi}	V_{uLi} / V_{uL1}	V_{uLFi} /V_{uLF1}
1 f_c = 42MPa	L1	91	41.7	3.7	25.3	–	309	1.26	1.00	–
	L2	89	42.0	3.8	25.5	3 φ10mm	460	1.12	1.49	–
	L3	88	42.2	3.8	25.8	5 φ 10mm	472	1.15	1.53	–
	L4	93	42.2	3.8	25.8	7 φ 5mm	467	1.07	1.51	–
2 f_c = 36MPa	LF1	90	35.8	3.9	23.9	–	390	–	–	1.00
	LF2	86	36.0	3.9	24.0	3 φ 10mm	517	–	–	1.33
	LF3	91	36.2	4.0	24.2	5 φ 10mm	541	–	–	1.39
	LF4	88	36.2	4.0	24.2	7 φ 5mm	501	–	–	1.28

D = effective slab depth; f_c = concrete compressive strength on testing day; f_t = tension strength on testing day; V_u = ultimate load; E_c = modulus of elasticity for concrete; V_{uLFi} = ultimate load for slabs with fibers; V_{uLi} = ultimate load for slabs without fibers

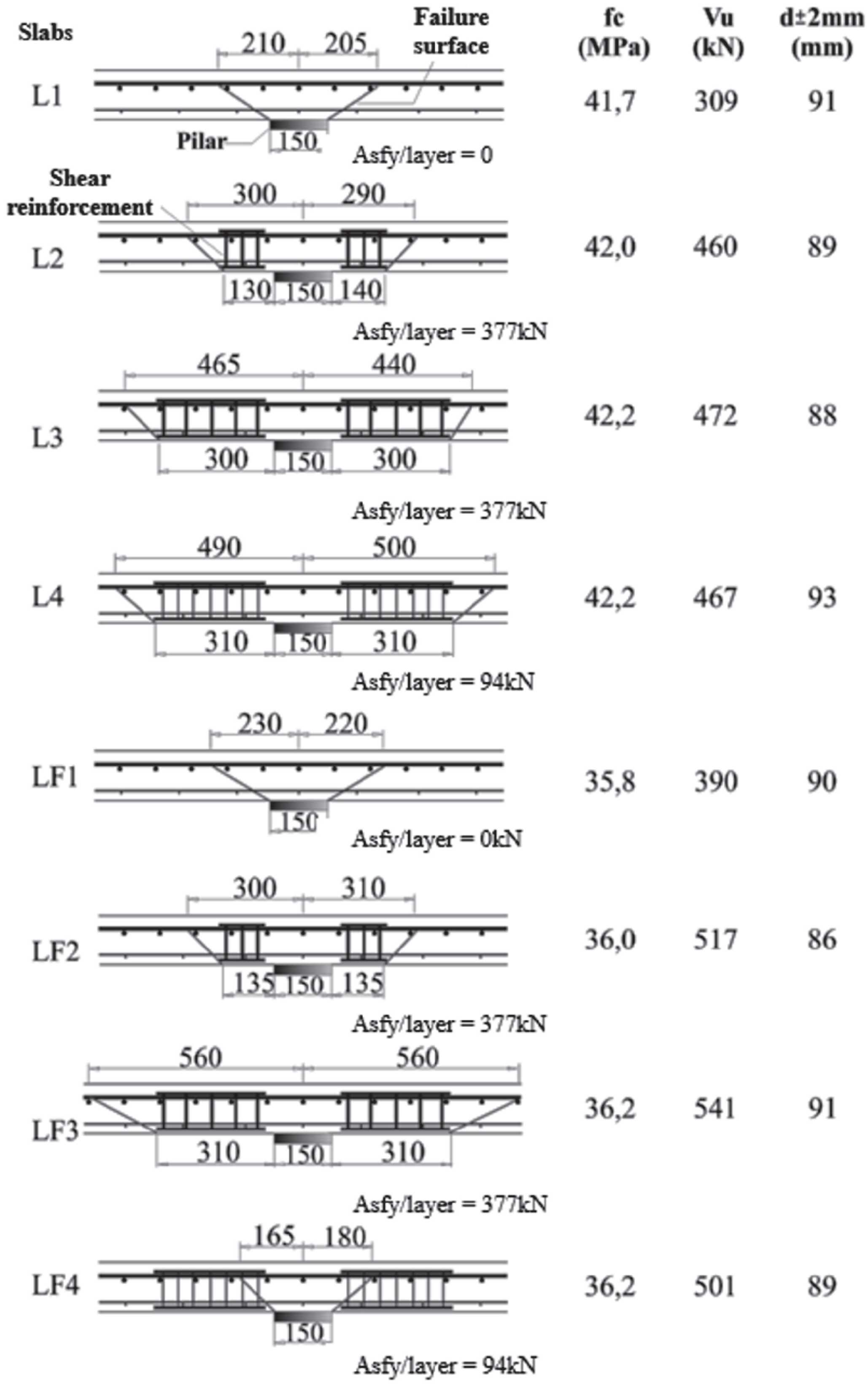
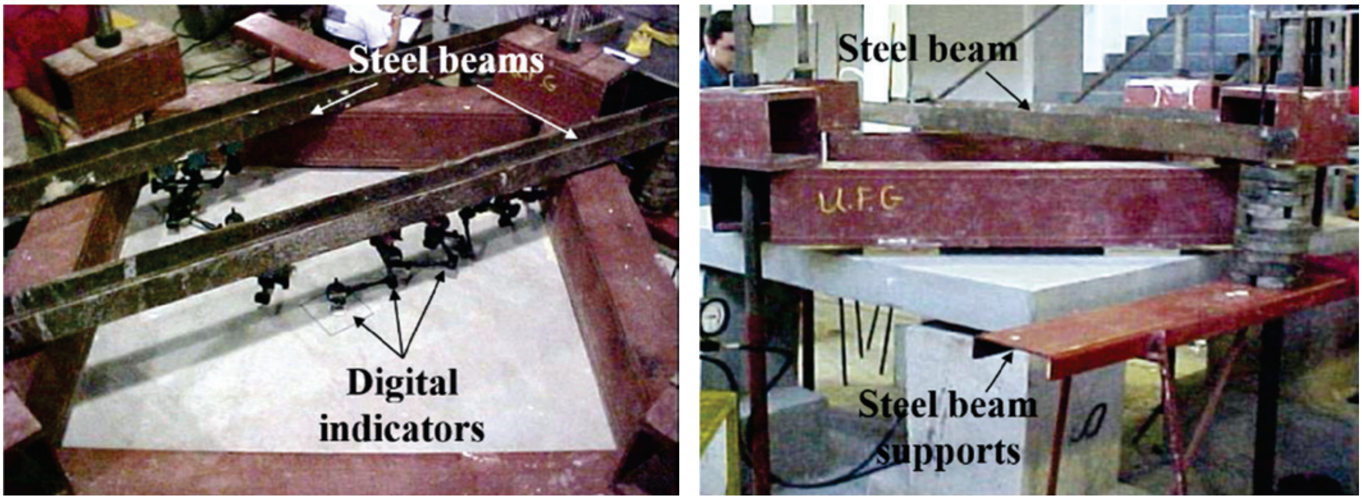


Figure 10
Failure surfaces



(a) Top view (b) Side view

Figure 11
Setup of digital indicators for measuring vertical displacements: (a) Top view; (b) Side view

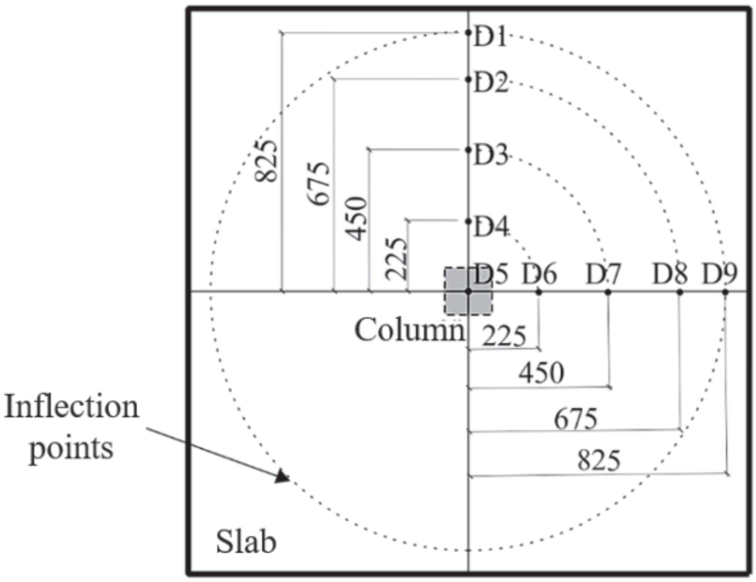
Slabs with fibers had higher ultimate loads than slabs without fibers. Fibers increase punching shear strength about 14%. The largest increase in ultimate load (26%) occurred in the slab without shear reinforcement (LF1).

3.2 Vertical slab displacements

Vertical slab displacements were measured by nine digital displacement indicators located at the slab's edge. Indicators were manufactured by Mitutoyo and had a 0.01 mm precision and a 14 mm gauge length. Indicator were mounted on a fixed C-channel steel beam supported on tripods as shown in Figure 11. Indicators were placed on the slab's top surface, radially spaced away from the column face as shown in Figure 12. Digital indicators D1 through D9 were used to measure vertical slab displacements with respect to the reaction strong floor.

All slabs presented a symmetrical vertical displacement two-way profile similar to the one shown in Figure 13 for slabs L4 and LF4. Displacements increased with loading and the largest displacements occurred at the slab's center. This was expected due to the nature and symmetry of the loading system.

In general, fibers increased displacements in slabs when comparing slabs with and without fibers. Comparing displacements for slabs L1 and LF1, without shear reinforcement, fibers increased



Digital indicators	Distance to slab center (mm)
D5	0
D4 and D6	225
D3 and D7	450
D2 and D8	675
D1 and D9	825

Figure 12
Placement of digital indicatores (units in mm)

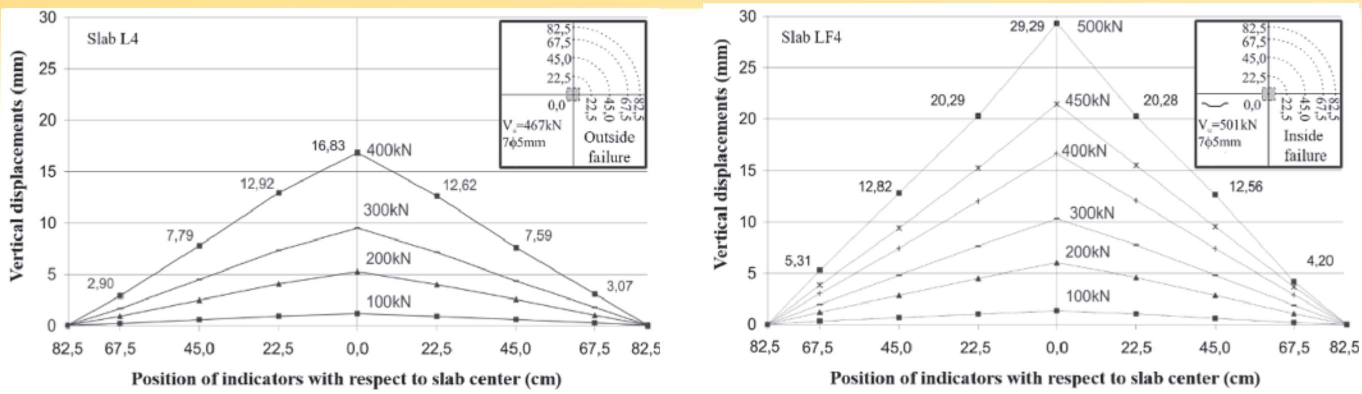


Figure 13
Vertical displacements vs position of indicators in slabs L4 and LF4

displacements for all loading stages, according to Figure 14. Slab LF2 had smaller displacements than slab L2 up to a load of 250 kN, but the situation reversed after this loading stage when displacements were larger for the slab with fibers. Slab LF3 always had smaller displacements than its counterpart slab LF3 for the same loading stages. Slab LF4 had the highest displacements of all slabs, including its counterpart slab L4.

An increase in the size of the reinforced shear region led to an increase in the slab's center displacement before failure. Slabs L3 and L4 had center displacements higher than slabs L1 and L2 at the same loading stage. At loading stage of 400 kN, the largest center displacement was 18.66 mm for slab L3, which is 10% greater than the center displacement of slab L4 and 19% more than the center displacement of slab L2. This shows that using a smaller number of shear studs and a smaller diameter stud influenced vertical displacements more than ultimate load.

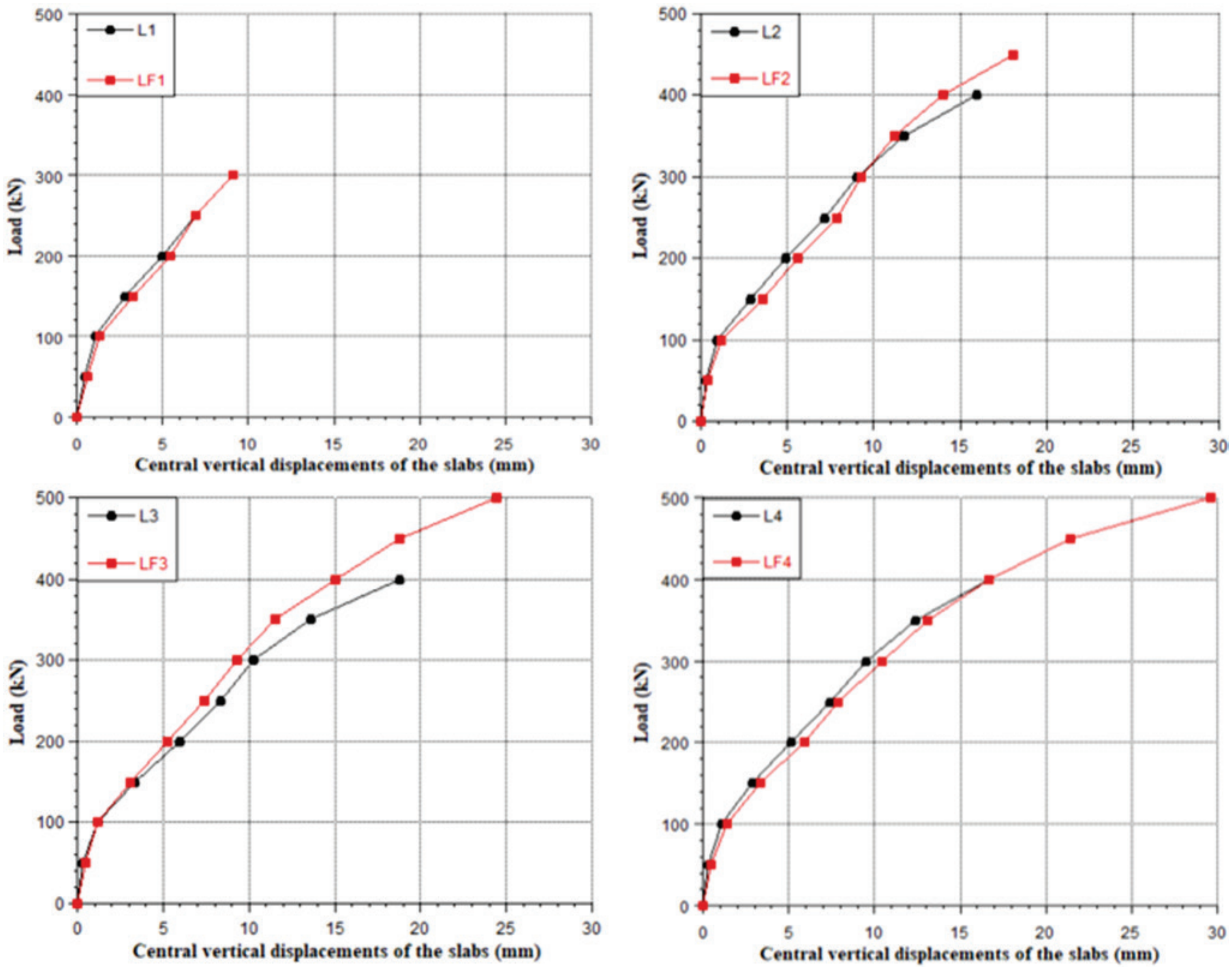


Figure 14
Load *vs* central vertical displacements of the slabs

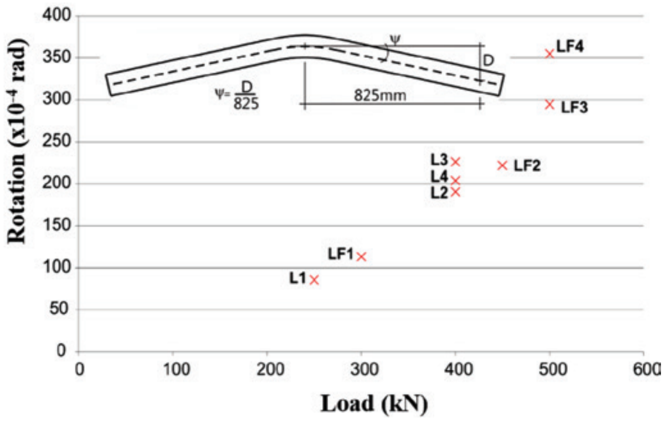


Figure 15
Slab rotations at ultimate loads

Difference in ultimate loads of slabs L3 and L4 is only 1%.
From Figure 14, the fibers increased the tenacity of the slabs by at least 21% (slab LF2 compared to L2) and by up to 114% (slab LF4 compared to L4). In the slab without shear reinforcement (LF1), this increase was 50%.
Slab rotation was calculated based on central vertical displacements and are plotted as a function of ultimate load in Figure 15. Rotations at ultimate loads were always higher for slabs with fibers when compared to their counterparts without fibers. But similar rotations at ultimate loads can occur depending on the shear reinforcement used, as shown for slabs L3 and LF2.

3.3 Cracking patterns

Cracking appeared on the slab's top surface and the slabs had similar cracking patterns. Radial cracking appeared first in all slabs, around the column, and propagated away from the column as loading increased. Figure 16 shows the cracking pattern of all slabs at higher loading stages (from 75% to 90% of the ultimate load).
Table 4 shows radial cracking loads V_r and displacements δ_r at the slab's center at the radial cracking load and comparisons of these values with ultimate loads V_u and displacements δ_u at ultimate loads for all slabs. Comparisons were made by calculating ratios V_r/V_u and δ_r/δ_u. Displacements at cracking loads for slabs without shear reinforcement were 13.2% (for slab L1) and 11.7% (for slab LF1) of the displacements at ultimate loads. For the other slabs, the ratio δ_r/δ_u ranged from 4.7% to 6.8% independently of the presence of fibers. This is due to a constant cracking load of 100 kN for all slabs, except for slab L4 which cracked at 75 kN.
Slabs without shear reinforcement also had the highest V_r/V_u ratios at 32.4% for slab L1 and 25.6% for slab LF1. For all other slabs the V_r/V_u ratios ranged from 16.1% to 21.7%. This is a similar behavior as when the displacement ratios δ_r/δ_u were compared.
Table 5 shows circumferential cracking loads V_c and displacements δ_c at the slab's center at the circumferential cracking load and comparisons of these values with ultimate loads V_u and displacements δ_u at ultimate loads for all slabs. Comparisons were made by calculating ratios V_c/V_u and δ_c/δ_u.
Circumferential cracking always appeared after radial cracking and higher loads V_c were expected. Slabs with fibers had lower

Table 4
Comparisons of radial cracking loads and displacements at cracking loads

Group	Slab	V_u (kN)	V_r (kN)	δ_r (mm)	δ_u (mm)	δ_r/δ_u (%)	V_r/V_u (%)
1	L1	309	100	0.93	7.05	13.2	32.4
	L2	460	100	0.98	15.73	6.2	21.7
	L3	472	100	1.23	18.66	6.6	21.2
	L4	467	75	1.15	16.83	6.8	16.1
2	LF1	390	100	1.27	10.85	11.7	25.6
	LF2	517	100	1.22	18.31	6.7	19.3
	LF3	541	100	1.22	24.32	5.0	18.5
	LF4	501	100	1.38	29.29	4.7	20.0

V_r = Cracking load at the first visual radial crack; V_u = Ultimate load; δ_r = Central vertical displacement at cracking load; δ_u = Central vertical displacement at ultimate load

Table 5
Comparisons of circumferential cracking loads and displacements at cracking loads

Group	Slab	V_u (kN)	V_c (kN)	δ_c (mm)	δ_u (mm)	δ_c/δ_u (%)	V_c/V_u (%)
1	L1	309	175	3.90	7.05	55.3	56.6
	L2	460	200	4.92	15.73	31.3	43.5
	L3	472	200	5.99	18.66	32.1	42.4
	L4	467	150	3.04	16.83	18.1	32.1
2	LF1	390	125	2.22	10.85	20.5	32.1
	LF2	517	150	3.46	18.31	18.9	29.0
	LF3	541	150	3.24	24.32	13.3	27.7
	LF4	501	100	1.38	29.29	4.7	20.0

V_c = Cracking load at the first circumferential crack; V_u = Ultimate load; δ_c = Central vertical displacement at cracking load; δ_u = Central vertical displacement at ultimate load

Figure 16
Slab cracking patterns at higher loading stages (70% to 90% of ultimate loads)

circumferential cracking loads than slabs without fibers (average of 27% lower). Displacement ratios δ_c/δ_u and load ratios V_c/V_u were always smaller (about 50% smaller) for slabs with fibers when compared to their counterparts without fibers. These ratios were higher for slabs without shear reinforcement. Slab LF4 had the largest central displacement and both radial and circumferential cracking occur first when compared to the other slabs (lowest ratios).

During testing, cracks in slabs with fibers had smaller thicknesses when observed visually. Slabs LF3 and LF4 had more thin cracks propagating from main radial cracks. These two slabs had shear reinforcement and concrete with fibers.

4. Conclusions

The main variables in this study were the use of steel fibers in the concrete and use of shear stud reinforcement. The shear reinforcement had 3, 5 or 7 layers of studs with stud diameters of 5mm or 10mm and spacing was 43mm or 63mm. Based on the results and within the limitations of these tests, the most important conclusions are:

a) Ultimate loads increased due to use of shear reinforcement and fibers. The ultimate load of slab LF3 (with fibers and shear studs) increase 75% when compared to the ultimate load of slab L1 (without shear reinforcement or fibers);
b) The use of fibers increased ultimate loads by 26% for the slab without shear reinforcement (slab LF1) and increased approximately 12% for the slabs with shear reinforcement (slabs LF2, LF3 and LF4);
c) Fibers change the mode of failure of slabs L4 and LF4 from outside to inside the shear reinforcement region. This type of failure presented the largest vertical displacements;
d) Vertical displacements were higher in slabs with fibers up to 74% when compared to their counterparts without fibers;
e) Radial cracking appeared at practically the same loading stage in all slabs independently of shear reinforcement and use of fibers in concrete. The slabs with fibers had a higher number of radial cracks with smaller thicknesses.

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