



Flat slabs strengthened to punching with carbon fiber reinforced polymer (CFRP) dowels

Helder Luiz da Silva Rodrigues, Priscila Moreira da Silva and Dênio Ramam Carvalho de Oliveira*

*Faculdade de Engenharia Civil, Universidade Federal do Pará, Rua Augusto Corrêa, 1, Guamá, 66075-110, Belém, Pará, Brazil. *Author for correspondence. E-mail: denio@ufpa.br*

ABSTRACT. This paper presents results of punching tests carried out in four reinforced concrete flat slabs, one of them without shear reinforcement and others strengthened with CFRP dowels. Slabs were 1000 mm square meters and 60 mm thick and were subjected to mid span loadings until failure. The strengthening arrangements were radial and cruciform, varying the number of layers of CFRP dowels. The results presented include vertical displacements, strain on steel and concrete, ultimate loads and failure mode, as well as estimation of resistance based on the Brazilian standards. It was observed significant improvement on punching resistance of the strengthened slabs when compared to the reference slab, highlighting the good performance for the strengthening system evaluated.

Keywords: flat slab, structural strengthening, punching, CFRP.

Lajes lisas reforçadas à punção com pinos de polímeros reforçados com fibra de carbono (PRFC)

RESUMO. Este trabalho apresenta resultados de ensaios de puncionamento realizados em quatro lajes de concreto armado, uma delas sem armadura de cisalhamento e três reforçadas com pinos de CFRP. As lajes eram quadradas com 1.000 mm de lado e 60 mm de espessura e foram submetidas a carregamentos centrais até a ruptura. Os pinos foram distribuídos radialmente e em cruz, variando-se o número de camadas de pinos de CFRP. Os resultados apresentados incluem deslocamentos verticais, deformações do aço e concreto, cargas últimas e modos de ruptura, além de estimativas normativas de resistência. Observou-se uma melhoria significativa na resistência ao puncionamento das lajes reforçadas em comparação à laje de referência, com destaque para o bom desempenho do sistema de reforço aplicado.

Palavras-chave: laje lisa, reforço estrutural, punção, PRFC.

Introduction

The flat slab structural system consists of slabs directly supported on columns and has been widely used due to several advantages when compared to other systems. Some of these advantages are: simplicity of formwork and rebar, reducing costs and runtime; reducing the final height of the building and thus reducing the material cost; and increasing the flexibility of layouts due to the absence of beams and capitals. However, this system has significant weaknesses in the slab-pillar connection due to the risk of sudden failure by punching. According to Binici and Bayrak (2003), the load increase for changes in the structure usage, construction errors, or even inconsistency with the current standards may lead to the need of increasing the flat slab punching resistance to ensure the structure safety. According to Li et al. (2007), the puncture-resistant capacity can be improved by

increasing the column section, increasing the effective depth of the slab, increasing the flexural reinforcement, using high-strength concrete or using shear reinforcement on slab-column connections. Among these methods, the most efficient is the shear reinforcement.

The use of Carbon Fiber Reinforced Polymer (CFRP) as strengthening material has been widely accepted due to its efficiency, easy usage and weightlessness, without interfering with the geometric and physical properties of the structure. According to Sissakis and Sheikh (2007), the use of CFRP contributes to the shear strength, ductility and energy dissipation capacity. It is also important to emphasize the importance of stiffness and strength of CFRP, which is much higher than other fibers, such as glass, which is important in controlling the formation of shear cracks as mentioned by Binici and Bayrak (2005). Among the

application techniques of CFRP, the Dowel System, proposed by Erdogan et al. (2011), can be highlighted as shown in the Figure 1 and with the main characteristics presented in the Table 1. The system involves the application of CFRP dowel, which is previously impregnated in holes in the slab thickness to act as shear reinforcement. Anchoring is accomplished by impregnating the excess portion of fiber sheet over an additional fiber strip on the upper and lower surfaces of the slab. This new strengthening system of CFRP provided maximum gain of resistance of 53%. In this research, some adjustments were made to the Dowel System. First, there was the removal step of bonding CFRP sheets to the surfaces of the slab, generating significant material savings. In addition, we can mention the development of CFRP dowels, in which are pre-molded without the use of resin and impregnated directly on the slab, and the filling of holes is made with epoxy resin, unlike the methodology proposed by Erdogan et al. (2011). Thus, this article aims to experimentally evaluate the resistance of two-way flat slabs of reinforced concrete without shear reinforcement strengthened to punching with carbon fiber.

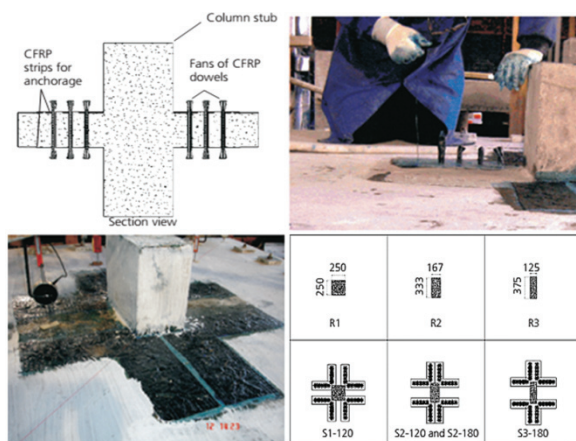


Figure 1. Dowel strengthening system proposed by Erdogan et al. (2011).

Table 1. Characteristics of the strengthening of Erdogan et al. (2011).

Specimen	Aspect ratio of column section	CFRP per hole: (height x width x thickness) mm	Number of rows	A_{CFRP} (mm ²)
S1-120	1	250 x 120 x 0,165	5	792
S2-120	2			
S2-180	2			
S3-180	3	250 x 180 x 0,165		1188

Codes' recommendation

Punching strength according to the NBR 6118

The calculation model of resistance to punching in flat slabs without shear reinforcement, according

to the Brazilian standard NBR 6118 (ABNT, 2014) suggests the verification of two control perimeters, C and C' . The perimeter C , which analyzes the diagonal compressive strength of the concrete at the column faces, can rupture by crushing of the strut; and the perimeter C' , where it is verified the connection resistance to punching at the distance $2d$ from the column, can collapse by diagonal tension, as shown in the Figure 2. The calculations to control the perimeters C and C' are demonstrated respectively by the Equations 1 and 2, where d is the effective depth of the slab along the control perimeter C' and ρ is the geometric rate of flexural reinforcement. In cases of slabs with shear reinforcements, it is necessary to determine the control perimeter C'' and $2d$, far from the outer layer of the reinforcement, as shown in the Figure 3, where the rupture can occur eternally at the reinforced region and the Equation 2 is used. The Equation 3 verifies the slab resistance, considering the contribution of the shear reinforcement.

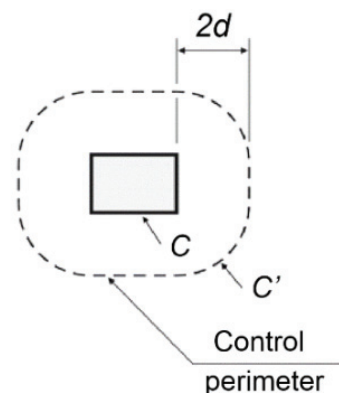


Figure 2. Control perimeter for internal columns (ABNT, 2014).

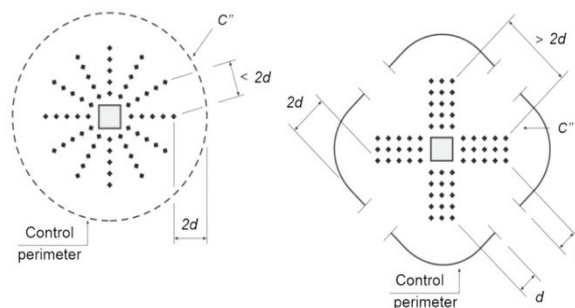


Figure 3. Control perimeter C'' (ABNT, 2014).

$$F_{Sd} \leq F_{Rd2} = 0,27 \cdot \left(1 - \frac{f_{ck}}{250}\right) \cdot f_{cd} \cdot C \cdot d \quad (1)$$

$$F_{Sd} \leq F_{Rd1} = 0,13 \cdot \left(1 + \sqrt{\frac{200}{d}}\right) \cdot (100 \cdot \rho \cdot f_{ck})^{1/3} \cdot C' \cdot d \quad (2)$$

$$\tau_{Sd} \leq \tau_{Rd3} = 0,10 \cdot \left(1 + \sqrt{\frac{200}{d}}\right) \cdot (100 \cdot \rho \cdot f_{ck})^{1/3} + 1,5 \cdot \left(\frac{d}{s_r}\right) \cdot A_{sw} \cdot f_{ywd} \quad (3)$$

where:

s_r is the radial spacing between punching reinforcement lines, limited to $s_r \leq 0,75 \cdot d$;

A_{sw} is the punching reinforcement area in a complete round parallel to C', calculated by $A_{sw} = n_h \cdot n_f \cdot d_h \cdot \pi \cdot e_f$, with n_h being the number of holes per punching reinforcement layer, n_f the number of turns of CFRP in a dowel, d_h the hole diameter and e_f is the thickness of the carbon fiber sheet;

f_{ywd} is the design resistance of punching reinforcement, limited to 435 MPa.

Flexural resistance

The flexural strength of the specimens was estimated based on the Yield Line Theory as adopted by Oliveira et al. (2004). The calculation of the ultimate flexural load P_{flex} as a function of the moment per meter m_{un} is shown in the Equation 4 and is calculated according to the Equations 5, 6 and 7. The yield line pattern adopted is shown in the Figure 4.

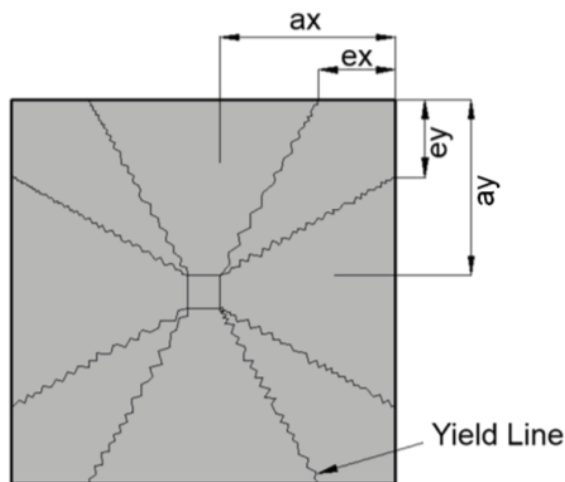


Figure 4. Yield lines.

$$m_{un} = \rho \cdot f_{ys} \cdot d^2 \cdot \left(1 - 0,5 \cdot \rho \cdot \frac{f_{ys}}{f'_c} \right) \quad (4)$$

$$P_{flex} = 2 \cdot m_{un} \cdot \left\{ \frac{l_x}{a_y} + \frac{l_y}{a_x} - 2 \cdot \left[\frac{a_y}{a_x} \cdot f_x + \frac{a_x}{a_y} \cdot f_y \right] \right\} \quad (5)$$

$$f_x = \frac{e_y}{a_y} \cdot \frac{\frac{e_x}{a_x} \cdot \left(\frac{a_y}{e_y} - 1 \right)}{1 + \frac{e_x}{a_x} \cdot \left(\frac{a_y}{e_y} - 1 \right)} \quad (6)$$

$$f_y = \frac{e_x}{a_x} \cdot \frac{\frac{e_y}{a_y} \cdot \left(\frac{a_x}{e_x} - 1 \right)}{1 + \frac{e_y}{a_y} \cdot \left(\frac{a_x}{e_x} - 1 \right)} \quad (7)$$

where:

l_x and l_y are the dimensions of the slabs in the two orthogonal directions;

a_x and a_y are the distances from the column face to the slab edge in the two orthogonal directions.

Materials and methods

Characteristics of the slabs

In this program, 4 two-way reinforced concrete slabs were tested. The specimens were square shaped with dimensions of 1,000 mm side (b_w) and 60 mm in thickness. The slabs were subjected to a concentric load by a square metal plate with dimensions of (85 x 85 x 50) mm³ simulating the reaction of a column. The flexural reinforcement ratio (ρ) was equal to 1.07% for all slabs, with an effective depth (d) of 47 mm. The concrete mix was designed for an average of 28 days and compressive strength of 30 MPa. The Table 2 presents the characteristics of the tested slabs regarding the distribution and number of reinforcement layers, as well as the fiber area (A_{CFRP}) used in each slab. The Figure 5 shows the arrangement of the CFRP dowels for the models studied.

Table 2. Main characteristics of the strengthened slabs.

Specimen	b_w (mm)	d (mm)	ρ (%)	Arrangement engthening	Rows	Layers	A_{CFRP} (mm ²)
L ₃	1000	47	1.07	cross	3	8	311
L ₄	1000	47	1.07	cross	4	8	415
L _{rad}	1000	47	1.07	radial	4	12	622

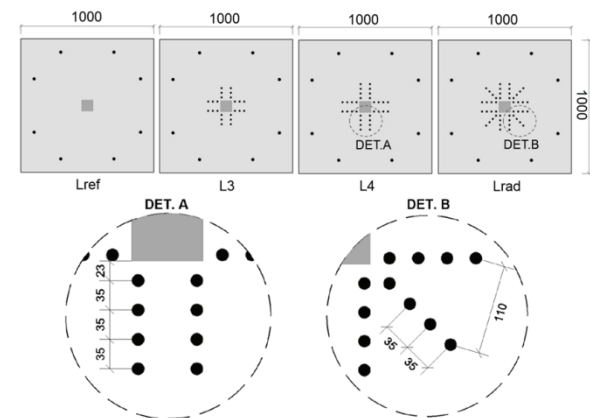


Figure 5. Arrangement of CFRP dowels (Dimensions in mm).

Flexural reinforcement

The flexural reinforcement of the slabs was built with CA50 steel bars. The main reinforcement bars consisted of 11 bars with 8.0 mm diameter in two orthogonal directions, each of them spaced by about 100 mm. The secondary reinforcement consisted of 7 bars with 6.3 mm diameter with a spacing of 163 mm. The Figure 6 presents the details of the flexural reinforcement of the slabs.

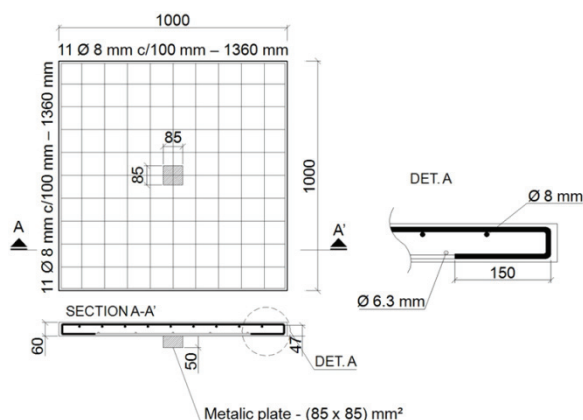


Figure 6. Flexural reinforcement (Dimensions in mm).

Punching strengthening

The punching strengthening was applied in 3 of 4 slabs tested, varying the number and arrangement of CFRP dowels, as shown in the Figure 7. The strengthening consisted in bonding the CFRP sheet in holes that were perpendicular to the slab surface. The holes were drilled by about 12.5 mm diameter using a hammer drill. The holes' edges were rounded off using a rotary rasp in order to avoid damage to the carbon fiber sheet due to the stress concentration at the sharp corners. The cleaning of the holes was performed using compressed air. The bonding process began with the application of epoxy primer on the surfaces that receive the sheet aiming to make regular the area and to improve the physical and chemical adherence of the surface of concrete. The next step was the manufacturing of carbon fiber dowel. The CFRP sheet was cut into strips with 78 mm width and rolled-up in order to achieve the shape of a tube with 120 mm in length, external diameter of 12.5 mm and two layers of CFRP. The epoxy resin was used for bonding the carbon fiber on the concrete as well as the layers of CFRP. After fixing the dowels in the holes, the remainder portion was folded and bent on the upper and lower surfaces of the slab in order to ensure the anchoring of the strengthening. To conclude the process, the holes were filled with resin.

Due to the impossibility of performing tests in the strengthening materials, the specifications were derived from the manual provided by the manufacturer, Rogertec. It was used carbon fiber sheet of 0.165 mm in thickness and tensile strength, and elastic modulus of 3,550 MPa and 235 GPa, respectively. The epoxy primer used was of 12 MPa in tensile strength, and tensile strain at 1-3%. The epoxy resin had tensile strength of 57 MPa, elastic modulus of 2,990 MPa and tensile elongation of 2.4%. The tensile strength of the CFRP laminate

(composite) was limited to 500 MPa, that is, the maximum resistance allowed by the Brazilian code for shear reinforcement.

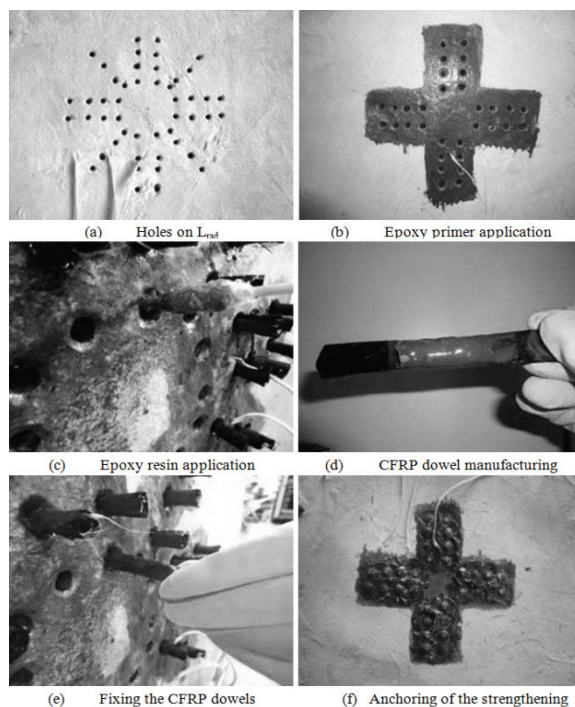


Figure 7. Method of dowel strengthening.

Instrumentation

Vertical displacements

The vertical displacements were measured at three fixed points pre-established on the upper face of the slabs using digital deflectometers with accuracy of 0.01 mm. Deflections at the column, midspan and at the support were measured. The same monitoring points were used in all the slabs in order to enable result comparisons. The deflectometers were fixed on a separate metal support in order to avoid interference in the reading due to the displacements of the test system. The Figure 8 shows the position of the vertical displacements monitored.

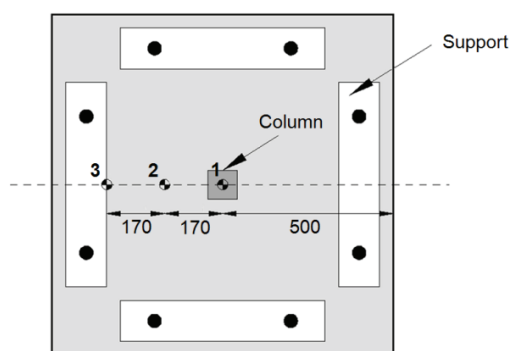


Figure 8. Position of the deflectometers (Dimensions in mm).

Strain of concrete and steel

The strain of flexural reinforcement and concrete were measured with electrical resistance strain gauges (ERSG) manufactured by EXCEL sensors Ind. Com. Exp. Ltda. For strain of concrete, strain gauges model PA-06-201BA-120L were used. They were placed in the tangential direction in order to register the highest strains. In the control slab, the gauge was distanced 50 mm from the face of the column and, in the strengthened slabs the gauge was distanced 70 mm from the column due to the amount of resin around the strengthened area and hole positions. The strains of the steel bars were measured with strain gauges model 120L-06-125AA PA fixed on three subsequent bars in the same direction, starting from the slab axis. Each bar had 1 extensometer fixed laterally, in order to avoid the effects from the local bending. The arrangement of ERSG in the flexural reinforcement was the same for all slabs, allowing a comparison of results. The Figure 9 shows the placement of the strain gauges on the flexural reinforcement and the concrete surface.

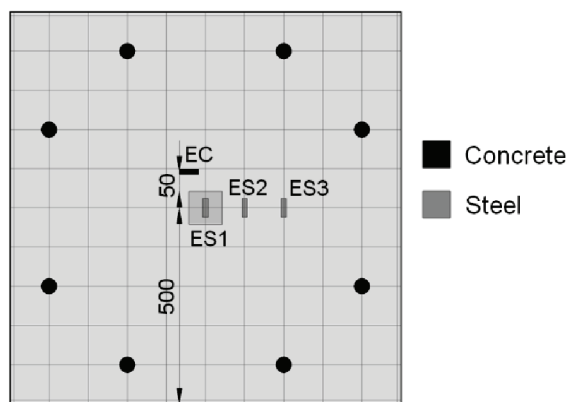


Figure 9. Position of the strain gauges (Dimensions in mm).

Test procedure

When tested, the slabs were supported on metallic reaction beams at the four sides, in order to distribute the loads along the edges of the slabs. Eight metal rods with 25.4 mm in diameter and yield strength of 400 MPa were used, being four of them fixed at the reaction slab and others were fixed through a reaction metal system. The loads were applied through a hydraulic jack of 1000 kN load capacity. A cell with 1000 kN load capacity and 1 kN accuracy was used to measure the applied loads. A metal plate with dimensions of 85 x 85 x 50 mm³ was used to simulate a square column section, wherein a plaster layer was fixed between the plate and the strengthened slabs in order to make regular the rough strengthened surface. The load was applied in the vertical direction, towards the bottom

up, with a load increase of 5 kN. The reading of the strain gauges during the test was performed using the data acquisition system Almemo. The schematic representation of the test setup is shown in the Figure 10. The Figure 11 shows the test setup at the Civil Engineering Laboratory of the UFPA.

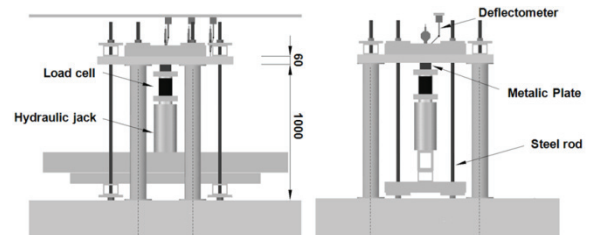


Figure 10. Test setup scheme (Dimensions in mm).

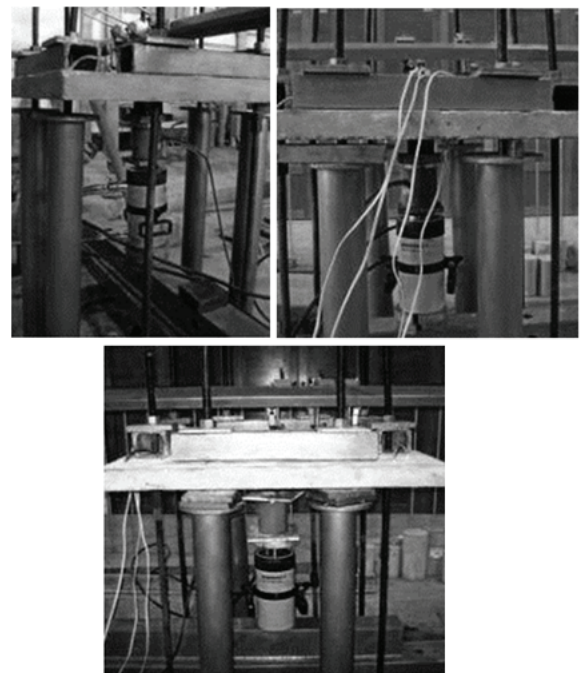


Figure 11. Test setup.

Results

Materials

Eight specimens were tested in order to determine the tensile and compressive strength of the concrete. The specimens were cylindrical with 100 mm in diameter and 200 mm in length. The tests were performed according to the Brazilian standard NBR 5739 (ABNT, 2007). The results for resistance of concrete were similar to those estimated, whereas the average compressive and tensile strength were of 39.7 and 10.7 MPa respectively, as presented in the Table 3. The steel bars were tested following the recommendations of the Brazilian standard NBR 6152 (ABNT, 2002).

Three samples of 8 mm in diameter from the same batch were tested. The average result of the tests was of 534 MPa for yield strength, 214 GPa for elastic modulus and 2.5 ‰ for yield strain.

Table 3. Results of the concrete.

Compression		Tensile	
Specimen	f_c (MPa)	Specimen	f_t (MPa)
1	39.5	5	10.2
2	35.9	6	11.1
3	41.4	7	10.3
4	42.0	8	11.1
Average	39.7	Average	10.7

Vertical displacements

Deflections were recorded for every load increase until failure. The Figure 12 shows the vertical displacements of the slabs. The results indicate that the strengthened slabs had a more ductile behavior when compared to the control slab. The Figure 13 shows the midspan deflections from deflectometer D1 and, it can be observed that the specimen L_{rad} presented the highest deflections, probably due to the strengthening arrangement in this model, presenting more holes filled with epoxy resin. This material is very ductile and may have caused reduction in the slab stiffness.

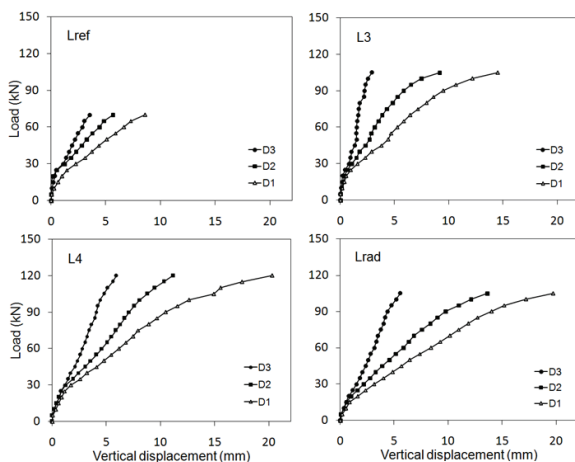


Figure 12. Vertical displacements.

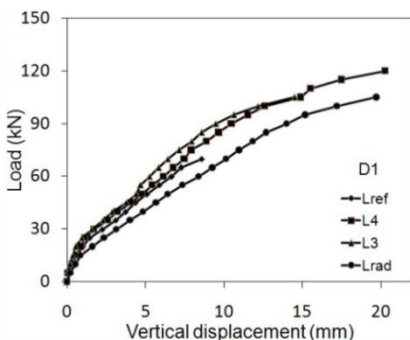


Figure 13. Vertical displacements at the center of the slabs.

Strains of concrete and steel

The Figure 14 shows the results for the strain in the concrete of each specimen. It must be noted that the strain gauges were not placed at their positions in all slabs, however, it can be observed that the strains of the non-strengthened slabs were much higher than the strengthened slabs, when the strain gauges were placed at 70 mm away from the column face, for the same loading levels, after 30 kN. The strengthened slabs showed similar behavior for the strains of the concrete. The curves for the strains of the flexural reinforcement are shown in the Figure 15. In the strengthened slabs, the bars near the column (position ES1) yielded before the specimen failure, featured a ductile behavior and showed that the slabs developed their full flexural strength capacity. The slab L_{rad} showed an anomalous behavior in the extensometer ES3, possibly due to some malfunction as well as to the extensometer ES3, slab L_3 , which showed irregular variation near the failure.

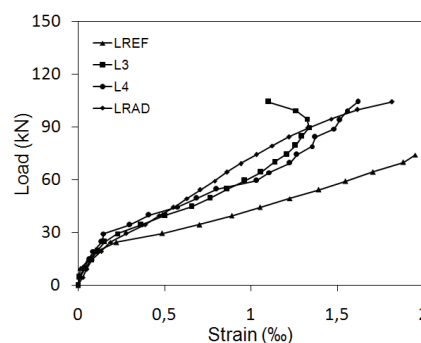


Figure 14. Strains of the concrete.

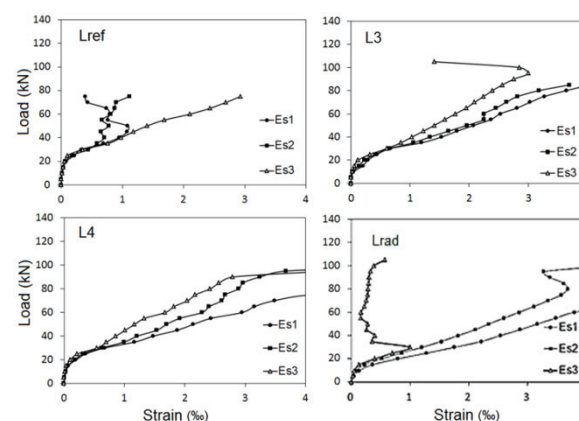


Figure 15. Strains of the flexural reinforcement.

Loads and failure modes

The failure mode determination was based on the behavior of the slabs during the tests, observing the strains of the concrete and the flexural reinforcement, the vertical displacements and the

cracking pattern. The ultimate load (P_u) was given as the maximum load recorded by the load cell. The control slab showed a sudden break with punching cone formation and absence of high vertical displacements, featuring punching failure (P) with ultimate load 15% lower than the estimated load expected by NBR 6118 (ABNT, 2014). The failure mode of the strengthened slabs was assigned as being the flexure-punching with the shear failure surface externally to the strengthened region (FPO), presenting ductile behavior in the final stages of the tests as evidenced by the flexural reinforcement yielding, high vertical displacements near failure and failure loads higher than those found for the control slab. This ductile behavior may also indicate that the anchoring systems of the dowels worked well. The results were compared to those obtained by Erdogan et al. (2011), the latest and the estimated charges are presented in the Table 4. The Figure 16 shows the cracking patterns of the current slabs. The maximum gain resistance obtained by Erdogan et al. (2011) for the slab S2-120, which was broke by punching the reinforced region (PI), was lower than the slab L_4 of the present research, which showed a

strength gain of 76% when compared to the reference slab. In the slab S2-120 was employed an amount of reinforcement 90% larger than the slab L_4 , without considering the additional strips in order to improve the anchoring pins.

As for the normative estimates (P_{NBR}), the lowest values were for failures externally to the strengthened region, with the most accurate results for the slabs of Erdogan et al. (2011). This may perhaps be due to the current slabs have been most affected by the number of holes, since the proportional amount of concrete removed from these slabs was twice higher, and this phenomenon was evident in the slab L_{rad} that used 50% more CFRP than the slab L_4 , and had higher deflections for the smaller loadings. However, despite the proximity of the normative estimates, the slabs S2-120 and S2-180 showed rupture within the strengthened region by punching, with the sectioning of the pins on the anchoring region (petal), indicating that the anchorages failed with loads near that ultimate, being unable to allow failures to occur beyond the strengthened region.

Table 4. Failure loads and modes.

Author	Slab	Failure mode	d (mm)	ρ (‰)	f_c (MPa)	P_u (kN)	P_{des} (kN)	P_{NBR} (kN)	P_u/P_{NBR}	P_u/P_{des}	P_u/P_{REF}
Current	L_{res}	P	47	1.07	40	71	83	84	0.85	0.86	-
	L_3	FPO				105		141	0.75	1.27	1.48
	L_4	FPO				125		159	0.89	1.51	1.76
	L_{rad}	FPO				112		166	0.67	1.35	1.57
Erdogan et al. (2011)	R1	P	114	1.41	32	500	581	418	1.19	0.86	-
	R2	P			29	423	579	404	1.05	0.73	-
	R3	P			30	414	583	409	1.01	0.71	-
	S1-120	PO			31	657	581	656	0.89	1.13	1.31
	S2-120	PI			33	649	579	612	0.95	1.12	1.53
	S2-180	PI			30	571	583	593	0.98	0.98	1.35
	S3-180	PO			30	564	581	593	0.98	0.97	1.36

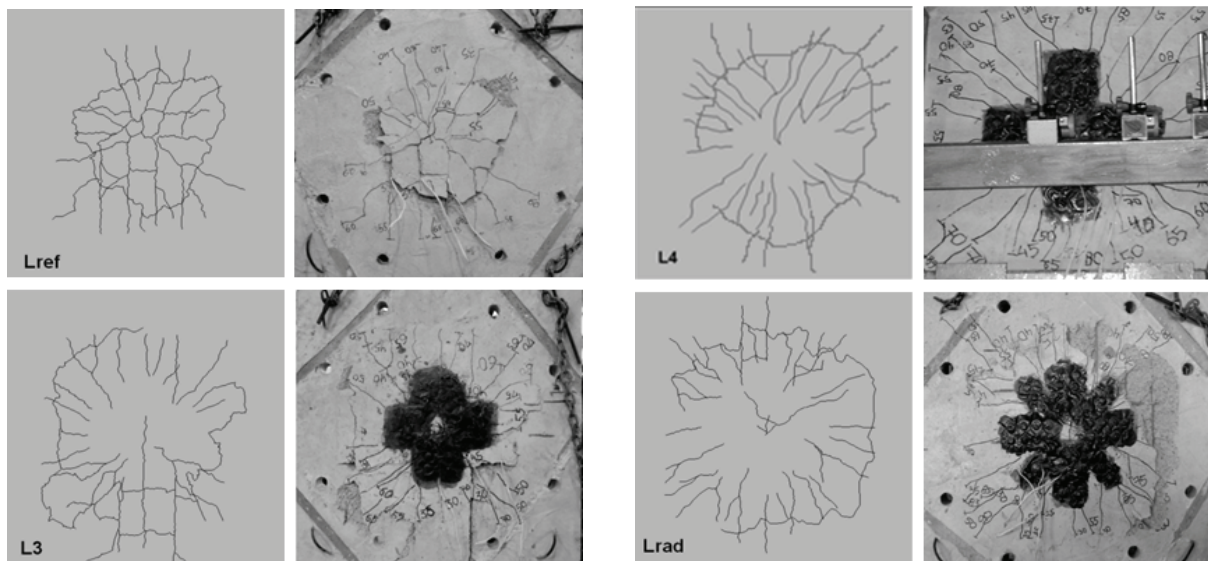


Figure 16. Cracking patterns of the slabs.

Conclusion

This study showed a punching strengthening system using carbon fiber dowels and the following conclusions were made. The strengthening generated a significant increase in the resistance of the slabs in all specimens tested, whereas the contribution to punching resistance was of 48% for the slab L_3 , 76% for the L_4 and 57% for the slab L_{rad} . Although the slab L_{rad} has received higher carbon fiber area, it has not had the greatest ultimate load, indicating that the presence of excessive holes may negatively influence the slab performance. Knowing that the punching is a sudden failure mode and must be avoided, it can be concluded that the strengthened slabs also showed better performance regarding the failure mode, since the strengthening models showed flexure-punching failure, which is characterized by ductility. Due to the simplicity of implementation and the contribution to the resistance of the tested slabs, the strengthening system for flat slabs, presented in this study, showed a satisfactory performance, proving to be an excellent alternative to structural rehabilitation. The average estimative of the Brazilian code was around 80% of the ultimate load for the current slabs tested and strengthened with carbon fiber composite.

Acknowledgements

The authors thank to CNPq and Ipeam for the financial support at all stages of the present research.

References

ABNT-Associação Brasileira de Normas Técnicas. **NBR 5739**: concrete - compression test of cylindrical specimens. Rio de Janeiro: ABNT, 2007.

ABNT-Associação Brasileira de Normas Técnicas. **NBR 6118**: design of structural concrete. Rio de Janeiro: ABNT, 2014.

ABNT-Associação Brasileira de Normas Técnicas. **NBR 6892**: metallic materials - tensile test at ambient temperature. Rio de Janeiro: ABNT, 2002.

BINICI, B.; BAYRAK, O. Punching shear strengthening of reinforced concrete flat plates using carbon fiber reinforced polymers. **Journal of Structural Engineering**, v. 129, n. 9, p. 1173-1182, 2003.

BINICI, B.; BAYRAK, O. Upgrading of slab-column connections using fiber reinforced polymers. **Engineering Structures**, v. 27, n. 1, p. 97-107, 2005.

ERDOGAN, H.; BINICI, B.; OZCEBE, G. Effect of column rectangularity on CFRP strengthened RC flat plates. **Magazine of Concrete Research**, v. 63, n. 7, p. 511-525, 2011.

LI, R.; CHO, Y. S.; ZHANG, S. Punching shear behavior of concrete flat plate slab reinforced with carbon fiber reinforced polymer rods. **Composites b**, v. 38, n. 5-6, p. 712-719, 2007.

OLIVEIRA, D. R. C.; MELO, G. S. S. A.; REGAN, P. E. Punching resistance of rc slabs with rectangular columns. **Magazine of Concrete Research**, v. 56, n. 3, p. 123-138, 2004.

SISSAKIS, K.; SHEIKH, S. A. Strengthening concrete slabs for punching shear with carbon fiber-reinforced polymer laminates. **ACI Structural Journal**, v. 104, n. 1, p. 49-59, 2007.

Received on March 25, 2015.

Accepted on June 8, 2015.

License information: This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.