Punching CFRP-based strengthening solutions for reinforced concrete flat slabs

Galileu S. Santos [1], Guilherme S. S. A. Melo [2], Joaquim A. O. Barros [3]

[1] PhD, Dep. Civil Eng., Brasília University, Brasília, Brazil, galileu.eng@gmail.com, corresponding Author
[2] Full Prof., UnB, Dep. Civil Eng., Brasília University, Brasília, Brazil, melog@unb.br,
[3] Full Prof., ISISE, Dep. Civil Eng., Minho University, Guimarães, Portugal, barros@civil.uminho.pt,

Abstract

This paper presents an experimental researh program on the punching strengthening of flat reinforced concrete (RC) slabs with carbon fibre reinforced polymer (CFRP) systems. The strengthening system consists of CFRP wet layup sheets that are installed into holes opened orthogonally to the RC slab, and bonded to the surrounding substract with epoxy adhesive. Two different techniques were adopted: one where the CFRP system fully wraps two consecutive holes, forming a close type stirrup; the second is formed by a type of flexible CFRP bar installed into each hole, working like a dowel.

The experimental program is composed of 12 real scale prototypes representative of RC slab-column connection (2500×2500 mm plan dimensions and 180 mm thickness). One of the prototypes was not strengthened for constituting the reference specimen, while the others were strengthened by adopting different arrangements for the strengthening systems, namely the pattern of the holes (cross versus radial), number of strengthening perimeters, holes per perimeter and CFRP cross sectional area per perimeter. A maximum increase of punching capacity of 67% was obtained by using the proposed strengthening techniques, having been possible to convert brittle punching failure into a ductile flexure one with the most effective punching strengthening configurations.

Keywords: Punching strengthening, CFRP, reinforced concrete slabs, experimental tests.

1. INTRODUCTION

The strengthening techniques for reinforced concrete (RC) structures aim to restore their initial target structural performance, which could have been affected by several causes like material ageing effects, errors on the design and/or execution processes, accidents, occurrence of natural damaging events, etc. Strengthening interventions can also be necessary when alterations on the load and supporting conditions are changing the stability of the structure in its serviceability and/or ultimate limit state conditions, SLS and/or ULS, respectively.

In the case of RC flat slabs supported on RC columns, ensuring their required punching capacity for attending the previous scenarios is a serious concern. In fact, punching shear failure is, in general, catastrophic with high probability of triggering a global collapse [1]. Due to this fact, several techniques have been proposed for avoiding the occurrence of punching shear failure in RC slabs supported in RC columns, namely: 1) enlarging the cross section of the top part of the RC column in order to increase the punching critical perimeter of the slab, which can be done by using several traditional materials and systems, like a RC capital, where an increase of the punching capacity up to 100% has been pointed out although the significant alterations of the column's initial geometry [2], a collar of steel profiles [2,3] where its high effectiveness for the punching strengthening even under seismic like loading conditions was demonstrated [3]; 2) increasing the flexural reinforcement ratio of the slab in the zone where punching failure can occur – this reinforcement restrains the crack opening, which increases the shear capacity, mainly due to aggregate interlock effect, but the total reinforcement ratio should be limited for do not promoting concrete crushing failure mode [4,5]; 3) applying specific punching reinforcement in the critical zone of the RC slab, in general in the form of steel dowels [2,6–8]; 4) by using fibre reinforced polymer (FRP) systems, generally of fibre carbon nature (CFRP), in the form of flexural reinforcements [9–14].

The first three types of strengthening techniques, currently designated as traditional ones due to the use of traditional materials, are more time consuming in their execution than the most recent ones based on the application of FRP materials, mainly the first one (collar systems in the head's column), which has also the inconvenience of altering significantly the geometry of the column. Amongst the traditional strengthening techniques (1 to 3), the third one is the fastest to execute and less invasive, since it requires the execution of holes crossing the slab where shear dowels (in general of steel nature) are inserted and bonded to the surrounding concrete substrate with cement or polymer based adhesives. The punching strengthening effectiveness in terms of maximum load, stiffness and ductility is also increased if the dowels are applied with a certain prestress level [6,8]. Converting punching in flexural failure mode was reported in [15] by using

CFRP rods as dowels systems. The holes for the installation of the dowels can have a certain inclination to assure better strengthening effectiveness for the shear reinforcements. This technique, designated as embedded through section (ETS), has already been applied with appreciable success in the shear strengthening of RC beams by using steel dowels [16] and even CFRP bars [17]. Analytical [18] and numerical [19] models have been proposed for modelling the strengthening contribution of ETS reinforcements with good predictive performance.

However, in relatively thin slabs the punching strengthening based on dowel systems can have small strengthening effectiveness due to the small embedment length when crossed by the punching surface. Sophisticated steel dowels with special anchorage extremities have been proposed in an attempt of overcoming these drawbacks [7], but the level of strengthening efficiency must be confronted with their relatively higher cost and installation time. To avoid interventions on the top surface of the slab, some of ETS punching strengthening techniques only require the opening of the holes from the slab's bottom surface without attaining its top surface, where special dowels are inserted from the bottom [2,20,21]. Although a level of punching strengthening effectiveness similar to that of conventional steel stirrups and headed studs has been reported, care must be taken for filling properly the holes with the adhesive, otherwise the strengthening effectiveness can be compromised due to inappropriate bond conditions.

FRPs are lightweight, not susceptible to corrosion, and relatively simple and fast to apply, do not altering significantly the initial geometry of the structure to strengthen, therefore are becoming interesting alternatives in the structural strengthening. Punching strengthening with FRP systems is being performed by externally bonded reinforcement (EBR) and the near surface mounted techniques. In the EBR technique, the FRP reinforcements, in the form of wet layup sheets or laminates are bonded to the slab's concrete top surface as flexural reinforcement. For adding extra punching strengthening to the one assured by the CFRP systems applied according to the EBR technique, shear metallic bolts are also used like dowels, and appreciable effectiveness in terms of punching capacity and deflection performance have been reported [22–24]. In the NSM technique, CFRP laminates or rods are inserted into thin grooves opened on the slab's top concrete cover [25]. In both strengthening techniques the CFRP systems are bonded to the concrete substrate with polymer-based adhesives. Since the CFRP systems are not directly exposed in the NSM technique, they have low probability of being damaged during the normal use of the slab. When adopting the EBR technique, to avoid damages on the exposed CFRP systems some protective layer should be applied.

In Harajli and Soudki [9] an increase of punching capacity up to 45% is pointed out, where the level of strengthening effectiveness has depended significantly on the CFRP strengthening configuration, stiffness and ratio, with some strengthening scenarios capable of increasing so significantly the punching stiffness and strength that failure was converted from a punching to a flexural failure. Less punching strengthening performance with CFRP sheets applied according to the EBR technique was reported by Marzouk and Ebead [10], which might be related to the larger scale of the prototypes tested by these authors in comparision to the ones in [9]. Relatively small punching strengthening effectiveness (<30%) was also pointed out by Sharaf *et al.* [12] and Soudki *et al.* [14] when using CFRP strips applied according to the EBR technique, and it was verified that the deflection performance of the strengthened prototypes has decreased with the increase of CFRP strengthening ratio (up to about 70% of the reference prototypes [12]). Glass FRP (GFRP) laminates applied according to the EBR technique have also been used for the punching strengthening of RC slabs with appreciable effectiveness (15 to 95%), mainly in slabs of relatively small concrete strength class (average compressive strength of 17 MPa) and flexural reinforcement ratio (0.59%), but the tested prototypes have relative small dimensions in order to avoid a size effect influence on the results [11]. The application of punching reinforcement with a certain prestress level has also been explored due to the capacity of, besides the reinforcement effect, introducing a favourable stress field in the slab in terms of punching resistance due to the prestress effect [26,27].When prestressed CFRP systems applied according to the EBR technique were used, punching strengthening increase less than 20% was obtained, the ductility has decreased and flexural failure was never attained in the strengthened prototypes, having the cracking load the most benefited by this strengthening technique [26,27]. By using sophisticated systems for anchoring prestressed CFRP straps, a punching strengthening increase up to 118% was reported [28,29].

By using the NSM and the EBR techniques for the punching strengthening of RC slabs, Moreno *et al.* [25] have verified that the first one was more effective, but the increase of punching capacity was limited to 15%, and failure of the strengthened prototypes was by punching.

Recently a new CFRP laminate, of clip or sticker configuration, was used for the simultaneous flexural and punching strengthening of RC slabs, which provided an increase of punching capacity of 40% compared to the reference slab [30]. The adopted CFRP laminate was not yet, however, a commercial one and their strengthening features are still being improved.

The present work aims to assess the punching strengthening potentialities of two CFRP-based techniques for RC flat slabs. The proposed techniques result from some improvements introduced in already existing ones, both adopting wet-layup type CFRP sheet, but with different geometry configuration for the strengthening elements (external stirrup [31–34] and dowel [35–37]). A comprehensive experimental program, composed of eleven real scale RC slabs, was carried out not only for comparing the punching strengthening performance of these two techniques in terms of load capacity and deflection performance of the strengthened slabs, but also other relevant aspects like: content of CFRP strengthening material applied; effectiveness of possible geometric arrangement of strengthening configurations; time to execute the strengthening interventions. The experimental program is described in detail, and the relevant results are presented and discussed.

2. THE CONCEPT OF THE PROPOSED PUNCHING STRENGTHENING TECHNIQUES

The two punching strengthening methodologies herein investigated are schematically represented in Figure 1. For the execution of both techniques, 25.4 mm diameter holes are drilled orthogonally to the middle plane of the RC slab, and CFRP wet layup sheets are inserted and bonded to the surrounding concrete substrate with an adhesive. The technique represented in Figure 1a, whose sequencial procedures for the installation of the CFRP reinforcement are detailed, is based on the concept proposed by Sissakis and Sheikh [33], designated in the present study as stitch strengthening method, where a strip or a layered set of strips of CFRP sheet (bonded each other by epoxy) are introduced into two consecutive holes by forming a type of closed stirrup (a certain overlapping length is assured for the bond transference).

While in the Sissakis and Sheikh [33], the strengthening technique (stitch) was applied in relatively small specimens, and the holes were executed while producing the specimens (pre-moulded), the stitch technique herein adopted was applied to real scale prototypes and following a methodology expected to occur in real strengthening scenarios, i.e. the holes are executed in the hardened concrete.

The second technique developed in the present work (ETS), whose procedures are schematically represented in Figure 1b, is an enhancement of the method proposed by Erdogan et al. [35]. According to this method, flexible dowels are formed by enrolling CFRP sheets in order to constitute strengthening elements of circular cross section that are introduced into the holes. While holes of relatively small diameter (14 mm) were used in the Erdogan et al. work [35], holes of larger diameter (25 mm) were adopted in the present work in order to have a better control on bonding, with epoxy, the CFRP to the wall’s surface of the hole, and filling properly the interior of the hole with high strength mortar (instead of polymer adhesive) for more cost competitive solutions. For improving the anchorage conditions of these strengthening flexible dowels, their extremities are cut in order to form a star configuration whose segments are bonded to the concrete substrate. The interior of these strengthening elements is filled by a cement based adhesive for enssuring a good balance in terms of stiffness and tensile performance. This type of strengthening technique is herein attributed the designation of embedded through section (ETS). In both techniques an epoxy adhesive was used to bond the CFRP shear strengthening systems to the surrounding concrete substrate.

3. EXPERIMENTAL PROGRAM

3.1. Geometry and reinforcement details of the prototypes

The dimensions of the tested prototypes were determined for being representative of the negative bending region of a slab supported on interior columns formed by panels of almost equal span length, *L*. This region is delimited by the sections of null bending moment, which according to the specific literature in this subject has a length of about 022*L* for uniform distributed load applied in the slab.

Since the slab span length most current in this type of construction system varies between 5 and 6.5 m, plan dimensions of 2500×2500 mm were adopted for the slab prototype, with a thickness of 180 mm, Figure 2. The slab is monolithically connected in its centre to two segments of RC column of square cross section of 300 mm edge, in order to have a more representative slab-column region.

The same flexural reinforcement (parallel to the borders of the slab) was adopted for all the prototypes, in both top and bottom zones of the slabs, Figure 3. In each of these zones an interior and an exterior (closer to the external surface of the slab) layer of steel bars of corrugated surface and equal diameter (16 mm diameter in the top zone and 8 mm in the bottom zone) were disposed mutually orthogonal, but of different spacing (the external reinforcement spaced at 100 mm and the internal at 90 mm) in order to take into account the smaller internal arm of the interior layers, therefore assuring equal flexural reinforcement ratio in both directions. The bottom flexural reinforcement aims to enssure the positive flexural capacity for facing tensile stresses in the bottom surface of the slab when demolding, transporting and installing, as well as to maintain the integrity of the slab-column connection after testing. To assure adequate anchorage conditions for the flexural reinforcement of the slab, in the extrimities of the bars (along the contour of the slab), U shape steel bars of 12.5 mm diameter were applied, with a spacing equal to the corresponding top steel layer (Figure 3).

The two column segments in each slab were reinforced longitudinaly with 8 steel bars of 20 mm diameter, one in each corner and one in the middle of the edge of the cross section (Figure 3). Steel hoops of 8 mm diameter spaced at 100 mm were applied in both column segments.

The steel class of all reinforcements corresponds to a characteristic tensile strength of 500 MPa according to the Brazilian ABNT NBR 7480 [38] standard.

3.2. Strengthening configurations

The experimental program is formed by twelve slab-colum prototypes, one serving for reference puposes (REF) and the other eleven were strengthened according to the strengthening configurations presented in Table 1 and represented in Figure 4.

The acronym for representing a prototype has the following structure: X-Y-Z(-W), where the X can be substituted by D or S for indicating the type of strengthening technique, dowel or ETS (D), or stitch (S) (a subscript *b* or *a* is added to S to indicate the holes are pre-molded, see Figure 6, or open in the hardened concrete, respectively); Y can be replaced by R or C for representing radial (R) and cross (C) strengthening configuration; Z represents the cross sectiona area of FRC (A_f) per perimeter, in mm^2; and W, only used in the configurations with the stitch technique, can be replaced by U or O, where U represents a discrete configuration resembling stirrups, and O a continuous closed form disposition for the strengthening arrangement. Two subscripts are added for the O disposition of the strengthening, the first one representing the plant configuration (d for diamond; s for square; c for circular) and the second one for the number of perimeters (6 or 8). For instance, S_b-C-297-O_{d6} represents the stitch technique (S) with pre-molded holes (subscript b) in a cross arrangement (C) with 297 mm^2 of A_f/perimeter, where the CFRP systems are disposed in a continuous closed form (O) of diamond plant configuration (subscript d) with 6 perimeters (subscript 6).

The unique difference between the REF and the strengthened prototypes is the absence of any punching strengthened system applied in the REF prototype. In Table 1 *d* is the internal arm of the top flexural reinforcement of the slab (average of the two mutually orthogonal layers), ρ_{sl} is the flexural reinforcement ratio (equal in both directions due to the reasons already exposed), and A_f/perimeter is the cross sectional area of the CFRP strengthening introduced in the holes per perimeter. Due to small differences registered (after the slabs have been tested) in the position of the flexural reinforcement of the tested prototypes, Table 1 indicates the measured *d* and the corresponding ρ_{sl}, where it can be concluded that ρ_{sl} has ranged from 1.43% to 1.61%. For the adopted punching strengthening configurations, the A_f was the same in all the perimeters of a certain configuration. The influence of the number of strengthening perimeters (6 and 8) and the disposal of the holes (in Cross or Radial disposition) on the punching strengthening effectiveness was investigated. To simplify the process of executing the holes, they were assured in the majority of the tested prototypes by applying a convenient mold before casting the prototype. Recognizing that this is not the real punching strengthening practice, in some of the prototypes the holes were cored when the concrete was in its hardened state, in order to acess the influence of this process on the punching strengthening effectiveness.

The prototypes S_b-C-132-U, S_b-C-132-O_{d6}, S_b-R-132-O_{s6}, S_b-R-132-O_{c6}, D_b-C-132 and D_b-R-132 have the same *s/d* and cross sectional area of CFRP per perimeter (A_f/perimeter), where *s* is the spacing between consecutive strengthening perimeter (Figure 4), equal to 90 mm in all prototypes (Figure 5). Therefore, according to the formulations available in the major design guidelines, the configurations adopted in these prototypes should assure similar punching strengthening contribution. However, since these formulations do not consider aspects like the geometric disposition (cross versus radial for the holes) and type of the strengthening technique (stitch or ETS), the results obtained from testing these prototypes also aim to contribute to clarify these aspects. Furthermore, in the S_b-C-132-U and S_b-C-132-O_{d6} prototypes that were strengthened according to a cross configuration of the holes and with a stitch technique, the anchorage conditions were, however, different in order to investigate their influence on the strengthening effectiveness. In fact, in S_b-C-132-U the diagonal zones are not wrapped with CFRP strips, while in S_b-C-132-O_{d6} these diagonal zones are wrapped (Figure 4).

In the S_a-C-99-U and S_a-C-165-U prototypes the holes were executed when concrete was in its hardened state (62 days after casting) in order to investigate the influence of the hole's surface characteristics on the strengthening effectiveness. In fact, drilling the holes in the concrete's hardened state represents a real strengthening intervention, which results in a rough surface of the concrete substrate, thereby enhanced bond conditions with the adhesive are expected. To avoid that steel reinforcements are damaged while drilling the holes with proper machine, an equipment of steel reinforcement detection was used, in agreement to what should be done in real practice. If some damage in the steel flexural reinforcement, however, occurs, which can happen in real applications due to the difficulty of detecting with high accuracy all the reinforcements, the consequent reduction of the flexural reinforcement ratio should be taken into account in the formulations for the evaluation of both the flexural and punching capacity of the strengthened RC slab. Cutting steel rebars not only reduces the flexural capacity, but also the punching since the dowel and aggregate interlock favourable resisting mechanisms are detrimentally affected. For estimating the reduction of the flexural capacity several reliable available formulations can be adopted, such is the one provided by the Model Code 2010. For evaluating its influence on the punching capacity, the formulation proposed elsewhere [35] can be used. This formulation is an adaptation of the EC2 proposal, and therefore includes the favourable resisting mechanism of the flexural reinforcement in the punching capacity of a RC slab.

The difference in these two prototypes (S_a-C-99-U and S_a-C-165-U) is the A_f, i.e. the cross sectional area of CFRP per perimeter (A_f/perimeter), in order to determine its influence on the strengthening effectiveness.

The S_b-R-132-O_{c6} prototype has a radial strengthening configuration with a spacing between consecutive holes in the perimeter respecting the recommendations of Eurocode 2 [39], since this standard limits to $2d$ this distance. This configuration was inspired in the proposal of Gomes and Regan [40], and the objective is the assessment of the influence of this limit on the punching strengthening effectiveness.

The S_b-R-132-O_{s6} prototype difers from the S_b-R-132-O_{c6} only on the distance between strengthening holes, where the limit of $2d$ in the perimeter was not accomplished in the S_b-R-132-O_{s6} prototype, but both have the same number of strengthening perimeters and the same A_f per perimeter.

The S_b-R-297-O_{c8} and S_b-C-297-O_{d8} prototypes have 8 strengthening perimeters and the same A_f per perimeter, but the strengthening configuration is different, radial in the S_b-R-297-O_{c8} prototype and cross configuration in the S_b-C-297-O_{d8} prototype.

The S_b-C-297-O_{d8} and S_b-C-297-O_{d6} prototypes have the same cross strengthening configuration and A_f per perimeter, but different number of strengthening perimeters, 8 in the S_b-C-297-O_{d8} and 6 in the S_b-C-297-O_{d6}. According to the recommendations of the Eurocode 2 [39], the strengthening configurations of these prototypes have the same outer punching failure perimeter (u_{out}), as well as equal values for the other variables taking part on the design equations predicting the punching capacity. Therefore, according to the Eurocode formulation, these two prototypes should have the same punching capacity if punching failure occurrs outside the punching strengthening zone. By comparing the results from the S_b-C-297-O_{d6} and S_b-C-297-O_{d8} prototypes the reliability of these recommendations was assessed.

Figure 5 represents the disposition of the holes executed in the slabs for the application of the CFRP strengthening systems.

3.3. Materials

Concrete

Table 2 presents the values of the compressive and splitting tensile strength of the concrete applied on the execution of the prototypes. The concrete was order from a ready mix concrete company for a target compressive strength class of 40 MPa (f_{ck}) of maximum aggregate size of 10 mm. The average compressive strength (f_{cm}) was determined by executing compression tests with cylinder specimens of 100 mm diameter and 200 mm height according to the recommendations of ABNT NBR 5739 [41]. The average splitting tensile strength ($f_{ctm,sp}$) was obtained from indirect tensile tests (Brazilian test setup) executed according to the recommendations of ABNT NBR 7222 [42]. For each concrete batch three specimens were tested for the evaluation of the f_{cm} and $f_{ctm,sp}$, and the age of the specimens when tested is also indicated in Table 2, which corresponds to the age when the corresponding prototypes were also tested.

Steel reinforcement

For the flexural reinforcement a steel class CA-50 of a characteristic tensile strength of 500 MPa was used (ABNT NBR 7480 [38]). Steel bars of 8, 12.5, 16 and 20 mm diameters (ϕ) were adopted, and their relevant tensile properties were determined by executing tensile tests according to the recommendations of ABNT NBR ISO 6892 [43]. For each diameter of each order (three orders were requested for the total experimental program), three specimens were tested, and the average results are indicated in Table 3, where ε_{sy} , f_{sy} and E_s are the yield strain, its corresponding yield stress, and the elasticity modulus, respectively. Small variation of the tensile properties for the same bar diameters was obtained amongst the three orders of the steel bars. The highest differences were registered in the bars of 8 mm diameter, but these bars were used in the bottom surface of the slabs, therefore without relevant impact of the punching behaviour of the tested prototypes.

CFRP strengthening system

The MBrace® CFRP system was adopted for the punching strengthening configurations. This system is formed by the following components: CF 130 fabric of unidirectional carbon fibers that is the structural strengthening component; MBrace Saturant for bonding CF 130 to the concrete substrate and amongst consecutive CF 130 layers (when more than one layer was applied); the MBrace Primer that was used for treating the concrete substrate; and MBrace Putty applied for rectifying geometric irregularities in the surface of the concrete substrate. The properties of the CF 130 and MBrace Saturant were provided by the supplier and are indicated in Table 4.

3.4. Execution of prototypes and strengthening procedures

A metallic mold was used capable of executing four slab-column prototypes for each cast. The top part of the RC column of each slab was built by using a timber mold installed just after the corresponding slab has been cast. For the prototypes with the holes already integrated in the slab, PVC tubes were pre-installed in the slab mold by using threaded steel rod welded to the metallic mold of the slab (Figure 6b). PVC conical segments were installed in both extrimities of each steel rod in order to assure a smooth transition at these extremities in an attempt of minimizing the occurrence of abrupt stress gradients in the CFRP strengthening systems in these zones (Figures 7b and 7c). A threaded steel nut was used to fix the bottom PVC cone against the slab mold in order to avoid the entrance of concrete inside the PVC tube, which was finally applied. The casting of a prototype involved the following three stages: 1) casting the bottom part of the RC column; 2) casting the slab; 3) application of the mold of the top part of the RC column and casting this part. The casting procedure was as fast as possible in order to assure a monolithic connection between slab and both parts of the column. After casting, the top surface of the slab was leveled to assure a constant thickness for the slab, and treated to become smooth.

After concrete has been cured, the concrete substrate of zones where CFRP is planned to be applied was treated by a machique equipped with a diamond disk for the removal of a thin cement past layer. The both extremities of the holes were also rounded for minimizing the occurrence of premature failure of the CFRP due to the development of high tensile stress gradients in these zones.

For the application of the stitch strengthening technique (Figure 1a), 25 strips of CF 130 were prepared. After the concrete has beentreated with the Primer and Putty according to the recommendations of the supplier, the wall of the holes and the zones of the concrete substrate planned to be in contact with these CFRP strips were impregnated by the Saturant. Immediately after this impregnation, the strips of CF 130 were bonded to the concrete substrate, and a final layer of MBrace Saturant was applied in order to assure the strips become fully saturated with the bond adhesive. For this strengthening technique a lap splice length of 150 mm was adopted for all the CF 130 strips. Figure 7 shows the sequence of strengthening procedures adopted in the stitch technique applied to the S_b-C-132-U prototype.

For the application of the ETS strengthening technique, 100×320 mm strips of CF 130 were cut from the roving for the production of the CFRP dowels. To assure a dowel configuration, the a CFRP strip of 100 mm width has involved a PVC tube of diameter (25.4 mm) smaller than the diameter of the hole, with the carbon fibers in the direction of the hole’s axis (orthogonal to the middle surface of the slab). Therefore, in each hole this tubular CFRP system is composed for four layers. After has been treated with the Primer and Putty according to the recommendations of the supplier, the wall of the holes and the concrete substrate planned to be in contact with the CFRP were impregnated with the MBrace Saturant. After the installation of the CFRP dowel, the PVC tube was removed, and the end parts of the CFRP dowel, outside the hole (in a length of 70 mm), were opened and glued to the corresponding slab's surface with a star configuration for providing anchorage conditions for the dowel. After the adhesive has been cured (a period of about 48 h was adopted, according to the recommendations of the supplier), the internal part of the CFRP dowel was filled with a high strength and fluid mortar (Sika grout 250). Figure 8 shows the sequence of strengthening procedures adopted in the ETS technique for the D_b-C-132 prototype.

3.5. Test setup and monitoring system

All prototypes were submitted to symmetric loading conditions in order to simulate a slab supported on an interior RC column. For testing, a reaction frame formed by steel profiles, fixed to the reaction RC slab of the laboratory, was used (Figure 9). The vertical load was applied by using four hydraulic actuators with predefined loading steps. Each actuator has applied the load directly to a steel beam profile that converted this load in two almost point loads on the top surface of the slab. Therefore, the slab's loading configuration was formed by eight almost point loads (Figure 9).

A spider 8 data acquisition system equipped with Catman software was used to record the strains, displacements and forces. These records were registered for each loading step of about 40 kN. The forces were measured with load cells of 1000 kN capacity, one per each actuator, and connected to the piston of the corresponding actuator. The displacements were measured by twelve linear variable displacement transducers (LVDTs) placed according to the scheme represented in Figure 10a (D01 to D12 represented by red circular markers). Figure 10b indicates the location of the electrical strain gauges used to measure the strains in the top layer of the flexural reinforcement (SG1 to SG4 represented by rectangular filled red markers). The SG3 coincides with the alignment of the column surface, while the SG4 is positioned at a radius distance from the slab's centre of 670 mm (coincident with the 6th perimeter, Figure 4). A region at intermediate distance of the previous ones was also intrumented by using SG2, symmetrically positioned in order to avoid excessive number of strain gauges in the same bar and in the same alignment. Another strain gauge, SG1, was positioned in the bar coinciding with the symmetry axis orthogonal to the previous bar, and in the alignment of the column's face.

4. RESULTS AND ANALYSIS

In this section the punching strengthening effectiveness of the adopted configurations is evaluated by analyzing the relevant results obtained in the experimental program. The strengthening performance was assessed in terms of load carrying capacity and deflection performance, and the failure modes are also presented and commented.

Table 5 includes the relevant results, where V_u , V_u^{REF} and V_u^{STR} are the maximum load capacity of all tested prototypes, of the reference, and of the strengthened ones, respectively. Taking into account that the compressive strength of the concrete of the tested prototypes was not the same, the maximum load capacity was updated accordingly, $V_{u,norm} = V_u \cdot \sqrt{f_c^{REF} / f_c^{STR}}$, according to the suggestion of [33,35], where f_c^{REF} and f_c^{STR} are the average compressive strength of the concrete of the reference and strengthened prototype, respectively. The increase in terms of load carrying capacity provided by the adopted strengthening configurations was evaluated based on the parameter $\left(V_{u,norm}^{STR} - V_{u,norm}^{REF}\right)/V_{u,norm}^{REF}$, whose values are indicated in the 3rd column of Table 5, and represented in Figure 11a.

In order to take into consideration the differences on the internal arm of the flexural reinforcement and the concrete strength, the adimensional parameter $\upsilon_u = V_u \big/ \left(b_0\ d\ \ f_{ctm}\right)$ was also evaluated, where b_0=4(c+d) is the perimeter at $d/2$ from the column's external face, according to the ACI 318-11 [44], and f_{ctm} is the average concrete tensile strength obtained according to the Model Code 2010 recomendations [45] by considering the f_{cm} registered experimentally. The υ_u values are indicated in the 4th column of Table 5 and also represented in Figure 11a. This table also includes the A_f/perimeter and the CFRP consumed (C_f) in each prototype that corresponds to the total area of CFRP introduced into the holes (5th and 6th columns of Table 5).

If the increase in terms of punching strength capacity provided by the adopted strengthening configurations ($V_{u,norm}^{STR} - V_{u,norm}^{REF}$) is divided by the consumed CFRP in the corresponding strengthening configuration, C_f, (values of 7th column of Table 5), results a parameter herein designated as "Strengthening Competetiveness Index, SCI", $\left(V_{u,norm}^{STR} - V_{u,norm}^{REF}\right)/C_f$, with dimensions of kN/m^2, which is represented in Figure 11b. It can be concluded that ETS technique (D type) is more competitive than stitch technique (S type) since, despite the higher punching strength capacity provided by the stitch technique, the ETS consumes much lower content of

CFRP (the exception is the S_b-R-132-O_{c6}). Furthermore, the ETS technique is faster and easier of applying. Amongst the punching configurations using the stitch technique, the most competitive was the one applied in the S_b-R-132-O_{c6} prototype. In the group of prototypes of equal A_f /perimeter (132 mm^2) and strengthened according to the stitch technique, the S_b-R-132-O_{c6} presented the largest SCI due to the favorable effect provided by the closed circular strengthening configuration adopted in this prototype, while the minimum value was verified in the S_b-R-132-O_{s6} (distance between strengthening holes in the each perimeter exceeds the recommended 2*d* limit [39]).

The localization and type of failure modes are also indicated in Table 5. For the classification of the failure mode, the type of failure surface, deflection capacity and strains in the flexural reinforcement were considered, as well as the maximum flexural capacity of the RC slab (V_{flex}) determined according to the yield line theory [46], whose values are also presented in the 8th column of Table 5.

Comparing V_u and V_{flex} it is verified that the flexural capacity was not exceeded in any of the tested prototypes, despite yield initiation of the flexural reinforcement of the S_b-R-297-O_{c8} and S_b-C-297-O_{d8} slabs has already occurred when they failed. The localization of the rupture surface is represented in Figure 12 to Figure 14. All the prototypes of the strengthening configurations of A_f/perimeter=132 mm^2 (the largest group of prototypes) have failed in punching. For this group of prototypes, the highest increment of the punching capacity was registered in the S_b-R-132-O_{c6} prototype (43%, and υ_u=0.92), followed by the S_b-C-132-O_{d6} prototype (41%, and υ_u=0.89) and S_b-R-132-O_{s6} prototype (37% and υ_u=0.86), which demonstrate the favorable effect of applying a continuous CFRP wrapping of circular configuration as possible, such is the case of S_b-R-132-O_{c6}. This strengthening configuration is very effective on arresting the propagation of radial cracks, since as closest is the CFRP wrapping configuration to the circular shape as higher is the effective CFRP strengthening ratio. In fact, this configuration ensures that when radial cracks are formed, the CFRP strips are almost orthogonal to these cracks, providing higher strengthening ratio. Furthermore, since in each strengthening perimeter the distance between consecutive holes is the minimum amongst the adopted configurations, highest stiffness and better anchorage conditions are ensured (note that a closed type CFRP stirrup is installed in each consecutive pair of holes). Comparing S_b-C-132-O_{d6} and S_b-R-132-O_{c6}, with the same A_f/perimeter (132 mm^2) and the same strengthening technique (stitch), the higher punching capacity registered in the S_b-R-132-O_{c6} seems to be justified, besides the reason already pointed out, by the higher number of holes per perimeter in this configuration, which increases the probability of a punching shear surface being crossed by a larger number of CFRP strengthening elements.

When the punching capacity of S_b-C-132-O_{d6} and S_b-C-132-U prototypes is compared, where the unique difference is the closed circular configuration in the S_b-C-132-O_{d6}, while in the S_b-C-132-U a discrete stitching configuration was adopted, the stitching strengthening arrangement of S_b-C-132-O_{d6} was about 14% more effective, which can be justified by the extra CFRP that assured the continuous nature to this wrapping configuration. As already indicated, this extra reinforcement has offered resistance to the propagation of radial cracks. Figure 12d and Figure 12c show that less inclined cracks and more cracks have formed in the S_b-C-132-O_{d6} prototype, therefore higher total area of punching shear cracks developed in consequence of the higher effectiveness of punching strengthening configuration in this prototype when compared to the S_b-C-132-U prototype.

When comparing the $\left(V_{u,norm}^{STR} - V_{u,norm}^{REF}\right)/V_{u,norm}^{REF}$ indicator for the group of prototypes with A_f/perimeter=132 mm^2 it can be concluded that, in average terms, the stitch technique is more effective in this respect than the ETS, revealing the favorable effect of using closed form configuration for the punching strengthening systems (in stitch technique – the horizontal parts provide better anchorage conditions and offer some resistance to the propagation of radial cracks). The results also indicate that the type of configuration in cross or radial has not significant influence on the punching capacity when stitch continuous perimetral configurations of equal A_f/perimeter are used. However, when the ETS technique is adopted, cross type configuration was more effective (38.9% and υ_u=0.88 in the D_b-C-132 versus 27.9% and υ_u=0.81 in the D_b-R-132).

No clear conclusions have been possible to extract from the influence of the roughness conditions of the wall of the holes, e.g. executing the holes according to the regular strengthening practice (“a” in Table 1 and *a* subscript in the designation of the prototypes), or using moulds during the casting process of the slabs (b in Table 1 and *b* subscript in the designation of the prototypes) such was the case in the major part of the tested prototypes for speeding up their strengthening process. In fact, comparing S_b-C-132-U (with “b” strategy) with S_a-C-99-U and S_a-C-165-U (both with “a” strategy), although the A_f/perimeter of the S_b-C-132-U (132 mm^2) is between the A_f/perimeter of the last two prototypes (99 mm^2 and 165 mm^2, respectively), the punching strengthening effectiveness of these three prototypes was quite close (varied between 26.3% nd 27.9%, with equal υ_u=0.82 in these three prototypes).

The influence of the number of strengthening perimeters on the punching capacity is assessed by comparing the results of S_b-R-132-O_{c6} and S_b-R-297-O_{c8} prototypes, where an increase of, respectively, 42.9% (υ_u=0.92) and 66.1% (υ_u=1.12) was registered. However, this increase of punching capacity was smaller than the increase of the A_f/perimeter between these two configurations (132 mm^2 and 297 mm^2 in the S_b-R-132-O_{c6} and S_b-R-297-O_{c8}, respectively), indicating that above a certain number of perimeters and punching strengthening holes, the strengthening effect reaches a limiting value.

The punching strengthened prototypes with the highest A_f/perimeter (297 mm^2), S_b-R-297-O_{c8}, S_b-C-297-O_{d6} and S_b-C-297-O_{d8}, have also demonstrated the effectiveness derived from increasing the number of perimeters, since despite having the same A_f/perimeter, the prototypes with 8 perimeters (S_b-R-297-O_{c8} and S_b-C-297-O_{d8}) presented an increase of the punching strengthening varing between 66.1% (υ_u=1.12) and 67.0% (υ_u=1.07), while the prototype with 6 perimeters (S_b-C-297-O_{d6}) this increase was limited to 53.7% (υ_u=0.99). The S_b-R-297-O_{c8} and S_b-C-297-O_{d8} prototypes were the only ones that failed in flexo-punching, e.g. when failed their flexural reinforcement has already yielded, as is seen Figure 15, where strain profiles in the flexural reinforcement for several load levels are represented, being the ε_{sy} the yield strain of the flexural reinforcement.

Despite the smaller prototypes used in [33], the average normalized maximum load obtained in the present work when using the stitch technique (43.2%) was almost equal to the average one registered by that researchers (44.8%). In case of ETS technique, when the cross type strengthening configurations are compared in terms of normalized maximum load obtained it is verified a 50% increase of strengthening effectiveness in the ones of the present work, while this increase is 30% in the radial configurations. This better performance was obtained in prototypes of larger dimensions than the ones tested in [35], therefore even larger strengthening effectiveness will be expected to obtain if prototypes of equal dimensions had been tested.

Figure 15 only presents representative strain fields in the flexural reinforcement, but in fact the flexural reinforcement of S_b-C-297-O_{d8} has also already yielded when failed. As expected, the strain level has decreased with the distance from the face of the column, and the maximum strain in the flexural reinforcement of the prototypes failed in punching was smaller than ε_{sy}, especially in the REF prototype, while in the strengthened ones maximum strains close to the ε_{sy} were registered. Assuming the punching design principles of the Eurocode [39] formulation can be applied for the CFRP-based punching strengthening configurations adopted in the tested prototypes, the S_b-C-297-O_{d6} and S_b-C-297-O_{d8} would present the same punching capacity. However, this last one prototype has developed much higher load carrying capacity, which demonstrates the relevance of the number of CFRP perimeters in this respect, an aspect not considered in this formulation.

The relationship between the total applied load and the average deflection ($F - \bar{u}$) for the tested prototypes is indicated in Figure 18 (downward deflection was considered positive), where the average deflection is the mean of the displacements measured by the LVDTs D01, D06, D07 and D12 (Figure 10a). In this graph, a different marker is used for the curves of the four groups of distinct A_f /perimeter, and the size of the marker is proportional to the A_f /perimeter. To distinguish the two types of strengthening techniques, stitch and ETS, a blue line is used for the prototypes strengthened according to the stitch technique, while red colour was selected for the lines corresponding to the prototypes strengthened with the ETS technique. The $F - \bar{u}$ curves were not recorded up to the end of the tests since the LVDTs were removed before this stage has been attained in order to prevent eventual damage in these devices at the rupture of the prototypes.

From the $F - \bar{u}$ curves it is verified that in the group of prototypes of equal A_f /perimeter (132 mm^2), those strengthened according to the ETS technique (D$_b$-R-132 and D$_b$-C-132) presented higher stiffness than the prototypes strengthened by the stitch technique. Despite having presented the stiffest $F - \bar{u}$ response and the largest increase of load carrying capacity, the S$_b$-C-297-O$_{d8}$ prototype shown, however, the smallest SCI amongst the prototypes of higher A_f/perimeter. When the full experimental programme is considered, the S$_a$-C-165-U has presented the minimum SCI.

5. CONCLUSIONS

This work presented an experimental program for assessing the punching strengthening effectiveness of the following two CFRP-based techniques for flat reinforced concrete (RC) slabs: one where the CFRP system fully wraps two consecutive holes, forming a closed type stirrup (stitch technique); the second is formed by a type of flexible CFRP bar installed in each hole, like a dowel (ETS technique). The strengthening effectivenss in terms of punching capacity was estimated by evaluating the $\left(V_{u,norm}^{STR} - V_{u,norm}^{REF}\right) / V_{u,norm}^{REF}$ parameter, where $V_{u,norm}^{REF}$ and $V_{u,norm}^{STR}$ are the normalized maximum load capacity of the reference and strengthened prototypes, respectively. For the first time in the punching strengthening of RC slabs with FRP system, a parameter was proposed for estimating simultaneously the effectiveness of the technique in terms of capacity and cost competitiveness, designated by *Strengthening Competitiveness Index, SCI,* $\left(V_{u,norm}^{STR} - V_{u,norm}^{REF}\right) / C_f$, where C_f is the consumed CFRP.

Twelve real scale prototypes representative of RC slab-column connection were tested, and based on the results the following relevant conclusions can be pointed out:

- ✓ Based on the SCI results, it was concluded that the ETS technique is more cost competitive than the stitch technique. Furthermore, the ETS technique is faster and easier to apply.
- ✓ Based on the applied load *vs* average deflection relationship registered on the tested prototypes it was verified that in the group of prototypes of equal A_f /perimeter (132 mm^2), those strengthened according to the ETS technique presented higher stiffness than the prototypes strengthened by the stitch technique.
- ✓ In terms of the $\left(V_{u,norm}^{STR}-V_{u,norm}^{REF}\right)/V_{u,norm}^{REF}$ parameter, however, the stitch technique was, in average terms, more effective than ETS, indicating the favorable effect of using closed form configuration for the punching strengthening systems (in stitch technique – the horizontal parts provide better anchorage conditions and offer some resistance to the propagation of radial cracks).
- ✓ When using stitch continuous perimetral configurations, similar increments of the punching capacity was obtained using cross or radial configuration in prototypes of equal A_f/perimeter. However, when the ETS technique is adopted, cross type configuration was more effective.
- ✓ Amongst the punching configurations using the stitch technique, the S_b-R-132-O_{c6} was the most competitive one (of higher SCI) due to the favorable effect provided by the circular perimetral strengthening configuration adopted in this prototype; the S_b-R-132-O_{s6} has presented the less competitive strengthening configuration (smaller SCI) – in this configuration the distance between strengthening holes in the each perimeter has exceeded the recommended limit by Eurocode 2, indicating the relevance of respecting this recommendation.
- ✓ All tested prototypes failed in punching, but the flexural reinforcement of the S_b-R-297-O_{c8} and S_b-C-297-O_{d8} prototypes with the largest number of strengthening perimeters (eight) has yielded at their failure.
- ✓ The prototypes strengthened with stitch continuous perimetral configuration and higher A_f/perimeter (297 mm^2) have demonstrated the favorable effect in terms of punching capacity of increasing the number of strengthening perimeters ($\left(V_{u,norm}^{STR}-V_{u,norm}^{REF}\right)/V_{u,norm}^{REF}$ of about 67% and 54% in the prototypes with, respectively, 8 and 6 perimeters). Assuming the punching design principles of the Eurocode formulation can be applied in the adopted punching strengthening configurations, the punching capacity of the prototypes with 6 and 8 strengthening perimeters would be the same, which was not the case, demonstrating the necessity of this aspect be considered in the design formulation.

- ✓ Despite the smaller prototypes used in [33], the $\left(V_{u,norm}^{STR} - V_{u,norm}^{REF}\right)/V_{u,norm}^{REF}$ obtained in the present work when using the stitch technique was almost equal to the average one registered by that researchers. In case of ETS technique, when the cross type strengthening configurations are compared in terms of normalized maximum load obtained [35], it was verified a 50% increase of strengthening effectiveness in the ones of the present work, while this increase was 30% in the radial configurations.
- ✓ By comparing the strengthening performance indexes in the largest group of prototypes of equal A_f/perimeter (132 mm^2) and strengthened with the stitch technique, it was concluded that a continuous CFRP wrapping of circular configuration (the one applied in the S$_b$-R-132-O$_{c6}$ prototype) is the most effective, due to its effectiveness on arresting the propagation of radial cracks. In fact, the closer the CFRP wrapping configuration is to the circular shape the higher is the effective CFRP strengthening ratio (the CFRP strips are more closest to the orthogonal to the radial cracks).
- ✓ By increasing the number of strengthening elements per perimeter, despite preserving the same A_f/perimeter (132 mm^2), has provided higher punching capacity to the prototypes strengthened with the stitch technique, which can be justified by the higher probability of a punching shear surface be crossed by larger number of CFRP strengthening elements. However, when the analysis is based on the SCI it was verified that above a certain number of punching strengthening holes, the strengthening effectiveness becomes not cost competitive.
- ✓ The stitch continuous perimetral configuration (S$_b$-C-132-O$_{d6}$) has provided higher punching capacity than the stitch discrete configuration (S$_b$-C-132-U, resembling stirrups). This is justified by the extra CFRP, which assured the continuous nature to the former wrapping configuration, in arresting the propagation of the radial cracks. This justification is also complemented with the observation of having formed less inclined cracks and more cracks in the stitch continuous perimetral configurations, leading to higher area of resisting punching shear surface.
- ✓ Although the relevant derived conclusions are based on results obtained in almost real scale prototypes, only one prototype was, however, tested for each strengthening configuration due to time, human and financial resources limitations in this research project. Therefore, more experimental programs with real scale prototypes are recommended to be executed for having more confidence on the relevant results required for design purposes.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge CNPq, CAPES and FCT (project PTDC/ECM-EST/1882/2014) for funding support provided to the research activities, and BASF for supplying the strengthening systems for the experimental program.

REFERENCES

[1] Gardner NJ, Huh J, Chung L. Lessons from the Sampoong department store collapse. Cem Concr Compos 2002;24:523–9. doi:https://doi.org/10.1016/S0958-9465(01)00068-3.

[2] Hassanzadeh G, Sundqvist H. Strengthening of Bridge Slabs on Columns. Nordic Concrete Research, The Nordic Concrete Federation. Publicação 1998.

[3] Widianto, Bayrak O, O. Jirsa J, Tian Y. Seismic Rehabilitation of Slab-Column Connections. ACI Struct J 2010;107:237–47. doi:10.14359/51663540.

[4] Regan PE. Behaviour of Reinforced Concrete Flat Slabs. Ciria Rep 89 1981:89.

[5] Marzouk A, Hussein H. Experimental Investigation on the Behavior of High-Strength Concrete Slabs. Struct J n.d.;88. doi:10.14359/1261.

[6] A. Ghali and A. Huizer MAS. Vertical Prestressing of Flat Plates Around Columns. Spec Publ 1974;42. doi:10.14359/17314.

[7] Inácio M, Ramos A, Faria D. Strengthening of flat slabs with transverse reinforcement by introduction of steel bolts using different anchorage approaches. Eng Struct 2012;44:63–77.

[8] S. Askar H. Usage of prestressed vertical bolts for retrofitting flat slabs damaged due to punching shear. Alexandria Eng J 2015;109.

[9] Harajli MH, Soudki KA. Shear Strengthening of Interior Slab–Column Connections Using Carbon Fiber-Reinforced Polymer Sheets. J Compos Constr 2003;7:145–53. doi:10.1061/(ASCE)1090-0268(2003)7:2(145).

[10] Ebead U, Marzouk H. Fiber-Reinforced Polymer Strengthening of Two-Way Slabs. ACI Struct J 2004;101. doi:10.14359/13387.

[11] Chen C-C, Li C-Y. Punching shear strength of reinforced concrete slabs strengthened with glass fiber-reinforced polymer laminates. ACI Struct J 2005;102:535.

[12] Sharaf MH, Soudki KA, Van Dusen M. CFRP Strengthening for Punching Shear of Interior Slab–Column Connections. J Compos Constr 2006;10:410–8. doi:10.1061/(ASCE)1090-0268(2006)10:5(410).

[13] Farghaly AS, Ueda T. Prediction of Punching Shear Strength of Two-Way Slabs Strengthened Externally with FRP Sheets. J Compos Constr 2011;15:181–93. doi:10.1061/(ASCE)CC.1943-5614.0000177.

[14] Soudki KA, El-Sayed AK, Vanzwol T. Strengthening of concrete slab-column connections using

CFRP strips. J King Saud Univ - Eng Sci 2012;24:25–33. doi:10.1016/j.jksues.2011.07.001.

[15] Meisami MH, Mostofinejad D, Nakamura H. Punching shear strengthening of two-way flat slabs using CFRP rods. Compos Struct 2013;99:112–22. doi:10.1016/j.compstruct.2012.11.028.

[16] Breveglieri M, Aprile A, Barros JAO. Shear strengthening of reinforced concrete beams strengthened using embedded through section steel bars. Eng Struct 2014;81:76–87. doi:https://doi.org/10.1016/j.engstruct.2014.09.026.

[17] Breveglieri M, Aprile A, Barros JAO. Embedded Through-Section shear strengthening technique using steel and CFRP bars in RC beams of different percentage of existing stirrups. Compos Struct 2015;126:101–13. doi:https://doi.org/10.1016/j.compstruct.2015.02.025.

[18] Breveglieri M, Aprile A, Barros J. RC beams strengthened in shear using the Embedded Through-Section technique: Experimental results and analytical formulation. Compos Part B Eng 2016;89.

[19] Breveglieri M, Barros JAO, Aprile A, Ventura-Gouveia A. Strategies for numerical modeling the behavior of RC beams strengthened in shear using the ETS technique. Eng Struct 2016;128:296–315. doi:https://doi.org/10.1016/j.engstruct.2016.09.027.

[20] Wörle P. Enhanced shear punching capacity by the use of post installed concrete screws. Eng Struct 2014;60:41–51. doi:10.1016/j.engstruct.2013.12.015.

[21] Fernández Ruiz M, Muttoni A, Kunz J. Strengthening of flat slabs against punching shear using post-installed shear reinforcement. ACI Struct J 2010;107:434–42.

[22] El-Salakawy E, Soudki KA, Polak MA. Punching Shear Behavior of Flat Slabs Strengthened with Fiber Reinforced Polymer Laminates. J Compos Constr 2004;8:384–92. doi:10.1061/(ASCE)1090-0268(2004)8:5(384).

[23] Harajli MH, Soudki KA, Kudsi T. Strengthening of Interior Slab–Column Connections Using a Combination of FRP Sheets and Steel Bolts. J Compos Constr 2006;10:399–409. doi:10.1061/(ASCE)1090-0268(2006)10:5(399).

[24] Urban T, Tarka J. Strengthening of Slab-Column Connections with CFRP Strips. Arch Civ Eng 2010;56:193–212. doi:10.2478/v.10169-010-0010-0.

[25] Moreno C, Ferreira D, Bennani A, Sarmento A, Noverraz M. Punching Shear Strengthening of Flat Slabs : Cfrp and Shear Reinforcement. Concr - Innov Des Fib Symp Copenhagen May 18-20, 2015 2015:1–16.

[26] Kim YJ, Longworth JM, Wight RG, Green MF. Punching Shear of Two-way Slabs Retrofitted with

Prestressed or Non-prestressed CFRP Sheets. J Reinf Plast Compos 2010;29:1206–23. doi:10.1177/0731684409103143.

[27] Abdullah A, Bailey CG, Wu ZJ. Tests investigating the punching shear of a column-slab connection strengthened with non-prestressed or prestressed FRP plates. Constr Build Mater 2013;48:1134–44. doi:10.1016/j.conbuildmat.2013.07.012.

[28] Keller T, Kenel A, Koppitz R. Carbon Fiber-Reinforced Polymer Punching Reinforcement and Strengthening of Concrete Flat Slabs. ACI Struct J 2013:919–28.

[29] Koppitz R, Kenel A, Keller T. Punching shear strengthening of flat slabs using prestressed carbon fiber-reinforced polymer straps. Eng Struct 2014;76:283–94. doi:10.1016/j.engstruct.2014.07.017.

[30] Barros JAO, Rezazadeh M, Laranjeira JPS, Hosseini MRM, Mastali M, Ramezansefat H. Simultaneous flexural and punching strengthening of RC slabs according to a new hybrid technique using U-shape CFRP laminates. Compos Struct 2016;159:600–14. doi:10.1016/j.compstruct.2016.10.009.

[31] Binici B, Bayrak O. Use of Fiber-Reinforced Polymers in Slab-Column Connection Upgrades. ACI Struct J 2005;102:93–102. doi:10.14359/13534.

[32] Binici B, Bayrak O. Upgrading of slab–column connections using fiber reinforced polymers. Eng Struct 2005;27:97–107. doi:https://doi.org/10.1016/j.engstruct.2004.09.005.

[33] Sissakis K, Sheikh S. Strengthening concrete slabs for punching shear with carbon fiber-reinforced polymer laminates. ACI Struct J 2007;104:49–59.

[34] Erdogan H, Zohrevand P, Mirmiran A. Effectiveness of Externally Applied CFRP Stirrups for Rehabilitation of Slab-Column Connections. J Compos Constr 2013;17:04013008. doi:10.1061/(ASCE)CC.1943-5614.0000389.

[35] Erdogan H, Binici B, Ozcebe G. Punching shear strengthening of flat-slabs with CFRP dowels. Mag Concr Res 2010;62:465–78. doi:10.1680/macr.2010.62.7.465.

[36] Meisami MH, Mostofinejad D, Nakamura H. Punching Shear Strengthening of Two-Way Flat Slabs with CFRP Grids. J Compos Constr 2014;18:04013047. doi:10.1061/(ASCE)CC.1943-5614.0000443.

[37] Meisami MH, Mostofinejad D, Nakamura H. Strengthening of flat slabs with FRP fan for punching shear. Compos Struct 2015;119:305–14. doi:10.1016/j.compstruct.2014.08.041.

[38] Brazilian Association of Technical Standards. ABNT NBR 7480 - Steel for the reinforcement of concrete structures - Specification, 2007 (in Portuguese) n.d.

[39] Eurocode 2, Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings, CEN,

EN 1992-1-1, Brussels, Belgium, 2004 n.d.

[40] Gomes R, Regan P. Punching strength of slabs reinforced for shear with offcuts of rolled steel I-section beams. Mag Concr Res 1999;51:121–9. doi:10.1680/macr.1999.51.2.121.

[41] Brazilian Association of Technical Standards. ABNT NBR 5739 Concrete - Compression test of cylindric specimens - Method of test, 2007 (in Portuguese) n.d.

[42] Brazilian Association of Technical Standards. ABNT NBR 7222 - Mortar and concrete - Determination of the tensile strength of cylindrical specimens submitted to diametrical compression - Method of test, 2011 (in Portuguese) n.d.

[43] Brazilian Association of Technical Standards. ABNT NBR ISO 6892 - Metallic materials - Tensile testing Part 1: Method of test at room temperature, 2013 (in Portuguese) n.d.

[44] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary, American Concrete Institute, Farmington Hills, Michigan, 2011 n.d.

[45] Fédération Internationale du Béton (fib), Model Code 2010 - Final draft, fédération internationale du béton, Bulletin 56, 2012 n.d.

[46] Hognestad RCE and E. Shearing Strength of Reinforced Concrete Slabs. ACI J Proc 1956;53. doi:10.14359/11501.