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Strengthening of flat slabs with transverse reinforcement by introduction of steel bolts using different anchorage approaches

Micael M.G. Inácio *, A. Pinho Ramos, Duarte M.V. Faria

UNIC, Department of Civil Engineering, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal

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ABSTRACT

The present work reports the experimental research carried out to study a strengthening method for flat slabs under punching by introduction of new shear reinforcement. Eight specimens were strengthened with the introduction of prestressed vertical bolts, using different anchorage approaches: large anchorage on surface, small anchorage on surface and small embedded anchorage. A reference specimen, unstrengthened, was also tested. The experimental punching loads, failure modes and shear reinforcement contribution are compared with the provisions of EC2, ACI 318-11 and MC2010. The tests results show that using small embedded anchorage plates is viable and efficient method for punching capacity improvement. Additionally is a method also with advantages of better aesthetics for the final strengthened structure.

1. Introduction

Structural systems using flat slabs are currently widely used because they are economical, easy and fast to build. Nevertheless at the slab-column connection a complex behaviour is developed due to the superposition of shear and flexural stresses near the column, that may lead to punching failure. In some cases, punching strength is insufficient due to several reasons, such as change of the building use, design and/or construction errors, corrosion of reinforcement and deterioration of concrete, leading to the necessity of repair and/or strengthen the structure.

Several techniques for strengthening interior slab-column connection against punching were developed and studied, such as, the introduction of additional concrete overlay [1], strengthening by means of epoxy-bonded steel plates [2–4] or fibre reinforced polymers [5–7], strengthening by replacing concrete with a higher grade concrete or fibre reinforced concretes [8,9], strengthening using concrete or steel collars [8,10], strengthening by introducing new shear reinforcement [11–15] and strengthening with post-tensioning using external permanent anchorages or using anchorages by bonding [16,17].

Most of the experimental tests carried out with post-installed shear reinforcement use large steel anchorage plates on the slabs surface. In this solution the anchorages have an unpleasant aesthetics, are difficult to occult and could difficult the structure functionality. The current work studies the use of small anchorages on the slabs surface and furthermore the embedment of the anchorage on the concrete cover. They relative behaviour and efficiency are discussed.

2. Experimental research

2.1. Specimens

The experimental programme consisted in testing nine reduced scale flat slab specimens up to failure by punching. Eight were strengthened with post-installed vertical steel bolts, and the remaining was tested without strengthening to be used as a reference slab (specimen R). The strengthened specimens are as follow: four slabs with large anchorage plates on the top and bottom surfaces of the slab (specimens M10, M6, M8 and M8a – Fig. 1a); two with small anchorage plates (specimens M6S and M8S – Fig. 1b) and two with small embedded anchorages (specimens M6SE and M8SE – Fig. 1c).

The specimens were $1800 \times 1800\ mm^2$ with 120 mm thick. They modelled the area near a column of an interior slab panel up to zero moment lines. The slab bottom flexure reinforcement consisted of a square mesh of 6 mm diameter bars, spaced at 200 mm and the top reinforcement consisted of a square mesh of 10 mm diameter bars spaced at 75 mm. The concrete cover of longitudinal reinforcement was about 10 mm and 20 mm in the bottom and top faces, respectively. During manufacture the effective

* Corresponding author. Address: Departamento de Engenharia Civil, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Campus da Caparica, 2829-516 Caparica, Portugal. Tel.: +351 966 745 612; fax: +351 212 948 398.

E-mail addresses: mmgi@fct.unl.pt (M.M.G. Inácio), ampr@fct.unl.pt (A. Pinho Ramos), duamvf@gmail.com (D.M.V. Faria).

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Notation

α	angle of critical shear crack with compression face of slab
β	angle of shear reinforcement with compression face of slab
ρ	reinforcement ratio of bar reinforcement
σ_{si}	stress in the shear reinforcement
σ_{sp}	initial prestress stress applied to the bolt
ψ	slab rotation
c	column side dimension
d	average effective depth
d_g	maximum aggregate size
d_v	reduced effective depth
$f_{0.2}$	0.2% proof strength of steel reinforcement or steel bolts
f_{ccm}	mean value of concrete compression strength on $150 \times 150 \times 150$ mm^3 cubes
f_{ck}	characteristic concrete compression strength on 150×300 mm^2 cylinders
f_{cm}	mean value of concrete compression strength on 150×300 mm^2 cylinders
f_t	ultimate strength of steel reinforcement
f_y	yield strength of steel reinforcement
$f_{y,ef}$	effective yield strength of steel bolts
$f_{y,w}$	yield strength of steel bolts
h	slab depth
h_w	vertical distance between tip of crack and point where shear reinforcement crosses the critical shear crack
k	scale factor according to EC2
k_s	critical shear crack opening factor
k_{sys}	coefficient that accounts for the performance punching shear reinforcement system
l_w	bolt length
$\mathrm{m_R}$	average flexural strength per unit length in the support strip
m_s	moment per unit length for calculation of the flexural reinforcement in the support strip
r_s	distance between the column axis and the position where the radial bending moment is zero
s_r	radial spacing of perimeters of shear reinforcement
u	length of the perimeter control ($u = \Sigma c + 4\pi d$ in EC2, $u = \Sigma c + 4d$ in ACI 318-11, $u = \Sigma c + \pi d$ in MC2010)
u^*	control perimeter defined at 1.5d in EC2, 0.5d in ACI and 0.5d_v in MC2010, from the outermost perimeter of the shear reinforcement
u_0	column perimeter
A_{si}	cross sectional area of a shear bar
A_{sw}	area of one perimeter of shear reinforcement around the column
A^*_{sw}	area of shear reinforcement inside the control perimeter
E_s	modulus of elasticity of longitudinal reinforcement
E_w	modulus of elasticity of shear reinforcement
V	applied load to the slab
V_{exp}	experimental punching load
V_{flex}	flexural capacity of slab
V_{min}	minimum value between V_{flex} and V_{Rm}
V_{Rm}	mean value of punching resistance
$V_{Rm,crush}$	mean value of punching shear resistance (governed by crushing of concrete struts)
$V_{Rm,in}$	mean value of punching shear resistance (governed by failure within the shear-reinforced zone)
$V_{Rm,out}$	mean value of punching shear resistance (governed by failure outside the shear-reinforced zone)
$V_{Rm,s}$	shear reinforcement contribution to punching shear strength
$V_{s,exp}$	experimental shear reinforcement contribution to punching shear strength

depth of the specimens was measured. Table 1 presents the average effective depths (d) of the tension reinforcement and its ratio (ρ).

The strengthening steel bolts used in these tests were cut from M6, M8 and M10 threaded bars, corresponding to 6 mm, 8 mm and 10 mm diameter, respectively. The middle sections of the bolts were machined to a uniform diameter of 4.6 mm, 6.0 mm and 7.7 mm, allowing the easy gluing of strain gauges. Fig. 2 presents the geometry of the strengthening bolts.

2.2. Monitoring

The vertical deflections of the specimens were measured at five different points using linear variable differential transformer (LVDT's) with a displacement stroke of 100 mm. One of the LVDT's was placed over the centre of the slab to measure the central deflection, while the other four LVDT's were placed on a supporting steel beam positioned over the slab top surface through a magnetic base. Two LVDT's were placed along the middle line to measure the deflection at 300 mm from the slab centre whereas other two were placed at 750 mm from the slab centre (Fig. 3a).

Three rebars of the top reinforcement of the specimens were monitored using pairs of diametrically opposed strain gauges. The strains gauge were glued in the middle section of alternated rebars being the distance between monitored rebars of 150 mm. Fig. 3b shows the position of rebars with strain gauges. The vertical load applied to the slab was measured by four load cells, one for each steel tendon, which fixed the slab to the strong floor. The force evolution of the strengthening steel bolts was measured using strain gauges glued in the middle section (Fig. 4). A pair of strain gauges was glued on 8 of the 16 strengthening steel bolts and so it was possible to compute the evolution of the forces in these bolts during tests.

2.3. Materials' properties

Compression tests on cubes of $150 \times 150 \times 150$ mm^3 (f_{ccm}) were carried out on the same day as the test of the corresponding slab. The results are listed in Table 2, together with cylinder compression strengths (f_{cm}) calculated as $0.80 f_{ccm}$. The yield stress (f_y), 0.2% proof strength ($f_{0.2}$), modulus of elasticity of shear reinforcement (E_w) and ultimate strength (f_t) of the longitudinal reinforcement and steel bolts are also included.

2.4. Test procedure

The specimens were subjected to central monotonic loading up to failure using a hydraulic jack positioned under the slab, through a steel plate with 200×200 mm^2 and 50 mm thickness. The slabs were fixed to the strong floor of the laboratory in eight points, using four steel tendons and spreader beams according to Fig. 5.

The loading was made in two consecutive phases. First the slabs were loaded up to approximately 60% of the experimental failure load of the reference specimen (R) and then were unloaded and strengthened (cracking stage). The strengthening technique consisted of drilling holes through the slab near the column and inserting steel bolts that are tightened against the slab surfaces. The remaining space between the steel bolts and the drilled holes