PUNCHING RESEARCH AT UNIVERSIDADE NOVA DE LISBOA

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Abstract

At the Civil Engineering Department of Universidade Nova de Lisboa punching research has been developed for several years. This paper reports the experimental analysis of reduced scale flat slab models under punching. The results of experimental tests on flat slabs without specific punching reinforcement, in prestressed flat slabs and in strengthened slabs using post-installed vertical steel bolts are presented. The experimental results are discussed and compared with EC2 (2004) and ACI 318-08 (2008) provisions. Results show that EC2 (2004) provisions provide good agreement with experimental results and that ACI 318-08 (2008) provisions result in safe estimates, although conservative, of punching loads.

Keywords: punching, slabs, prestress, strengthening.

1 Introduction

Flat slabs are widely used in many countries because of their economic and functional advantages. Although simple in appearance, a flat slab system presents a complex load bearing behaviour, especially in the slab-column connection. The punching resistance is an important subject in the design of flat slabs, frequently being the conditioning factor in choosing its thickness.

This paper presents the results of various experimental investigations carried out at Universidade Nova de Lisboa regarding flat slabs without specific punching reinforcement, strengthened with vertical steel bolts and prestressed flat slabs. The increased use of this kind of slabs lead to the necessity of studying suitable strengthening methods associated to punching failure. So, experimental research was also developed regarding the study of two strengthening techniques related to punching, namely, strengthening using post-tensioning with anchorages by bonding and strengthening using post-installed vertical steel bolts, that can be applied for several reasons such as, e.g., construction or design errors, poor quality or inadequate materials, overloading and accidents. The strengthening method to be used in any particular situation depends on technical and economical factors, and may be a complex task.

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In this paper the experimental setups and materials used in the experimental research are described and punching loads are compared with EC2 (2004) [5] and ACI 318-08 (2008) [6] provisions regarding punching.

2 Models description

2.1 Models geometry

The experimental work described in this paper consists basically in four different groups of reduced scale reinforced concrete flat slab models tested up to failure by punching. The first group consists in 6 slabs whose objective was to study the effect of compression due to prestress on punching load [1]; the second with 9 slabs whose objective was to study the effect of deviation forces from prestress on the punching load [2]; the third consisted of 7 strengthened slabs using post-tensioning with anchorages by bonding [3] and at last a forth group of 9 slabs used to study punching strengthening using post-installed vertical steel bolts [4,5]. In all these groups plain or reference slabs were tested in order to compare its results with the post-tensioned and the strengthened slabs. The dimensions of slabs AR and DF were 2300x2300 mm^2, some with 100 mm and others with 120 mm thickness, while slabs ID and MI were 1800x1800 mm^2 with 120 mm thickness. In all slabs, the punching load was applied by hydraulic jack positioned under the slab, through a steel plate with 200x200 mm^2 placed in center. Eight points on the top of the slab were connected to the strong floor of the laboratory using steel tendons and spreader beams (Fig. 1).

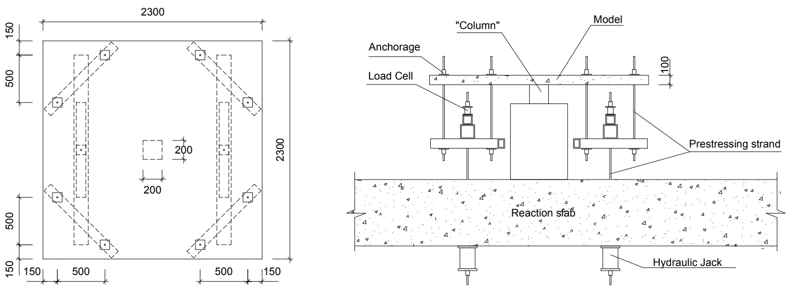

Fig. 1 Model geometry (ex. Model AR2-reference slab)

The models simulated the area near a column of an interior slab panel up to the zero moment lines. The bottom reinforcement consisted of 6 mm rebars every 200 mm in all slabs, in both orthogonal directions. In Tab. 1 is presented for each slab its depth (h), average effective depth (d) and top reinforcement ratio (ρ_l). To study the compression effect of prestress in punching behaviour Ramos [1] tested six slabs (AR2 to AR7) with variations of the levels of compression force applied in one or both orthogonal directions. The in-plane compression forces were applied to the slab edges by hydraulic jacks and external prestressing tendons on steel beams (Fig. 2). The internal in-plane forces were kept constant during the tests by using a load maintainer device connected to the hydraulic jacks. In slabs AR3 and AR4 the in-plane forces were applied only in one direction, and in the remaining slabs (AR5, AR6 and AR7) they were applied in both orthogonal directions.

Fig. 2 System used to apply the in-plane force in slabs

After the specimens were compressed the vertical load was incremented until failure, using the two hydraulic jacks positioned under the laboratory floor. The prestress in slabs AR used to study the effect of deviation forces (AR8 to AR16) consisted on four unbonded 12,7 mm diameter tendons, with a cross section area of 100 mm^2, in the two orthogonal directions. The prestressed tendons location can be seen in Fig. 3.

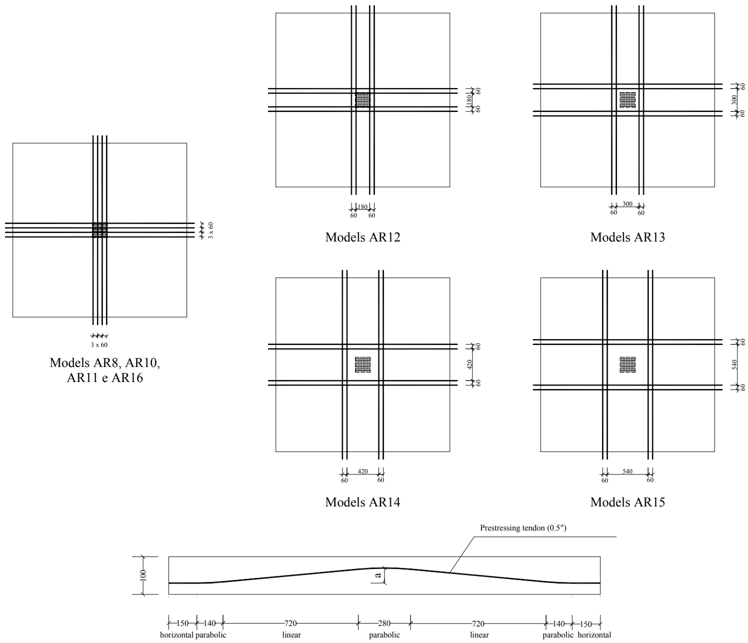

Fig. 3 Prestress tendons location and profile (slabs AR slab for prestress deviation forces effect)

In this second group of slabs the tendons profiles were trapezoidal, with the downward tendon deviation forces over the loaded area and the upward deviation forces at

1000 mm from the centre of the loaded area (Fig. 3). The prestress vertical deviation (a) was 40 mm.

Regarding the strengthened slabs using post-tensioning with anchorages by bonding, either with unidirectional or bidirectional prestress, the tendons profiles and location was the one presented in Fig. 4.

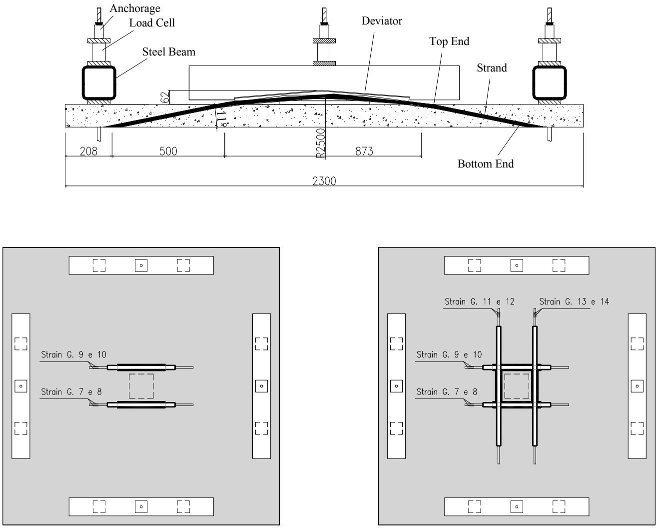

Fig. 4 Prestress profile and tendons location (slabs DF)

With respect to the slabs strengthen with post-installed steel bolts, its positioning was the one presented in Fig. 5. The steel bolts used in slabs ID3, ID5, MI1 and MI3 were M6, in slabs ID4, MI2 and MI4 were M8 and in slab ID2 were M10. The bolts anchorage used in slabs ID were large and were placed on the concrete surface, while the slabs MI1 and MI2 have small bolts anchorage placed on the surface of the slab and slabs MI2 and MI3 have small bolts anchorage embedded in the concrete cover.

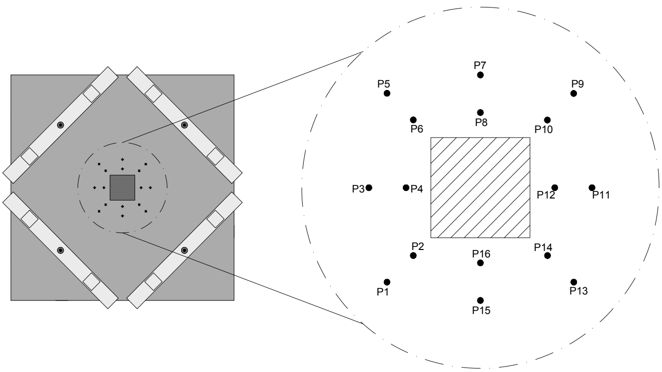

Fig. 5 Post-installed steel bots (slabs ID and MI)

2.2 Materials properties

To assess the strength of the concrete used in the production of the test specimens, compression tests on cubes of 15x15x15cm^3 were carried out ($f_{cm,cube}$). The results are listed in Table 1.

Tab. 1 Slabs properties

Model	**h (mm)**	**d (mm)**	ρ_l **(%)**	$f_{cm,cube}$ **(MPa)**
		Reference Slabs		
AR2	100	80	1.6	48.9
AR9	100	82	1.6	46.4
DF1	100	69	1.9	31.0
DF4	120	88	1.2	24.7
ID1	120	87	1.2	49.2
		Slabs for compression effect study		
AR3	100	80	1.6	46.8
AR4	100	80	1.6	53.9
AR5	100	80	1.6	44.6
AR6	100	80	1.6	46.2
AR7	100	80	1.6	54.8
		Slabs for deviation forces effect study		
AR8	100	80	1.6	52.0
AR10	100	80	1.6	51.8
AR11	100	80	1.6	47.5
AR12	100	77	1.7	39.1
AR13	100	80	1.6	40.6
AR14	100	80	1.6	35.2
AR15	100	80	1.6	39.6
AR16	100	80	1.6	38.2
		Slabs strengthened with post-tensioning		
DF2	100	67	2.0	33.0
DF3	100	67	2.0	31.5
DF5	120	85	1.2	26.0
DF6	120	85	1.3	26.3
DF7	120	89	1.2	27.0
		Slabs strengthened with post-installed steel bolts		
ID2	120	94	1.3	52.3
ID3	120	90	1.2	59.6
ID4	120	90	1.2	59.7
ID5	120	94	1.1	59.8
MI1	120	91	1.2	45.4
MI2	120	94	1.1	48.4
MI3	120	91	1.0	33.5
MI4	120	91	1.0	33.5

3 Experimental results and comparison with codes

3.1 EC2 (2004) provisions

The resistance without punching shear reinforcement, using EC2 [6] was calculated with the following expression (Eqs. (1) to (4)):

$$V_{Rm} = \left(0.18 \cdot k \cdot (100 \cdot \rho \cdot f_{cm})^{1/3} + k_1 \cdot \sigma_{cp}\right) \cdot u \cdot d \quad (1)$$

$$\rho = \sqrt{\rho_y \cdot \rho_z} \leq 0{,}02 \quad (2)$$

$$\sigma_{cp} = \frac{\sigma_{cpy} + \sigma_{cpz}}{2} \quad (3)$$

$$d = \frac{d_y + d_z}{2} \quad (4)$$

The limitation of the parameter $k=\left(1+\sqrt{200/d}\right)$ in EC2 [6] to a maximum of 2 was neglected and k_1=0.1. In the quantification of punching resistance the mean values for the compressive resistance of concrete were used and the partial safety coefficient was neglected. Reinforcement ratio values are calculated taking into account a slab width equal to the column width plus 3d for each side. Deviation forces are computed based on the work of Ramos [2], who proposed that their calculation should be based on the vertical components of prestress forces in the strands running within distances of $0.5d_p$ from the column sides (d_p is the prestress strand effective depth), so $V_{eff}=V_{exp}-V_{dev}$, where V_{eff} is the effective punching load, V_{exp} is the experimental punching load and V_{dev} is the deviation forces due to the prestress. Values considered for the cylinder compression strength (f_{cm}) were obtained with the relations presented in EC2 [6].

According to EC2 [6], the resistance with punching shear reinforcement was calculated using the lowest value obtained by following expressions (Eqs. (5) and (6)):

$$V_{Rm} = 0.135 \cdot k \cdot (100 \cdot \rho \cdot f_{cm})^{1/3} \cdot u \cdot d + A_{sw} \cdot f_{sy,ef} \quad (5)$$

$$V_{Rm} = 0.18 \cdot k \cdot (100 \cdot \rho \cdot f_{cm})^{1/3} \cdot u^* \cdot d \quad (6)$$

Where A_{sw} is the area of shear reinforcement inside the control perimeter u defined at 2d from the column faces, u^* is the control perimeter defined at 2d from the outermost perimeter of shear reinforcement and $f_{sy,ef}$ is the effective strength of the punching shear reinforcement, according to $f_{sy,ef} = (250+0.25d)\cdot 1.15 < f_{sy}$, and f_{sy} is the yield strength of the steel bolts.

3.2 ACI 318-08 provisions

For the calculation of the resistance without punching shear reinforcement and without any prestress effect, using ACI 318-08 [7], the relevant expression for square columns, with side lengths less than 4d is Eq. (7):

$$V_{Rm} = \frac{\sqrt{f_{cm}} \cdot u \cdot d}{3} \tag{7}$$

The resistance capacity of flat slabs with punching shear reinforcement was given by the lowest value obtained by the following expressions (Eqs. (8) to (10)):

$$V_{Rm} = \frac{\sqrt{f_{cm}} \cdot u \cdot d}{6} + A_{sw} \cdot f_{sy} \tag{8}$$

$$V_{Rm} = \left(40 \cdot \frac{d}{u^*} + 2\right) \cdot \frac{\sqrt{f_{cm}} \cdot u^* \cdot d}{12} \tag{9}$$

$$V_{Rm} = \frac{\sqrt{f_{cm}}}{3} \cdot u^* \cdot d \tag{10}$$

In prestressed slabs the following expression is used (Eq. (11)):

$$V_{Rm} = \left[\left(0.29\sqrt{f_{cm}} + 0.3 \cdot \sigma_{cp}\right) \cdot u \cdot d + V_{dev}\right] \tag{11}$$

According to ACI 318-08 [7], Eq. (7) is applicable when $f_{ck} \leq 35$ MPa (corresponding to an approximate value of $f_{cm} \leq 43$ MPa), with bidirectional prestress and when the average compressive stress in concrete in each direction due to prestress is between 0.9 MPa and 3.5 MPa. Though this expression is not strictly applicable to most of the models presented here, it was nevertheless used to estimate the ACI 318-08 [7] predicted punching load. Deviation forces are computed based on the vertical component of prestress forces crossing the control perimeter defined in ACI 318-08 [7], at a distance of 0.5d from the column perimeter.

3.3 Experimental punching loads and comparison with code provisions

Tab. 2 Reference and AR slabs results

Model	V_{exp} (kN)	Code	V_{eff} (kN)	V_{Rm} (kN)	V_{eff}/V_{Rm}
Reference Slabs					
AR2	258	EC2	258	270	0.96
		ACI 318-08	258	187	1.38
AR9	251	EC2	251	273	0.92
		ACI 318-08	251	187	1.34
DF1	191	EC2	191	203	0.94
		ACI 318-08	191	138	1.38
DF4	199	EC2	199	217	0.92
		ACI 318-08	199	168	1.18
ID1	269	EC2	269	270	1.00
		ACI 318-08	269	209	1.29
Slabs for compression effect study					
AR3	270	EC2	270	288	0.96
		ACI 318-08	270	186	1.45
AR4	252	EC2	252	312	0.84
		ACI 318-08	252	212	1.19
AR5	251	EC2	251	306	0.86
		ACI 318-08	251	210	1.20
AR6	250	EC2	250	308	0.85
		ACI 318-08	250	211	1.18
AR7	288	EC2	288	340	0.90
		ACI 318-08	288	247	1.17
Slabs for deviation forces effect study					
AR8	380	EC2	308	278	1.11
		ACI 318-08	380	241	1.57
AR10	371	EC2	315	278	1.13
		ACI 318-08	371	226	1.64
AR11	342	EC2	302	269	1.12
		ACI 318-08	342	202	1.70
AR12	280	EC2	247	239	1.03
		ACI 318-08	280	171	1.64
AR13	261	EC2	261	253	1.03
		ACI 318-08	261	148	1.76
AR14	208	EC2	208	240	0.87
		ACI 318-08	208	137	1.52
AR15	262	EC2	262	250	1.05
		ACI 318-08	262	146	1.79
AR16	351	EC2	277	249	1.11
		ACI 318-08	351	218	1.61

Tab. 3 DF, ID and MI slabs results

Model	V_{exp} (kN)	Code	V_{eff} (kN)	V_{Rm} (kN)	V_{eff}/V_{Rm}
Slabs strengthened with post-tensioning					
DF2	273	EC2	212	207	1.02
		ACI 318-08	273	192	1.42
DF3	255	EC2	192	204	0.94
		ACI 318-08	255	190	1.34
DF5	295	EC2	215	222	0.97
		ACI 318-08	295	237	1.25
DF6	293	EC2	208	220	0.95
		ACI 318-08	293	240	1.22
DF7	320	EC2	235	235	1.00
		ACI 318-08	320	256	1.25
Slabs strengthened with post-installed steel bolts					
ID2	406	EC2	406	392	1.03
		ACI 318-08	406	315	1.29
ID3	331	EC2	331	305	1.08
		ACI 318-08	331	231	1.43
ID4	381	EC2	381	365	1.04
		ACI 318-08	381	357	1.07
ID5	366	EC2	366	374	0.98
		ACI 318-08	366	364	1.01
MI1	329	EC2	329	289	1.14
		ACI 318-08	329	247	1.33
MI2	352	EC2	352	359	0.98
		ACI 318-08	352	364	0.97
MI3	274	EC2	274	264	1.04
		ACI 318-08	274	232	1.18
MI4	273	EC2	273	322	0.85
		ACI 318-08	273	288	0.95

4 Conclusions

Based in the results presented before it may be stated that EC2 [6] is able to correctly predict punching loads. Otherwise the ACI 318-08 [7] is too conservative, as it seriously underestimates the punching resistance. The average relation V_{eff}/V_{Rm} when using EC2 [6] was 0.95, 0.88, 1.06, 0.98 and 1.02 for reference slabs, for slabs used for the compression effect study, for slabs used for deviation forces effect study, for slabs strengthened with post-tensioning and for slabs strengthened with post-installed steel bolts, respectively, and so the values are near to the target value of 1.00. The corresponding relations V_{eff}/V_{Rm} using ACI 318-08 [7] were 1.31, 1.24, 1.65, 1.30 and 1.15, respectively, results that are somewhat conservative.

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