Engineering Structures 44 (2012) 63-77

Contents lists available at SciVerse ScienceDirect

## **Engineering Structures**

journal homepage: www.elsevier.com/locate/engstruct

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

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#### ARTICLE INFO

Article history: Received 15 December 2011 Revised 17 April 2012 Accepted 23 May 2012 Available online 29 June 2012

Keywords: Reinforced concrete Anchorage Strengthening Flat slab Punching

#### 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.

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#### 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 posttensioning 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  $1800 \times 1800 \text{ mm}^2$  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





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Notation

| $\alpha$ angle of critical shear crack with compression face of<br>slab $m_s$<br>moment per unit length for calculation of the flexural<br>reinforcement in the support strip $\beta$ angle of shear reinforcement with compression face of<br>slab $m_s$<br>moment per unit length for calculation of the flexural<br>reinforcement in the support strip $\rho$ reinforcement ratio of bar reinforcement<br>$\sigma_{si}$ $m_s$<br>stress in the shear reinforcement<br>$\sigma_{si}$ moment per unit length for calculation of the flexural<br>reinforcement in the support strip $\phi$ reinforcement ratio of bar reinforcement<br>$\sigma_{si}$ $m_s$<br>stress in the shear reinforcement<br>$m_s$ moment per unit length for calculation of the flexural<br>reinforcement in the support strip $\phi$ reinforcement value of concrete compression strength on<br>$150 \times 150$ mm² cylinders $u$ $2C \times 4\pi d$ in ACI and<br>$0.52$ , in MC2010, from the outermost perimeter of the<br>shear reinforcement inside the control perimeter<br>$A_{si}$ $f_{cem}$ mean value of concrete compression strength on<br>$150 \times 300$ mm² cylinders $M_{sw}$<br>area of shear reinforcement inside the control perimeter<br>$E_{w}$ $f_{eff}$ ultimate strength of steel reinforcement<br>$M_{sy}$ $M_{sw}$<br>area of shear reinforcement ing load<br>$M_{min}$ $f_{yef}$ effective yield strength of steel reinforcement<br>$M_{sy}$ $M_{sm}$<br>$M_{sy}$ $f_{w}$ vield strength of steel perinforcement<br>$M_{sy}$ $M_{sm}$<br>$M_{sy}$ $f_{yef}$ ultimate strength of steel bolts<br>$M_{yef}$ $M_{sm}$<br>$M_{sy}$ $f_{w}$ vield strength of steel perinforcement<br>$M_{sy}$ $M_{sy}$<br>$M_{sy}$ $h_{w}$ </th <th></th> <th></th> <th></th> <th></th>  |                   |   |                       |  |
|---|-------------------|---|-----------------------|--|
| $ \begin{array}{llllllllllllllllllllllllllllllllllll$   | α                 | angle of critical shear crack with compression face of slab                       | ms                    | moment per unit length for calculation of the flexural reinforcement in the support strip    |
| $ \begin{array}{lll} \rho & \mbox{reinforcement ratio of bar reinforcement} & s_r & \mbox{rather} radial spacing of perimeters of shear reinforcement} & u & \mbox{length} of the perimeter control (u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, u = \Sigma c + \pi d i n EC2, 0.5d i n AC1 and c & column side dimension & u^* & control perimeter defined at 1.5d in EC2, 0.5d in AC1 and 0.5d_v in MC2010, from the outermost perimeter of the shear reinforcement around the reinforcement of steel reinforcement or steel bolts form mean value of concrete compression strength on 150 × 150 mm^2 cubes & modulus of elasticity of longitudinal reinforcement for the column for 150 \times 300 \text{ mm}^2 cylinders E_v modulus of elasticity of longitudinal reinforcement for the shear reinforcement V_{\text{fex}} flexural capacity of shear reinforcement for the column forcement V_{\text{fex}} flexural capacity of shear verinforcement for the shear reinforcement for the shear reinforcement for the shear reinforcement for the column for the c$   | β                 | angle of shear reinforcement with compression face of slab                        | rs                    | distance between the column axis and the position<br>where the radial bending moment is zero |
| $\sigma_{si}$<br>$\sigma_{sp}$ stress in the shear reinforcement<br>$\sigma_{sp}$ $u$ length of the perimeter control $(u = \Sigma c + 4\pi d \text{ in } \text{LC2}, u = \Sigma c$ | $\rho$            | reinforcement ratio of bar reinforcement  | S <sub>r</sub>        | radial spacing of perimeters of shear reinforcement  |
| $\sigma_{sp}$ initial prestress stress applied to the bolt $u = \Sigma c + 4d$ in $ACI 318-11$ , $u = \Sigma c + \pi d$ in $MC2010$ ) $\psi$ slab rotation $u^*$ control perimeter defined at 1.5d in EC2, 0.5d in ACI and $c$ column side dimension $0.5d_{v}$ in $MC2010$ , from the outermost perimeter of the $d_{u}$ average effective depthshear reinforcement $d_{v}$ reduced effective depth $A_{si}$ $f_{0.2}$ $0.2\%$ proof strength of steel reinforcement or steel bolts $A_{sw}$ $f_{ccm}$ mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $A_{sw}$ $f_{cm}$ mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $A_{sw}$ $f_{cm}$ mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $V_{mex}$ $f_{t}$ ultimate strength of steel reinforcement $V_{exp}$ $f_{y,ef}$ effective yield strength of steel reinforcement $V_{mex}$ $f_{y,ef}$ effective yield strength of steel bolts $V_{mx}$ $h_{w}$ vertical distance between tip of crack and point where<br>shear reinforcement crosses the critical shear crack $V_{mx}$ $h_{w}$ scale factor according to EC2 $V_{mx}$ $k_{s}$ coefficient that accounts for the performance punching<br>shear reinforcement system $V_{mxs}$ $h_{w}$ bolt length $V_{sexp}$ $q_{w}$ bolt length $V_{mx}$ $q_{w}$ bolt length $V_{mx}$ $q_{w}$ bolt length $V_{mx}$ $q_{w}$ bolt length $V_{mx}$ </td <td><math>\sigma_{ m si}</math></td> <td>stress in the shear reinforcement</td> <td>и</td> <td>length of the perimeter control (<math>u = \Sigma c + 4\pi d</math> in EC2,</td>   | $\sigma_{ m si}$  | stress in the shear reinforcement   | и                     | length of the perimeter control ( $u = \Sigma c + 4\pi d$ in EC2,                            |
| $\psi'$ slab rotation $u^*$ control perimeter defined at 1.5d in EC2, 0.5d in ACI and<br>0.5d, in MC2010, from the outermost perimeter of the<br>shear reinforcement $d$ average effective depth $0.5d$ , in MC2010, from the outermost perimeter of the<br>shear reinforcement $d_y$ maximum aggregate size $u_0$ column perimeter $d_v$ reduced effective depth $A_{si}$ cross sectional area of a shear bar $f_{0.2}$ $0.2\%$ proof strength of steel reinforcement or steel bolts $A_{sw}$ area of one perimeter of shear reinforcement around the<br>column $f_{ccm}$ nean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $A_{sw}^*$ area of shear reinforcement inside the control perimeter $f_{cm}$ mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $A_{sw}^*$ area of shear reinforcement $f_{f}$ ultimate strength of steel reinforcement<br>$f_{y,eff}$ effective yield strength of steel reinforcement<br>vield strength of steel bolts $V_{exp}$ $f_{y,w}$ yield strength of steel bolts $V_{min}$ mean value of punching shear resistance<br>(governed by<br>failure within the shear-reinforced zone) $h_w$ vertical distance between tip of crack and point where<br>shear reinforcement system $V_{min}$ mean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone) $h_w$ bolt length<br>m<br>mwetage flactor according to EC2<br>ks $V_{min}$ mean value of punching shear reinforcement contribution to<br>punching shear reinforcement contribution to<br>punching shear reinforcement contribution to<br>punching s   | $\sigma_{ m sp}$  | initial prestress stress applied to the bolt                                      |                       | $u = \Sigma c + 4d$ in ACI 318-11, $u = \Sigma c + \pi d$ in MC2010)                         |
| ccolumn side dimension0.5dv in MC2010, from the outermost perimeter of the<br>shear reinforcementdaverage effective depthshear reinforcementdvreduced effective depthaverage ffective depthf0.20.2% proof strength of steel reinforcement or steel boltsf.fccmmean value of concrete compression strength on<br>$150 \times 150 \times 150  \text{mm}^3$ cubesAswarea of shear reinforcement inside the control perimeterfcmmean value of concrete compression strength on<br>$150 \times 300  \text{mm}^2$ cylindersfrultimate strength of steel reinforcement<br>$150 \times 300  \text{mm}^2$ cylindersfvyield strength of steel reinforcement<br>$150 \times 300  \text{mm}^2$ cylindersfvwield strength of steel reinforcement<br>$150 \times 300  \text{mm}^2$ cylindersfvyield strength of steel reinforcement<br>$150 \times 300  \text{mm}^2$ cylindersfvwield strength of steel reinforcement<br>$150 \times 300  \text{mm}^2$ cylindersfvyield strength of steel reinforcement<br>$150 \times 300  \text{mm}^2$ cylindersfvwield strength of steel bolts<br>$150 \times 300  \text{mm}^2$ cylindersfvwield strength of steel bolts<br>$150 \times \text{steel bolts}$ fvslab depthhwvertical distance between tip of crack and point where<br>shear reinforcement crosses the critical shear crack<br>$k_s$<br>critical shear crack opening factorkscale factor according to EC2<br>$k_s$ kscale factor accordi  | $\psi^{\uparrow}$ | slab rotation   | $u^*$                 | control perimeter defined at 1.5 <i>d</i> in EC2, 0.5 <i>d</i> in ACI and                    |
| daverage effective depthshear reinforcement $d_g$ maximum aggregate size $u_0$ column perimeter $d_v$ reduced effective depth $A_{si}$ cross sectional area of a shear bar $f_{0.2}$ $0.2\%$ proof strength of steel reinforcement or steel bolts $A_{sw}$ area of one perimeter of shear reinforcement around the<br>column $f_{ccm}$ mean value of concrete compression strength on<br>$150 \times 150 \text{ mm}^3$ cubes $A_{sw}$ area of shear reinforcement inside the control perimeter $f_{ck}$ characteristic concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $B_{sw}$ area of shear reinforcement inside the control perimeter $f_{cm}$ mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $V_{sw}$ applied load to the slab $f_t$ ultimate strength of steel reinforcement<br>$f_y$ yield strength of steel reinforcement $V_{min}$ minimum value between $V_{flex}$ and $V_{Rm}$ $f_{y,ef}$ effective yield strength of steel bolts<br>$f_{w}$ $V_{min}$ mean value of punching shear resistance (governed by<br>crushing of concrete struts) $h_w$ vertical distance between tip of crack and point where<br>shear reinforcement crosses the critical shear crack<br>$k_s$ $V_{Rm,outrmean value of punching shear resistance (governed byfailure outside the shear-reinforced zone)k_sscale factor according to EC2k_sV_{Rm,outrmean value of punching shear resistance (governed byfailure outside the shear-reinforced zone)k_wbolt lengthm_Raverage flexural strength per unit length in the supportstrengV$  | С                 | column side dimension   |                       | $0.5d_v$ in MC2010, from the outermost perimeter of the                                      |
|   | d                 | average effective depth   |                       | shear reinforcement  |
|   | $d_{ m g}$        | maximum aggregate size  | $u_0$                 | column perimeter   |
| $f_{0.2}$ $0.2\%$ proof strength of steel reinforcement or steel bolts<br>$f_{crm}$ $A_{sw}$ area of one perimeter of shear reinforcement around the<br>column $f_{crm}$ mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $A_{sw}$ area of one perimeter of shear reinforcement inside the control perimeter $f_{cm}$ mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $A_{sw}$ area of shear reinforcement inside the control perimeter $f_{cm}$ mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $B_{w}$ area of shear reinforcement inside the control perimeter $f_{cm}$ mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $W_{exp}$ area of shear reinforcement $f_{r}$ ultimate strength of steel reinforcement $V_{min}$ applied load to the slab $f_{y,w}$ yield strength of steel perimeter $V_{min}$ minimum value between $V_{flex}$ and $V_{rm}$ $f_{y,w}$ yield strength of steel bolts $V_{rm}$ mean value of punching shear resistance $f_{y,w}$ yield strength of steel bolts $V_{rm}$ mean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone) $h$ slab depth $V_{rm,out}$ mean value of punching shear resistance (governed by<br>failure outside the shear-reinforced zone) $k_{sys}$ coefficient that accounts for the performance punching<br>shear reinforcement system $V_{rm,s}$ $l_w$ bolt length $V_{s,exp}$ shear reinforcement contribution to<br>punching shear strength $k_s$ crit  | $d_{v}$           | reduced effective depth   | A <sub>si</sub>       | cross sectional area of a shear bar  |
|   | $f_{0.2}$         | 0.2% proof strength of steel reinforcement or steel bolts                         | A <sub>sw</sub>       | area of one perimeter of shear reinforcement around the                                      |
| $150 \times 150 \times 150 \text{ mm}^3$ cubes $A_{sw}^*$<br>swarea of shear reinforcement inside the control perimeter $f_{ck}$ characteristic concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $K_s$<br>mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $V_w$<br>applied load to the slab $f_{cm}$ mean value of concrete compression strength on<br>$150 \times 300 \text{ mm}^2$ cylinders $V_w$<br>applied load to the slab $f_t$ ultimate strength of steel reinforcement $V_{exp}$<br>experimental punching load $f_y$ yield strength of steel reinforcement $V_{flex}$<br>min $f_{y,ef}$ effective yield strength of steel bolts $V_{km}$<br>mean value of punching resistance $f_{y,w}$ yield strength of steel bolts $V_{km}$<br>mean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone) $h_w$ vertical distance between tip of crack and point where<br>shear reinforcement crosses the critical shear crack<br>$k_s$ $V_{Rm,out}$<br>mean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone) $k_{sys}$ coefficient that accounts for the performance punching<br>shear reinforcement system $V_{Rm,s}$<br>shear reinforcement contribution to punching shear<br>strength $l_w$ bolt length<br>mR<br>average flexural strength per unit length in the support<br>strip $V_{s,exp}$ experimental shear reinforcement contribution to<br>punching shear strength  | $f_{\rm ccm}$     | mean value of concrete compression strength on                                    |                       | column   |
|   |                   | $150 \times 150 \times 150 \text{ mm}^3 \text{ cubes}$                            | $A^*_{sw}$            | area of shear reinforcement inside the control perimeter                                     |
| $150 \times 300 \text{ mm}^2 \text{ cylinders}E_wmodulus of elasticity of shear reinforcementf_{cm}mean value of concrete compression strength on150 \times 300 \text{ mm}^2 cylindersVapplied load to the slabf_tultimate strength of steel reinforcementV_{exp}experimental punching loadf_yyield strength of steel reinforcementV_{fex}flexural capacity of slabf_{y,vef}effective yield strength of steel boltsV_{min}mean value of punching resistancef_{y,w}yield strength of steel boltsV_{Rm}mean value of punching shear resistance (governed bycrushing of concrete struts)hslab depthV_{mn,crush}mean value of punching shear resistance (governed bycrushing of concrete struts)h_wvertical distance between tip of crack and point whereshear reinforcement crosses the critical shear crackV_{Rm,out}k_sscale factor according to EC2V_{Rm,out}mean value of punching shear resistance (governed byfailure outside the shear-reinforced zone)k_{sys}coefficient that accounts for the performance punchingshear reinforcement systemV_{Rm,s}shear reinforcement contribution to punching shearstrengthl_wbolt lengthV_{s,exp}experimental shear reinforcement contribution topunching shear strengthn_Raverage flexural strength per unit length in the supportstripV_{s,exp}experimental shear reinforcement contribution topunching shear strength$   | $f_{ck}$          | characteristic concrete compression strength on                                   | Es                    | modulus of elasticity of longitudinal reinforcement  |
|   |                   | $150 \times 300 \text{ mm}^2 \text{ cylinders}$                                   | Ew                    | modulus of elasticity of shear reinforcement   |
| $150 \times 300 \text{ mm}^2$ cylinders $V_{exp}$ experimental punching load $f_t$ ultimate strength of steel reinforcement $V_{flex}$ flexural capacity of slab $f_y$ yield strength of steel reinforcement $V_{min}$ minimum value between $V_{flex}$ and $V_{Rm}$ $f_{y,ef}$ effective yield strength of steel bolts $V_{Rm}$ mean value of punching shear resistance $f_{y,w}$ yield strength of steel bolts $V_{Rm}$ mean value of punching shear resistance (governed by<br>crushing of concrete struts) $h$ slab depthmean value of punching shear resistance (governed by<br>rushing of concrete struts) $h_w$ vertical distance between tip of crack and point where<br>shear reinforcement crosses the critical shear crack $V_{Rm,in}$ $k_s$ critical shear crack opening factormean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone) $k_{sys}$ coefficient that accounts for the performance punching<br>shear reinforcement system $V_{Rm,s}$ $l_w$ bolt length $V_{s,exp}$ experimental shear reinforcement contribution to<br>punching shear strength $l_w$ bolt length $V_{s,exp}$ experimental shear reinforcement contribution to<br>punching shear strength  | $f_{\rm cm}$      | mean value of concrete compression strength on                                    | V                     | applied load to the slab   |
| $f_t$ ultimate strength of steel reinforcement $V_{flex}$ flexural capacity of slab $f_y$ yield strength of steel reinforcement $V_{min}$ minimum value between $V_{flex}$ and $V_{Rm}$ $f_{y,ef}$ effective yield strength of steel bolts $V_{Rm}$ mean value of punching resistance $f_{y,w}$ yield strength of steel bolts $V_{Rm}$ mean value of punching shear resistance (governed by crushing of concrete struts) $h$ slab depthmean value of punching shear resistance (governed by shear reinforcement crosses the critical shear crack $V_{Rm,in}$ $k$ scale factor according to EC2 $V_{Rm,out}$ mean value of punching shear resistance (governed by failure within the shear-reinforced zone) $k_{sys}$ coefficient that accounts for the performance punching shear reinforcement contribution to punching shear strength $l_w$ bolt length $V_{s,exp}$ $m_R$ average flexural strength per unit length in the support strip $V_{s,exp}$  |                   | $150 \times 300 \text{ mm}^2 \text{ cylinders}$                                   | $V_{exp}$             | experimental punching load   |
| $f_y$ yield strength of steel reinforcement $V_{min}$ minimum value between $V_{flex}$ and $V_{Rm}$ $f_{y,ef}$ effective yield strength of steel bolts $V_{Rm}$ mean value of punching resistance $f_{y,w}$ yield strength of steel bolts $V_{Rm}$ mean value of punching shear resistance (governed by<br>crushing of concrete struts) $h_w$ vertical distance between tip of crack and point where<br>shear reinforcement crosses the critical shear crack $V_{Rm,in}$ mean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone) $k$ scale factor according to EC2 $V_{Rm,out}$ mean value of punching shear resistance (governed by<br>failure outside the shear-reinforced zone) $k_{sys}$ coefficient that accounts for the performance punching<br>shear reinforcement system $V_{Rm,s}$ shear reinforcement contribution to punching shear<br>strength $l_w$ bolt length<br>mr<br>average flexural strength per unit length in the support<br>strip $V_{s,exp}$ experimental shear reinforcement contribution to<br>punching shear strength  | $f_{ m t}$        | ultimate strength of steel reinforcement  | $V_{\rm flex}$        | flexural capacity of slab  |
| $f_{y,ef}$ effective yield strength of steel bolts $V_{Rm}$ mean value of punching resistance $f_{y,w}$ yield strength of steel bolts $V_{Rm}$ mean value of punching shear resistance (governed by<br>crushing of concrete struts) $h$ slab depth $V_{Rm,crush}$ mean value of punching shear resistance (governed by<br>crushing of concrete struts) $h_w$ vertical distance between tip of crack and point where<br>shear reinforcement crosses the critical shear crack $V_{Rm,in}$ mean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone) $k$ scale factor according to EC2 $V_{Rm,out}$ mean value of punching shear resistance (governed by<br>failure outside the shear-reinforced zone) $k_{sys}$ coefficient that accounts for the performance punching<br>shear reinforcement system $V_{Rm,s}$ shear reinforcement contribution to punching shear<br>strength $l_w$ bolt length<br>m_Raverage flexural strength per unit length in the support<br>strip $V_{s,exp}$ experimental shear reinforcement contribution to<br>punching shear strength  | $f_{\mathbf{y}}$  | yield strength of steel reinforcement   | $V_{\rm min}$         | minimum value between $V_{\text{flex}}$ and $V_{\text{Rm}}$                                  |
| $f_{y,w}$ yield strength of steel bolts $V_{Rm,crush}$ mean value of punching shear resistance (governed by<br>crushing of concrete struts) $h_w$ vertical distance between tip of crack and point where<br>shear reinforcement crosses the critical shear crack $V_{Rm,in}$ mean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone) $k$ scale factor according to EC2 $V_{Rm,out}$ mean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone) $k_{sys}$ critical shear crack opening factor<br>shear reinforcement system $V_{Rm,s}$ shear reinforcement contribution to punching shear<br>shear reinforcement system $l_w$ bolt length<br>m_Raverage flexural strength per unit length in the support<br>strip $V_{s,exp}$ experimental shear reinforcement contribution to<br>punching shear strength   | $f_{\rm y,ef}$    | effective yield strength of steel bolts   | $V_{\rm Rm}$          | mean value of punching resistance  |
| hslab depthcrushing of concrete struts)h_wvertical distance between tip of crack and point where<br>shear reinforcement crosses the critical shear crackVRm,inmean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone)kscale factor according to EC2VRm,outmean value of punching shear resistance (governed by<br>failure outside the shear-reinforced zone)k_scritical shear crack opening factorVRm,outmean value of punching shear resistance (governed by<br>failure outside the shear-reinforced zone)k_syscoefficient that accounts for the performance punching<br>shear reinforcement systemShear reinforcement contribution to punching shear<br>strengthl_wbolt length<br>mRaverage flexural strength per unit length in the support<br>stripvs.expexperimental shear reinforcement contribution to<br>punching shear strength  | $f_{\rm y,w}$     | yield strength of steel bolts   | V <sub>Rm,crush</sub> | mean value of punching shear resistance (governed by   |
| $h_w$ vertical distance between tip of crack and point where<br>shear reinforcement crosses the critical shear crack<br>k $V_{\rm Rm,in}$ mean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone)kscale factor according to EC2<br>ks $V_{\rm Rm,out}$ mean value of punching shear resistance (governed by<br>failure within the shear-reinforced zone)kscale factor according to EC2<br>ks $V_{\rm Rm,out}$ mean value of punching shear resistance (governed by<br>failure outside the shear-reinforced zone)k_syscoefficient that accounts for the performance punching<br>shear reinforcement system $V_{\rm Rm,s}$ shear reinforcement contribution to punching shear<br>strength $l_w$ bolt length<br>average flexural strength per unit length in the support<br>strip $V_{\rm sexp}$ experimental shear reinforcement contribution to<br>punching shear strength   | h                 | slab depth  |                       | crushing of concrete struts)   |
| shear reinforcement crosses the critical shear crackfailure within the shear-reinforced zone)kscale factor according to EC2VRm,outmean value of punching shear resistance (governed by<br>failure outside the shear-reinforced zone)kcritical shear crack opening factorVRm,outmean value of punching shear resistance (governed by<br>failure outside the shear-reinforced zone)kcoefficient that accounts for the performance punching<br>shear reinforcement systemVRm,sshear reinforcement contribution to punching shear<br>strengthlwbolt lengthVs,expexperimental shear reinforcement contribution to<br>punching shear strengthmRaverage flexural strength per unit length in the support<br>strippunching shear strength   | $h_{w}$           | vertical distance between tip of crack and point where                            | V <sub>Rm,in</sub>    | mean value of punching shear resistance (governed by   |
| kscale factor according to EC2 $V_{\rm Rm,out}$ mean value of punching shear resistance (governed by<br>failure outside the shear-reinforced zone)kcritical shear crack opening factor $V_{\rm Rm,out}$ mean value of punching shear resistance (governed by<br>failure outside the shear-reinforced zone)kcoefficient that accounts for the performance punching<br>shear reinforcement systemNemsshear reinforcement contribution to punching shear<br>strengthlbolt length<br>average flexural strength per unit length in the support<br>strip $V_{\rm s,exp}$ experimental shear reinforcement contribution to<br>punching shear strength  |                   | shear reinforcement crosses the critical shear crack                              |                       | failure within the shear-reinforced zone)  |
| k_scritical shear crack opening factorfailure outside the shear-reinforced zone)k_{sys}coefficient that accounts for the performance punching<br>shear reinforcement systemVRm,sshear reinforcement contribution to punching shear<br>strengthl_wbolt lengthVs,expexperimental shear reinforcement contribution to<br>punching shear strengthm_Raverage flexural strength per unit length in the support<br>stripvs,exppunching shear strength  | k                 | scale factor according to EC2   | V <sub>Rm,out</sub>   | mean value of punching shear resistance (governed by   |
| k_{sys}coefficient that accounts for the performance punching<br>shear reinforcement systemVRm,sshear reinforcement contribution to punching shear<br>strengthl_wbolt lengthVs,expexperimental shear reinforcement contribution to<br>punching shearexperimental shear reinforcement contribution to<br>punching shear strengthm_Raverage flexural strength per unit length in the support<br>stripvs,exppunching shear strength  | k <sub>s</sub>    | critical shear crack opening factor   |                       | failure outside the shear-reinforced zone)   |
| lwbolt lengthVs,expexperimental shear reinforcement contribution tomRaverage flexural strength per unit length in the supportpunching shear strengthstripstrengthstrength   | $k_{\rm sys}$     | coefficient that accounts for the performance punching shear reinforcement system | V <sub>Rm,s</sub>     | shear reinforcement contribution to punching shear strength                                  |
| m <sub>R</sub> average flexural strength per unit length in the support punching shear strength strip   | $l_{w}$           | bolt length   | $V_{\rm s,exp}$       | experimental shear reinforcement contribution to   |
|   | m <sub>R</sub>    | average flexural strength per unit length in the support strip                    | · · · · ·             | punching shear strength  |

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

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  $150 \times 150 \times 150 \text{ mm}^3$  ( $f_{ccm}$ ) 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  $0.80f_{ccm}$ . 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  $200 \times 200 \text{ mm}^2$  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 Download English Version:

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