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# The effect of the vertical component of prestress forces on the punching strength of flat slabs

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ABSTRACT

The use of prestress in flat slabs is a common solution, mainly because it allows larger spans and thinner slabs. Nevertheless, smaller thicknesses near the slab-column connections, along with the superposition of high shear and flexural stresses, arise the question of the slab capacity to resist punching. The punching failure results from the superposition of shear and flexural stresses near the column, and is associated to the formation of a pyramidal plug of concrete which punches through the slab. It is a local and brittle failure. The use of prestress can increase the punching capacity of flat slabs-column connections.

This work presents the experimental analysis of flat slab specimens with tendons under punching. Nine slabs were tested using unbonded prestress with high strength steel tendons. The influences on the punching capacity of the vertical component of the prestress forces resulting from inclined tendons near the column and their distance to the column are analysed. The in-plane compression force due to prestress was not applied to the slabs, in order to evaluate only the deviation force influence. This work aims to improve the understanding of the behaviour of prestressed flat slabs under punching load in order to properly evaluate the punching resistance of this kind of structures. The experimental punching loads are compared with the provisions of EC2, ACI 318-11 and MC2010.



## 1. Introduction

Prestressed flat slabs have been in use for several decades now. The advantages between this structural solution and a non-prestressed flat slab are various, e.g.: enables deflections and cracks under service conditions to be kept under control; allows larger spans and thinner slabs, which implies reduced costs on materials and labour; less weight also originates smaller earthquake forces, which is an important factor in seismic zones.

Punching resistance is an important issue in the design of concrete flat slabs, frequently being the conditioning factor in choosing its thickness. The punching failure results from the superposition of shear and flexural stresses near the column, and is associated to the formation of a pyramidal plug of concrete which punches through the slab. It is a brittle and local failure and may initiate a progressive collapse and in some cases a global structural failure. The loss of a support at a slab-column connection, leads to the increase of stresses in the nearby slab-column connections and enhance their probability of failure. The use of prestress can increase the punching capacity of flat slab-column connections, mostly due to the vertical component resulting from inclined tendons near the column, the compression forces resulting from prestress and the moments due prestress eccentricities.

Research has been developed in this subject by several authors [1–8], but the isolation of the effects of in-plane compression, the vertical component resulting from inclined prestressing tendons and moments provoked by the prestress eccentricities is not usually done in such tests, taking all its effects acting simultaneously. In a previous work Ramos [9] presented some tests where the effects of the in-plane forces on the punching capacity were investigated.

The present work reports the experimental analysis of flat slabs with tendons under punching, in order to study the influence on the punching capacity of the vertical component of the tendon forces, resulting from inclined tendons near the column, and their distance from the column. In order to evaluate only the influence of the vertical deviation forces of the prestressing tendons, the in-plane forces in the tendons were anchored to exterior steel frames and did not act on the slabs. Nine specimens were tested: eight using unbonded prestress tendons and one without tendons

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**Nomenclature**

| | |
|---|---|
| $a$ | average vertical deviations of tendons |
| $d$ | mean effective depths of the ordinary reinforcement |
| $d_g$ | maximum aggregate size |
| $d_p$ | mean effective depths of tendons |
| $E_s$ | steel modulus of elasticity |
| $f_{cm}$ | mean value of concrete cylinder strength |
| $f_{cm,cube}$ | mean value of concrete cube compressive strength |
| $f_{p0.1}$ | 0.1% proof strength of prestressing steel |
| $f_y$ | yield strength of reinforcement |
| $m_p$ | average decompression moment per unit length due to prestressing |
| $m_s$ | average applied moment per unit length |
| $m_R$ | resistance moment per unit length |
| $P$ | prestress force in each orthogonal direction |
| $r_s$ | radius from the centre of the column to the zero moment line |
| $u$ | length of the control perimeter for punching |
| $V_p$ | sum of the vertical components of prestress forces assumed to be transferred directly to the support by inclined compression (deviation force) |
| $V_{eff}$ | effective punching load ($V_{exp} - V_p$) |
| $V_{exp}$ | experimental failure load |
| $V_{R,EC2}$ | predicted punching resistance using EC2 |
| $V_{R,ACI}$ | predicted punching resistance using ACI 318-11 |
| $V_{R,MC}$ | predicted punching resistance using Model Code 2010 |
| $\psi$ | slab rotation |
| $\sigma_{cp}$ | mean in-plane compression stress |
| $\rho$ | flexural reinforcement ratio |

(AR9), to be used as a reference slab. This work aims to improve the understanding of the behaviour of flat slabs under punching in order to properly evaluate the punching capacity of this kind of structures. A short review of the design methods of Eurocode 2 [10], the ACI 318-11 [11] and the fib Model Code for Concrete Structures 2010 [12], which is based in the Critical Shear Crack Theory proposed by Muttoni [13], are also presented. The experimental results obtained are compared with the three design methods.

## 2. Experimental research

The experimental analysis described in this paper consisted in testing eight flat slab specimens with high strength steel tendons and one without tendons up to failure by punching. The slab without tendons (AR9) was tested to be used for comparison purposes to the other ones. The test specimens were divided into two sets: one to analyse the effect of the vertical component of the tendon forces near the column, with all the tendons crossing the loaded area (slabs AR8, AR10 and AR11), and another one to study the effect of the distance of the tendons from the column on the punching capacity, where the tendons were placed at different distances from the loaded area (slabs AR12 to AR16).

The test specimens were $2300 \times 2300\ mm^2$ and 100 mm thick. They modelled the area near a column of an interior slab panel up to the zero moment lines. The vertical load was applied by a hydraulic jack positioned under the slab, through a steel plate with $200 \times 200\ mm^2$ in the centre of the slab, which simulated the column. The borders of the slab were connected by tendons and spreader beams to the laboratory strong floor in eight points (Fig. 1).

The bottom and top reinforcement consisted of twelve 6 mm rebars at 200 mm centres and thirty-nine 10 mm rebars at 60 mm centres respectively, in both orthogonal directions. The concrete cover was about 10 mm in both faces. The mean effective depth of the ordinary reinforcement ($d$) can be seen in Table 1.

The prestress consisted on four unbonded 12.7 mm nominal diameter tendons, with a cross section area of $100\ mm^2$ each, in both orthogonal directions. The prestressed tendons location can be seen in Fig. 2. The tendons profiles were trapezoidal, with the downward tendon deviation forces over the central loaded area and the upward deviation forces at 1000 mm from the centre of the loaded area (Fig. 3). The prestress tendons average vertical deviation ($a$), measured during the construction of the models, can also be seen in Table 1.

The concrete was made with ordinary Portland cement, natural sand and crushed limestone aggregate with a maximum size of 15.6 mm. To assess the strength of the concrete used in the production of the test specimens, compression tests were made in 150 mm cubes ($f_{cm,cube}$ – see Table 2). This table also presents the considered mean value of cylinder compression strength ($f_{cm}$) taken as 0.8 of $f_{cm,cube}$. To assess the reinforcement steel yield strength ($f_y$) and the 0.1% proof strength of prestressing steel ($f_{p0.1}$) tensile tests were carry out. The results obtained are also presented in Table 2.

The prestress forces were applied after the test specimens were loaded with an initial 50 kN vertical load, in order to avoid cracking on the bottom surface during the prestressing process. Subsequently the vertical load was monotonically increased until failure. The prestress forces were applied to the tendons by eight hydraulic jacks (four in each direction). As the intention of these tests was only to study the effect of the vertical deviation forces of the prestressing tendons, external steel frames were used to anchor the tendons, avoiding that the compression force of the prestress was transmitted to the slab edges (Fig. 4). With the slab deformation, the tendons have the tendency to increase their prestress force, especially if they are short ones, as was the case of the tested specimens. To avoid this, a load maintainer device was used in the hydraulic jacks used to apply the prestress forces in order to keep then constant during the tests. The prestress force applied in each direction of the specimens is presented in Table 3.

During the tests, the total applied load, the actual prestress force on the tendons, the strains in the some of the top reinforcement rebars and the vertical displacements of the specimens were measured.

## 3. Tests results

### 3.1. Punching capacity

All the slabs failed by punching and their ultimate loads ($V_{exp}$), including self-weight, are given in Table 3. In all the slabs the failure surface had the shape of a pyramidal plug of concrete, starting at the bottom of the slab around the column perimeter and arriving at the top rebar level at a distance about 2d from the column perimeter. Some experimental models were saw cut transversally after being tested (AR9, AR13, AR14 and AR16), enabling the measurement of the angle between the punching failure surface with the horizontal. In average that angle varied between 29° and 36° on the specimens with tendons and was around 30° on the