

# STRENGTHENING OF FLAT SLABS WITH TRANSVERSE REINFORCEMENT

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**Summary:** *This paper describes the experimental research carried out to study a strengthening method for flat slabs under punching using transversal shear reinforcement in the form steel bolts.*

## 1 INTRODUCTION

In flat slabs the force and moments transferred between the slab and the column cause high shear and bending stresses in the slab, near the column. These stresses produce concrete cracking and may lead to the slab failure. The punching failure is associated with the formation of a pyramidal plug of concrete which punches through the slab. The punching failure results from the superposition of shear and flexural stresses in the slab. It is a local and brittle failure mechanism.

Nowadays, flats slabs are a common solution for buildings because they are economical, easy and fast to build. The need to study suitable strengthening and/or repairing methods is associated to the increased use of this kind of slab.

There are many reasons to repair and/or strengthen flats slabs (e.g. construction or design errors, poor quality or inadequate materials, overloading and accidents). The repair and/or strengthening method (or methods) to be used in any particular situation depends on technical and economical factors, and may be a complex task.

The present work reports the experimental research carried out to study a strengthening method for flat slabs under punching using transversal prestress. Variations of this method have been studied by various authors namely: Ghali et al [1], Ramos et al [2], El-Sakawy et al [3] and Harajli et al [4]. Five experimental slabs were produced and tested. The experimental results are compared with predictions based on Eurocode 2 [5].

## 2 EXPERIMENTAL MODELS

The experimental analysis described in this paper comprises the testing five reduced scale flat slab models up to failure by punching: four with transversal bolts acting as punching shear reinforcement and another one without transversal reinforcement, to be used as reference.

The specimens were 1800x1800 mm<sup>2</sup> and 120 mm thick. They modelled the area near a column of an interior slab panel up to the zero moment lines (Figure 1). The punching load was applied by a hydraulic jack positioned under the slab, through a steel plate with 200x200 mm<sup>2</sup> in the centre of the slab. Eight points on the top of the slab were connected to the strong floor of the laboratory using steel tendons and spreader beams.

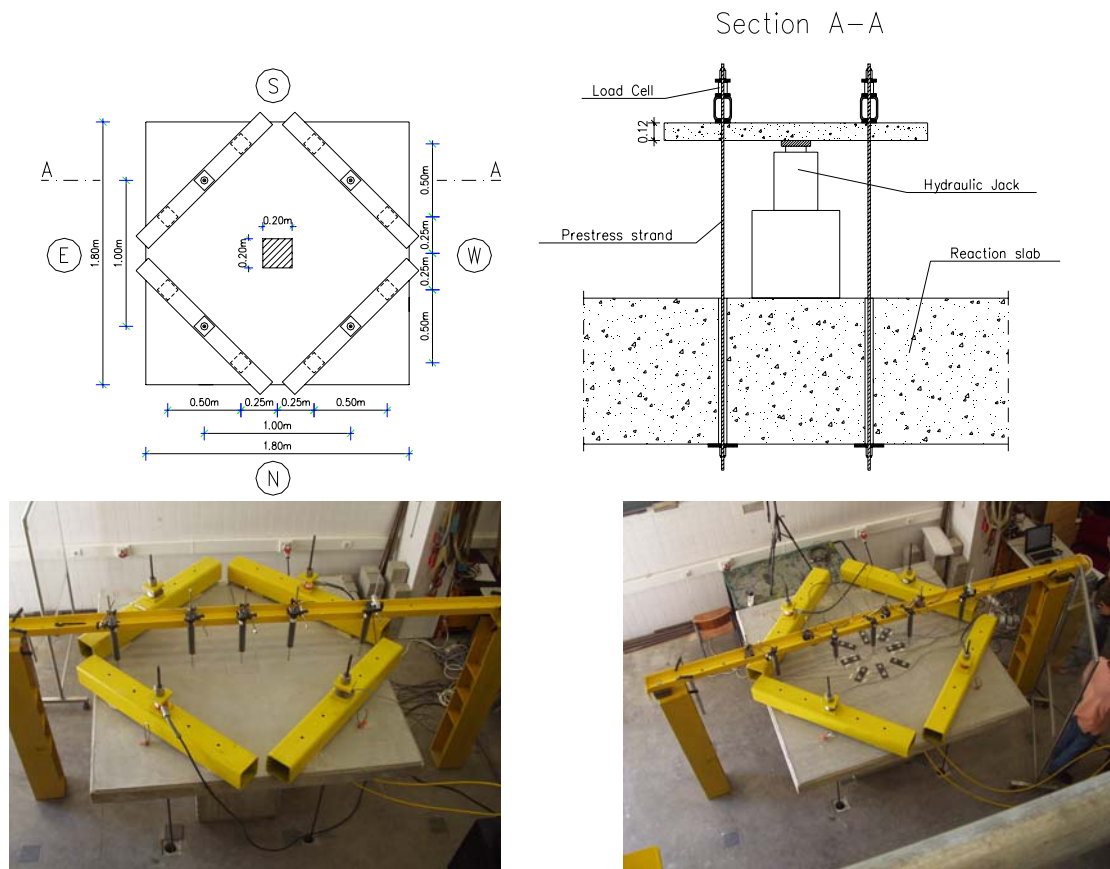


Figure 1 : Test geometry

The bottom and top reinforcement consisted of 6 mm rebars every 200 mm and 10 mm rebars every 75 mm, respectively, in both orthogonal directions. The clear cover was about 20 mm on the top reinforcement and 10 mm on the bottom. The top reinforcement with the greater effective depth was in the N-S direction, and the mean effective depths ( $d$ ) are presented in Table 3.

The test slabs ID2 to ID5 were loaded up to approximately 60 % of the experimental failure load of the reference model (ID1). A large amount of flexural cracking was present at that stage. The test slabs were then unloaded and strengthened. The strengthening method used consisted of drilling vertical holes through the slab near the column, and inserting steel bolts which were prestressed against the slab surfaces. The principal variables considered in this research were the area of shear reinforcement and the prestress force applied initially to the bolts. The punching shear reinforcement consisted in sixteen transversal steel bolts placed in two layers around the column. The first layer was about  $0.5d$  from the column and the second approximately  $0.75d$  from the first. The forces in the bolts were transmitted to the concrete slab through a 5 mm tick steel plate, which served as an anchor plate for two bolts. The position of the strengthening steel bolts can be seen in Figure 2. The steel bolts used in these tests were cut from M10, M8 and M6 threaded bar. The middle sections of the bolts were machined to an uniform diameter of 7.7 mm, 6.0 mm and 4.6 mm respectively and strain gauges were glued to measure the evolution of the force in the bolts (Figure 3). The bolts were then tightened with an initial force per bolt of 11.2 kN (ID2-M10), 2.9 kN (ID3-M6), 6.7 kN (ID4-M8) and 1.4 kN – adjusted (ID5-M8). Finally the slabs were loaded up to failure.

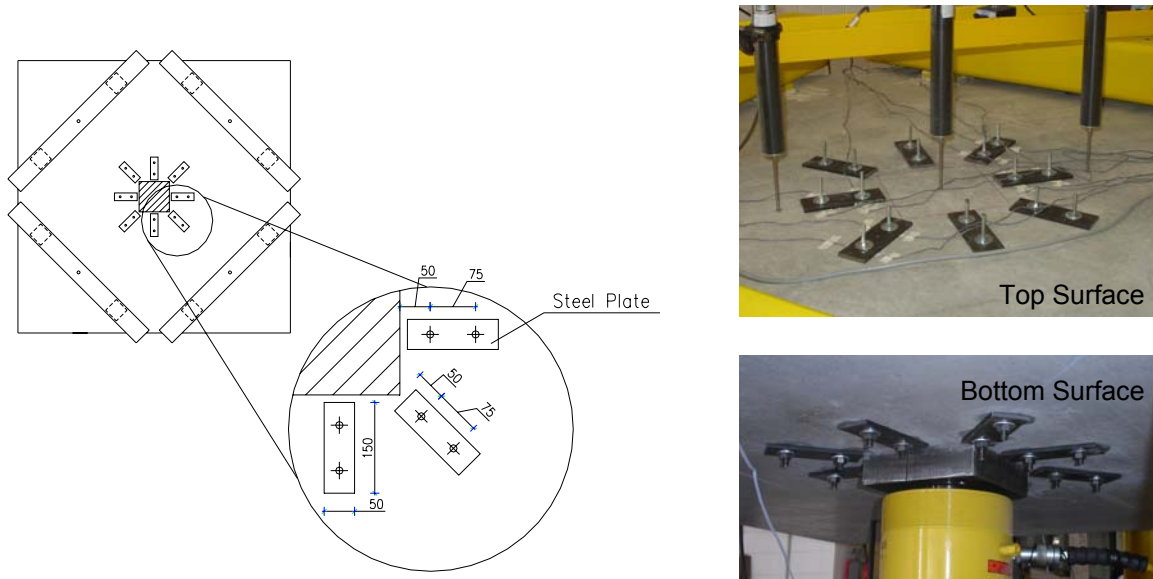


Figure 2 : Geometry of the punching shear reinforcement (dimensions in mm)

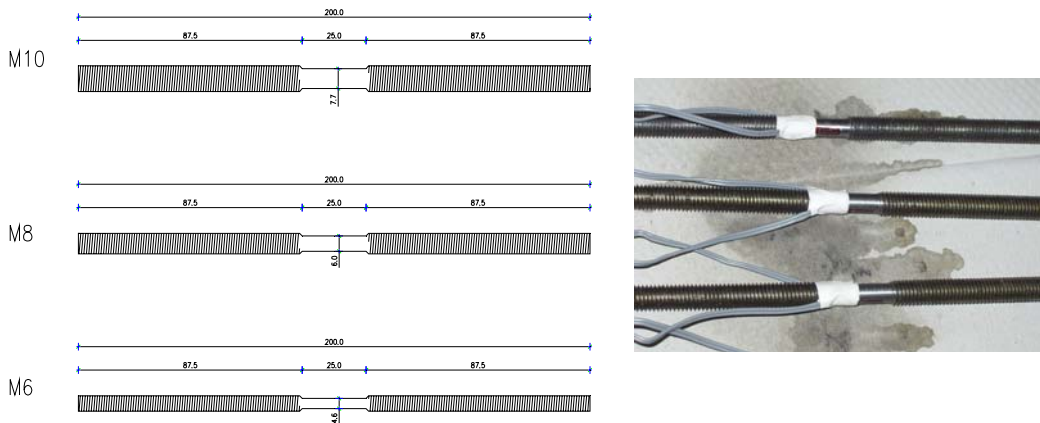


Figure 3 : Shear reinforcement used in tests (dimensions in mm)

The strains in the steel bolts (in the machined area) and in three of the top reinforcement bars, the vertical displacements at five points and the total applied load were measured during the tests.

### 3 MATERIALS PROPERTIES

For accessing the concrete strength used in the specimens, compression tests on cubes of  $150 \times 150 \times 150 \text{ mm}^3$  ( $f_{cm, cu}$ ) were carried out. The results are showed in Table 1. The reinforcement steel and the bolts tensile yielding strength ( $f_{sy}$ ) and breaking strength ( $f_{su}$ ) are presented in Table 2.

Table 1 : Concrete Properties

Model	ID1	ID2	ID3	ID4	ID5
$f_{cm,cu}$ (MPa)	49.2	52.3	59.6	59.7	59.8

Table 2 : Reinforcement Steel and Bolts Properties

	Ø6	Ø10	M6	M8	M10
$f_{sy}$ (MPa)	588	445	349	442	453
$f_{su}$ (MPa)	697	582	505	605	597

#### 4 TEST RESULTS

All the slabs failed by punching and their ultimate loads ( $V_{exp}$ ), including self weight are given in Table 3.

In model ID1 the first cracks to appear at a load of around 95 kN. These were flexural cracks on the top surface, around the perimeter of the support. With the increase of vertical load, radial cracks started to occur and spread out from the loaded area towards the slab edges. Subsequently the inclined cracking within the slab thickness that afterwards developed into the punching failure surface, started to be noticed on the top surface. 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 to the top surface at a distance about  $2d$  from the column perimeter.



Figure 4 : Top and Bottom surface of Model ID1 after punching failure

On the models with transversal reinforcement the crack development followed a similar pattern. The first tangential cracks started to be noticed between 100kN and 110kN, and the radial cracking at around 120kN. The failure surface was external to the perimeter defined by the strengthening bolts in Models ID2 and ID4, and in Models ID3 and ID5 it occurred through the strengthening bolts.

The strains on the top reinforcement bars grew with the increase of the vertical load. On the models reinforced with the vertical bolts the strains on the top reinforcement were slightly smaller than in Model ID1, for the same load stage.



Figure 5 : Bottom surfaces of Models ID2 to ID5 after punching failure

The recorded vertical deflections on the models with strengthening bolts were also smaller than the observed in the reference model for the same load. It appears that the presence of the reinforcing bolts led to an increment of the stiffness of the slab. The deformations of the slabs are approximately rigid body rotations about axes close to the edges of the loaded area.

The force in the vertical bolts stayed approximately constant until the applied load reached about the slab predicted resistance without shear reinforcement. Then the forces grow quickly with the increase of vertical load. The forces in the bolts of the innermost layer were usually higher than in the outermost layer.



Figure 6 : Bolts after punching failure in Models ID3 and ID5

## 5 COMPARISONS OF ACTUAL AND PREDICTED STRENGTHS

Comparisons are made here between the strengths of the slabs described above and predictions made by the methods recommended by the Eurocode 2 – EC2 [5]. Table 3 presents the results of the comparisons.

For the calculation of the unfactored resistance without punching shear reinforcement, using EC2, the following expression was used:

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

Where  $k = 1 + \sqrt{200/d}$  ( $d$  in mm);  $f_{cm}$  is the concrete cylinder strength;  $d$  is the mean effective depth of the bonded flexural reinforcement  $= \frac{1}{2} (d_x + d_y)$ ;  $\rho$  is the bonded flexural reinforcement ratio that may be calculated as  $\sqrt{\rho_x \rho_y}$ , with the  $\rho_x$  and  $\rho_y$  being the ratios in orthogonal directions. In each direction the ratio should be calculated for a width equal to the side dimension of the column or loaded area plus  $3d$  to either side of it;  $u$  is the length of a control perimeter at  $2d$  from a loaded area ( $u = 4c + 4\pi d$  for a square loaded area of side length  $c$ ). The value of  $k$  is limited to 2.0 in EC2 but this restriction was neglected in the calculations presented. Also in the calculations presented the concrete cylinder strength ( $f_{cm}$ ) was taken as being 80% of the concrete cube compressive strength ( $f_{cm,cu}$ ) presented in Table 1.

When vertical shear reinforcement is used the unfactored resistance according to EC2 may be calculated using the following equation:

$$V_{Rm} = 0.135 k (100 \rho f_{cm})^{1/3} u d + A_{sw} f_{yw} \quad (2)$$

Where  $A_{sw}$  is the area of shear reinforcement inside the control perimeter and  $f_{yw}$  is the yield strength of the shear reinforcement.

Table 3 : Comparison between experimental and predicted failure loads

Model	d (mm)	Experimental Results		Predicted values using EC2				$V_{exp}/V_{Rm}$
		$V_{exp}$ (kN)	Failure mode	$V_{Rm,1}$ (kN)	$V_{Rm,2}$ (kN)	$V_{Rm,3}$ (kN)	Failure mode	
ID1	87	269	inside	<b>274</b>	-	-	inside	0.98
ID2	84	406	outside	-	542	<b>396</b>	outside	1.03
ID3	90	331	through shear reinforcement	-	<b>316</b>	430	through shear reinforcement	1.05
ID4	90	381	outside	-	<b>425</b>	432	through shear reinforcement	0.90
ID5	94	366	through shear reinforcement	-	<b>431</b>	442	through shear reinforcement	0.85

$V_{exp}$  – experimental failure load;  $V_{Rm,1}$  – predicted punching resistance according to EC2 at a control perimeter  $2d$  from the column;  $V_{Rm,2}$  – predicted punching resistance according to EC2 with shear reinforcement;  $V_{Rm,3}$  – predicted punching resistance according to EC2 at a control perimeter  $2d$  from the outermost perimeter of shear reinforcement.

It was observed that the use of shear reinforcement in the form of vertical bolts led to an increment on the punching failure load. When compared with the reference model it was obtained an increment of resistance between 23% using the M6 bolts, and 50%, when it was used bolts obtained from M10 threaded bar. Decreasing the initial prestress applied to the bolts from 6.7 kN (Model ID4) to 1.4 kN (Model ID5) resulted in a small decrease of approximately 4% on the obtained failure load.

The predicted failure loads according to EC2 were calculated using equation (1) at a control perimeter  $2d$  from the column in Model ID1. For the others models it was considered the smaller of two values: the punching resistance with shear reinforcement using equation (2) or the punching resistance at a control perimeter  $2d$  from the outermost perimeter of shear reinforcement using again equation (1). The considered values are in bold in Table 3. The EC2 predictions for the failure loads give satisfactory results when compared with the experimental values obtained. In fact the average ratio  $V_{exp}/V_{Rm}$  was 0.96, a slightly unsafe result, but in the same magnitude of that ratio in the reference model (0.98). This may well be the result of the treatment of the depth factor  $k$ . If EC2's limit  $k \leq 2.0$  had been applied the predictions would have been 20% lower.

The predictions for the failure mode agreed quite well with the experimental results. The only exception was in Model ID4. However in that model the punching resistance through the shear reinforcement (425 kN) is almost equal than the obtained without shear reinforcement at a control perimeter  $2d$  from the outermost perimeter of the shear reinforcement (432 kN).

## 6 CONCLUSIONS

In this paper it is described an easy and economical method to apply to flat slabs that need to be retrofitted, aiming to have a better punching behaviour. Experimental tests were performed to analyse their efficiency. The method consists of using prestressed steel bolts through the slab thickness near the column, and anchored in steel plates on the slab surfaces.

Five slabs were tested and the achieved punching resistance on the models with shear reinforcement were higher than the obtained in the reference model. In fact it was obtained an increment of resistance between 23% using the M6 bolts, and 50%, when it was used bolts obtained from M10 threaded bar.

The EC2 predictions for the failure loads and failure modes agreed quite well with the experimental results.

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