STRENGTHENING OF REINFORCED CONCRETE SLABS USING POST-TENSIONING WITH ANCHORAGES BY BONDING

Duarte Faria*, Valter Lúcio, António Ramos*****

*PhD Student, Science and Technology Faculty, New University of Lisbon, Portugal

** Associated Professor, Science and Technology Faculty, New University of Lisbon, Portugal

*** Assistant Professor, Science and Technology Faculty, New University of Lisbon, Portugal

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Abstract:

Strengthening of concrete slabs by means of post-tensioning is a very effective method regarding ultimate and serviceability limit states. Nevertheless the traditional post-tensioning method uses external permanent anchorages that can affect aesthetics and need space. The study developed is mainly experimental and aims the introduction of post-tension in reinforced concrete slabs for strengthening purposes, using anchorages by bonding between the prestress tendon and the concrete. These anchorages are materialized with the help of a bonding agent (epoxy resin adhesive). The studied subjects are: development of drilling and injection techniques, study of the bonding agent (pull-out and push-in testing to determine bond stress/slip relationships and prestress transmission lengths), prestressing system and temporary anchorages, and development of applications for the system, like strengthening of flat slabs for punching, bending and deformations control.

1. INTRODUCTION

Flat slabs are a common solution for buildings because they are economical, easy and fast to build. The main drawback of this structural system is the fact that there is high concentration of stresses in the slab-column connection area. The need to study suitable strengthening methods is associated to the increased use of this kind of slabs. There are many reasons to strengthen flats slabs which are, 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. This paper aims to describe a system for strengthening reinforced concrete flat slabs that allows solving the most common problems in slabs already mentioned above, as well as in terms of deformation and cracking. It consists in the introduction of post-tension in reinforced concrete slabs for strengthening purposes, using anchorages by bonding between a high strength steel prestress tendon and the concrete, becoming a very effective method regarding ultimate and serviceability limit states. This method brings some advantages in relation to the traditional strengthening with prestress that are discussed in the following section.

2. SYSTEM DESCRIPTION

The system consists on drilling the existing slab, install of the strands of high strength steel, prestressing the steel with temporary anchorages, the injection with a bonding agent and its hardening, release of the provisional anchorages and transfer of the prestress forces to the concrete. It is a post-installed prestress using the pre-tension anchorage method.

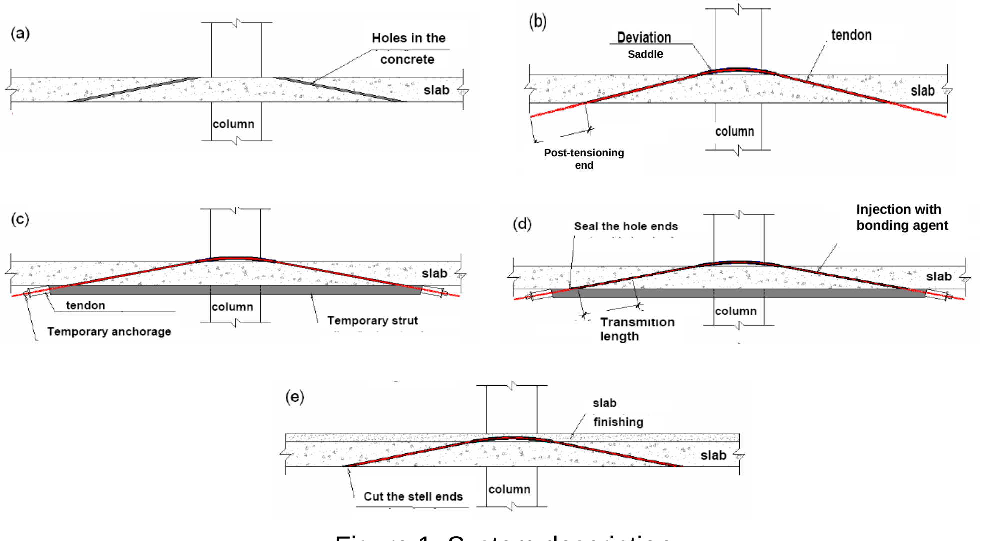


Figure 1: System description

The bonding agent used is an epoxy adhesive, since it has good tensile and shear strength, good resistance to oil, moisture and many solvents. It has a low contraction in the cure, high resistance to creep and is appointed for applications of space-filling.
The main advantages of this system are: the strengthened element does not need to be unloaded; no need for new deformations to mobilize the strengthening; does not add weight to the structure; reduces cracking; controls deformations; increases strength in flexure and punching; does not have external permanent anchorages; it is cheap and easy to install, and does not compromises aesthetics and useable space. While in traditional prestress strengthening the anchorage forces are localized, in this system the stresses in the anchorage zones are introduced gradually along the transfer length.
The strengthening of reinforced concrete slabs using the post-tension method is a highly efficient method with regard to ultimate and serviceability limit states.
With this strengthening method it is possible to transfer the loads from the span of the slab directly to the column through the tendons, so that the undesirable concentration of stresses and deformations are reduced.

3. BOND MECHANISM

The biggest issue of this system is the bond behaviour of the strand embedment with adhesive. The mechanisms that contribute to the bond transfer of the prestress are adhesion, friction and mechanical action. After the adhesive component is lost, the bond stress increases with slip and the frictional component plays an important role. The radial compressive stresses connected to friction appear mainly from the Poisson effect at the prestress transfer. The frictional component is also enhanced by some kind of mechanical action[1] due to the typical shape of the strand, characterized by helical outer wires around a straight centre wire. In this case there adhesive ribs between the helical outer wires are also formed, and some of them are sheared off, so mechanical action from rib bearing also plays an important role.
For the development of this work, the intention is not the quantification of the various mechanisms involved, but the prediction of the bond behaviour of seven wires strands of high strength steel with 15.3 mm nominal diameter (140 mm^2 cross section, 260 kN characteristic maximum force, 224 kN characteristic proof force at 0.1%), when sealed in 18 mm diameter holes using an epoxy adhesive (the holes have a diameter 18% wider than the diameter of the strand).

4. EXPERIMENTAL INVESTIGATION

"Pull-out" and "push-in" tests were executed for the characterization of bonding behaviour. These two types of tests pretend to simulate the bond behaviour that may be found when the pre-tension method is used.
The "pull out" test tries to simulate the behaviour in tension of the strand when it is tensioned due to an increase of the loading in the slab, until the ultimate limit state is reached. The "push-in" test is intended to simulate the behaviour of the strand when the prestress force, applied before the injection of the hole with the adhesive,

is transferred to the concrete. From these tests it is possible to quantify the maximum allowable initial force to install in the strand, taking into account the drilled length available, and what is the maximum force that can be supported by the strand when the ultimate limit state is reached. After determining the bond characteristics of the strands sealed with the chosen adhesive, the tests of the strengthened slabs with the proposed system followed, which attained a predicted punching failure.

4.1 Pull-out tests

The pull-out tests consist in pulling out the strands sealed with the adhesive in a concrete block. The characteristics of the strand and the hole diameter were described above. An electro-pneumatic rotary-impact drill was used to drill the holes, which were afterwards cleaned thru blowing and brushing. Three series of tests were made with 100 mm, 150 mm and 200 mm embedment depths, resulting in the corresponding relations (embedment depth/strand diameter) h/d of 6.6, 9.8 and 13.2.

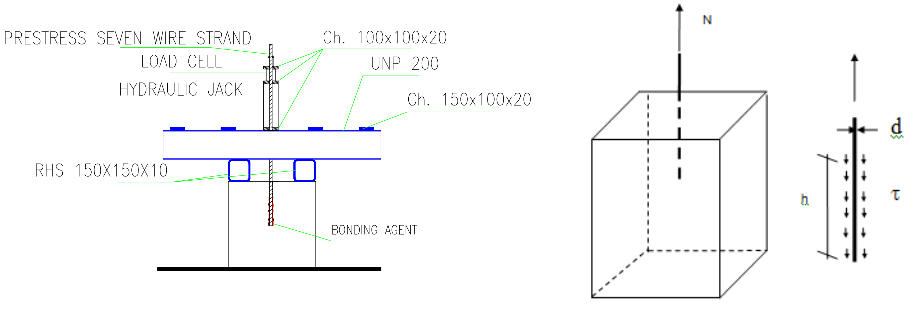


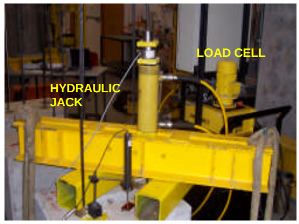
Figure 2: Pull-out test

During the tests the slipping of the strand in a rotating helical way could be observed, in the strand/adhesive interface, corresponding to the shape of the surface of the strand, as would be expected because the adhesive took that shape during healing. The force was measured with a load cell and slipping with the help of two displacement transducers. The results of the various pull-out tests are presented in the table 1, where τ_{max} is the maximum bond stress and τ_{el} is the maximum elastic bond stress (at the end of the elastic behaviour). According to Cook et al.[2] and Krishnamurthy[3] a constant bond stress over the embedment length and a bond strength not dependent on the embedment length may be assumed when employing a reinforcing bar or threaded rod to perform an adhesive anchor. So, it's reasonable to assume the same in cases where strands are used. According to these authors it is also possible to use the diameter of the anchor rod instead of the hole diameter with a small annular clearance. The mean compressive strengths of concrete cubes were between 25MPa to 30MPa. Then, the averages of the bond stress at maximum elastic force and at maximum force were obtained by adopting the uniform bond stress model, according to the following:

$$\tau = \frac{N}{\pi\, d\, h} \qquad (1)$$

Where, N represents the load applied to the tendon; d represents the nominal diameter of the strand and h represents the embedment length.

Test	τ_{el} (MPa)	Average of the Max. Elastic Bond Stresses (MPa)	τ_{max} (MPa)	Average of the Max. Bond Stresses (MPa)
C1-20 cm	6,3	6,3	17,8	13,6
C2-20 cm	5,9		13,3	
C3-20 cm	4,8		12,6	
C4-20 cm	5,3		13,6	
C5-20 cm	7,3		10,0	
C1-15 cm	5,5		13,1	
C2-15 cm	5,3		10,1	
C3-15 cm	5,2		12,8	
C4-15 cm	5,9		12,2	
C5-15 cm	9,5		14,0	
C1-10 cm	6,1		9,9	
C2-10 cm	5,8		19,6	
C3-10 cm	7,1		10,5	
C4-10 cm	6,2		10,9	
C5-10 cm	8,8		23,0	



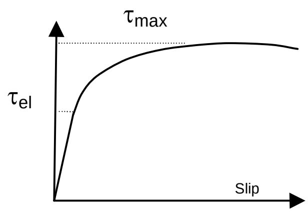


Table 1: Results of pull-out tests

4.2 Push-in tests

The push-in tests consisted in drilling a hole in a concrete block and the introduction of high strength steel strands. Afterwards the strands are tensioned, and the annular gap left between the strand and the walls of the hole are filled with adhesive. After curing of the adhesive the strand is unstressed on one end, and the difference in load between both sides is supported by bonding.

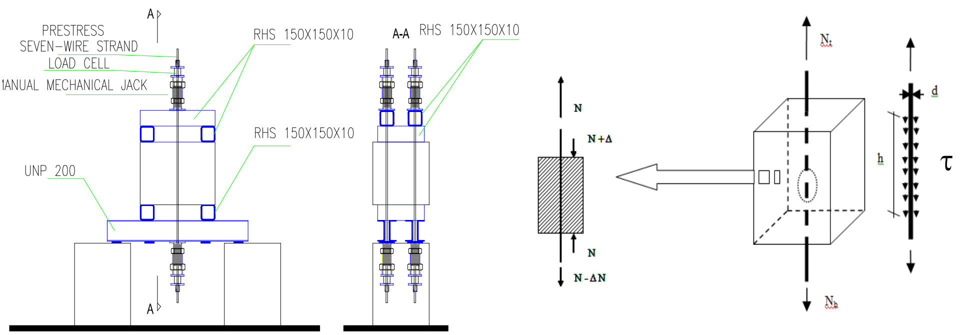


Figure 3: Push-in tests

The hole was made using the same procedure as in the pull-out tests. Six series of tests were made with 250 mm, 350 mm, 450 mm, 550 mm, 650 mm and 800 mm embedment lengths. The transfer length is obtained from this test series with different embedment lengths. For each length, the force in the opposite end of the unstressed one was measured (transmitted force). For a given load, the transfer length is the smallest embedment length needed to transfer that load from the strand to the concrete. In Figure 4 it can be observed that the transfer length for a load of 175 kN is about 650 mm. For each length two tests were carried out, represented by the blue and red bars in the following figure.

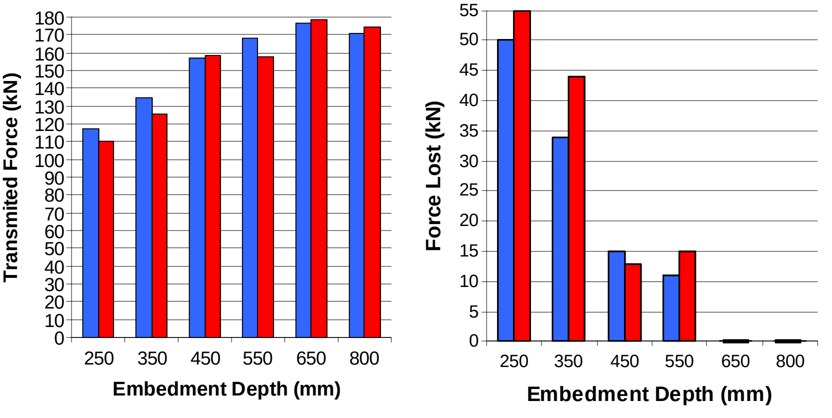


Figure 4: Push-in tests results

4.3 Slab Tests

With the objective of testing the proposed system in a slab, experimental specimens were produced, with 2300mmx2300mm and 100mm thick. The slabs were conceived to have punching shear failure. A reference slab (L1) was tested without strengthening. The test arrangement and the installation of the strengthening system is shown in Figure 5, and it followed the procedure described in section 2.

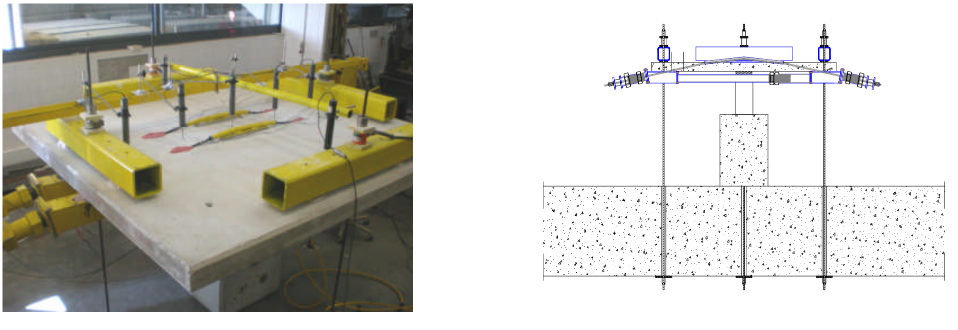


Figure 5: Test arrangement for a strengthened slab

The slab bottom flexure reinforcement consisted of a mesh of 6 mm diameter bars, spaced at 200 mm in each direction. The top flexure reinforcement consisted of a mesh of 10 mm diameter bars spaced at 60 mm in each direction. The column was simulated with a steel plate 200mmx200mmx50mm. The slab vertical deflections and the strains in three top reinforcement bars were monitored using displacement transducers and strain gauges. The magnitude of the applied load was obtained by four load cells positioned at the four strands that fixed the slab to the strong floor of the laboratory. The forces in the strands used to strengthen the slab were monitored using strain gauges. The strengthened slabs reached higher punching loads and when it was strengthened its deformations and cracking were reduced. This could be observed through the displacement transducers positioned in the top of the slab and in the strain gauges positioned in the top flexure mesh. The positioning of the strands in relation to the column was done accordingly to the results obtained by Ramos[4], about 50 mm (≈$d_p/2$) away from the column perimeter, so that these are effective towards improving punching shear failure.

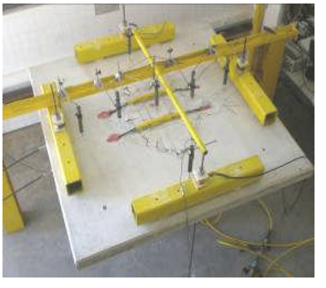


Figure 6: Punching shear failure of the strengthened slab

A summary of the obtained results is presented in the next table. In this table, the experimental failure load (V_{exp}) is compared with the values obtained using EC2[5] and ACI 318-08[6]. In the quantification of the punching resistance the mean values of the materials strengths, without partial coefficients, were used.

Model	$V_{deviation}$ (kN)	V_{exp} (kN)	Code	V_{eff} (kN)	V_{Rm} (kN)	V_{eff}/V_{Rm}
L1	0,00	190,95	EC2	190,95	203,58	0,94
			ACI 318	190,95	137,35	1,39
L2	63,96	272,86	EC2	208,90	207,14	1,01
			ACI 318	272,86	193,69	1,41
L3	55,99	254,74	EC2	198,75	204,04	0,97
			ACI 318	254,74	190,95	1,33

Table 2: Results of slab tests

In this table $V_{deviation}$ stand for the prestress deviation force, V_{exp} the experimental punching shear force, $V_{eff} = V_{exp}-V_{deviation}$ for EC2 and V_{exp} for ACI 318 (the restrictions for ACI 318 regarding mean in-plane compressive stresses were neglected), and V_{Rm} is the predicted failure load. It can be observed, from the results, that EC2 gives close results to the ones measured, instead of ACI-318 that is always conservative.

5. CONCLUSIONS

Regarding the development of this strengthening technique there was made an an experimental programme was made, based on pull-out tests, push-in tests and punching tests on slabs with 100 mm thickness. The average of the maximum elastic bond stresses obtained was of 6,3 MPa and the average of the maximum bond stresses was 13,6 MPa. From the push-in tests it can be stated that the transfer length for a load of 175 kN is about 650 mm. From the experimental tests in slabs it may be concluded that this strengthening technique allowed a punching resistance increase between 28% and 35% with only one way direction prestress and that the prestress made it possible to reduce deformations by 50%. It is possible to use EC2 to estimate punching resistance using this type of strengthening. There is ongoing research on this subject regarding long-term behaviour, different slab geometries and two way directions prestress.

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