DEVELOPMENT OF A DESIGN PROPOSAL FOR A FLAT SLAB STRENGTHENING SYSTEM USING PRESTRESS WITH ANCHORAGES BY BONDING

Duarte Faria, Válter Lúcio and António Ramos

UNIC, Civil Engineering Department, Faculdade de Ciências e Tecnologia, Universidade NOVA de Lisboa, 2829-516 Monte de Caparica, Portugal

Abstract

In this work, the development of a design proposal regarding the application of a new strengthening technique of flat slabs, consisting of post-tensioning with anchorages by bonding is presented. This design proposal is based in experimental tests results, namely, pull-out and push-in bond tests of prestress strands and slab punching tests, whose main results are presented. Taking into account the experimental results of the bond tests, it was possible to determine a bond stress/slip law for both, the transmition and pull-out stages, that enabled to draw simple design rules for the allowable transmition and maximum pull-out loads. Afterwards, and based in the previously determined bond stress/slip laws, a design proposal is presented that is able to predict the strand forces evolution, taking into account its free and bonded lengths, as the slab is loaded up to punching failure, turning possible the computation of the increase of the prestress deviation forces, reducing the effective punching loads, thus increasing the punching capacity.

Keywords: Punching, Bond, Strengthening, Post-tensioning

1 Introduction

In this work it is presented the development of a design proposal of an “active” strengthening technique that uses post-tensioning with steel strands, but instead of using external permanent anchorages, it uses anchorages by bonding embedded in the existing concrete element. In this paper the main results are presented in order to expose the development of the design proposal, once the detailed results of each stage of the experimental campaign have already been presented in previous papers Faria et al. (2011a,b) Although not concerning directly this paper, in a previous work, results considering post-punching behaviour were also presented in Faria et al. (2012).

2 System description

The strengthening system proposed here consists of introducing post-tensioning using anchorages formed by bonding a prestressing steel strand to the concrete. The strengthening procedure is based on the following stages (Fig. 1): drilling the slab (Fig. 1a) and setting up the strands (Fig. 1b), prestressing the steel with temporary anchorages (Fig. 1c), injecting with a bonding agent (Fig. 1d), releasing the provisional anchorages and transferring the prestress forces to the concrete (Fig. 1e). Prestress may be unidirectional or bidirectional and have several strands on each column side, or if the slab to be strengthened is a roof slab then steel strands may be positioned above the column. Deviators are only supported near the centre, above/close to the column and act as cantilevers. Regarding the equipment that is illustrated in Fig. 1, it consists of a strut capable of sustaining the horizontal component of the prestress force, two actuators at the ends of the strut and a deviator, positioned at the top of the slab. Only the deviator stays in the structure and thus must be embedded in the slab finishing. So, most of this equipment is not required once the bonding agent has been cured and it can be reused in other prestressing operations. Detailed information about the used equipment may be found in Faria et al. (2011b).

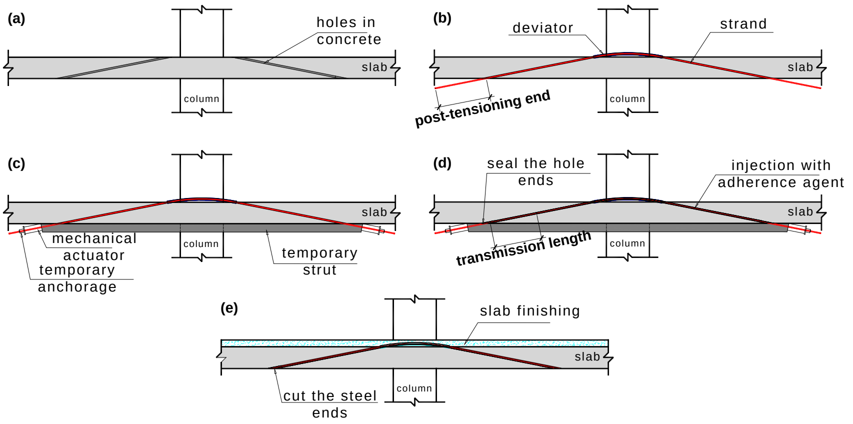

Fig. 1- System description

3 Experimental testing

Regarding the experimental investigation, whose objective was to study the strengthening technique efficiency, it was planned and executed an experimental tests campaign, divided in the following stages: pull-out and push-in tests of bonded steel strands Faria et al. (2011a) and slab punching tests Faria et al. (2011b). The main experimental results of each of the above referred stages are briefly described in the following sections.

3.1 Bond tests and bond behaviour model

Knowing the behaviour during the transmission and pull-out of bonded steel strands to concrete is of primary importance for the application of this strengthening technique, and so experimental tests consisting of pull-out and push-in tests were performed. These two types of tests were designed to simulate the bond behaviour that may be found in the present strengthening technique: pull-out tests simulate the behaviour of a strand when its tension is increased by loading on the slab; push-in tests simulate the behaviour of the strand when the prestress force, that is applied before injecting the hole with the bonding agent (the bonding agent used was HILTI’s HIT RE-500), is transferred to the concrete by bonding. From pull-out tests with a short embedment length (l=100 mm, l/d_s=6.6), where the assumption of a constant distribution of bond stress along the bonded length is acceptable, it was possible to define a local bond-slip law. In order to take into account the results scatter it was adopted an upper and lower bound laws with ±25% dispersion. The best fit local non-linear bond stress/slip law obtained is represented by Eq. (1) Faria et al. (2011a). The laws for upper and lower bound are obtained by multiplying Eq. (1) by 1.25 and 0.75, respectively, where δ is the relation between slip (s) and the strand diameter (d_s).

$$\tau_b(\delta)=C\cdot(\delta)^b \qquad \text{with C=13.4 and b=0.175} \quad \text{for } \delta\leq 5/15.2 \qquad (1a)$$

$$\tau_b(\delta)=11\,\text{MPa} \qquad \text{for } \delta>5/15.2 \qquad (1b)$$

where τ_b stands for the bond stress. Solving the governing equation of the bond phenomenon (Faria et al. (2011a); Balázs (1987)), theoretical results for the maximum pull-out loads and transmittable loads were obtained adopting the derived non-linear local bond/slip relationship. It was concluded that for the range of values studied l/d_s, it is acceptable the assumption of a constant bond stress. So, it was determined that the average of the various obtained individual bond stress values gives a value of 12.0 MPa with a corresponding COV of 0.18 (Coefficient of Variation) for pull-out results, and a value of 5.2 MPa with a COV of 0.21 for push-in tests (Faria et al. (2011a)).

3.2 Slab tests

Slab tests (Faria et al. (2011b)), whose main objective is to study the strengthening technique performance (Fig. 2), consisted on testing seven slabs up to failure by punching. A considerable decrease in displacements was observed at loads of about 80 kN when the prestress was applied. Displacement reduction and consequent crack width reduction is considerable for all strengthened models, meaning that this system is effective regarding serviceability limit states. Based on the slab displacements it is possible to compute slab rotations ψ and it was concluded that prestressed slabs present lower values of ψd for the same load level when compared to non strengthened slabs. From the experimental results it was found that this strengthening technique was effective regarding punching capacity, since the increase in punching capacity raised up to 54% when compared to unstrengthened slabs (Faria et al. (2011b)).

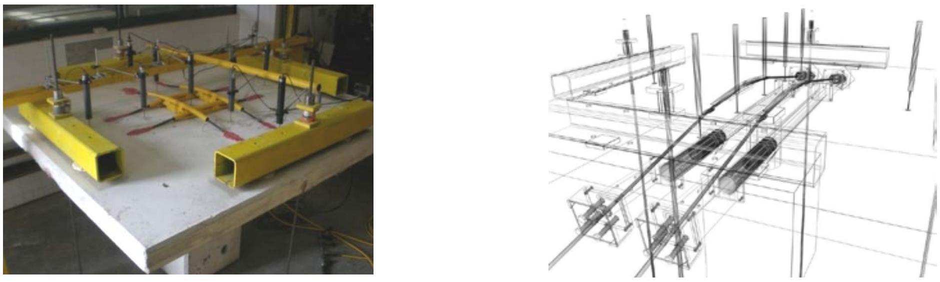

Fig. 2 – Slab tests view.

Punching design recommendations in MC2010 (2012) present a new design philosophy based on the critical shear crack theory developed by Muttoni, (2008) and Ruiz and Muttoni (2009), for slabs without and with transverse reinforcement, respectively. This theory allows the calculation of the slab capacity and its rotation at failure. In Faria et al. (2011b) it was shown that the average relation between experimental and computed values for ψd was very close to unity (with relatively small COV), while the average ratio between experimental effective loads and computed capacity of strengthened slabs was of 1.15 when using MC2010 (2012) level II of approach (Muttoni and Ruiz, (2012)). Using Level III of approach, similar results are reached.

4 Application of the bond behaviour model to the strengthening system

As seen in section 3.2 it is possible to compute ψd with good accuracy using the MC2010 (2012) methodology. The strand force increment is related to the slab rotation and therefore, final strand forces and deviation forces from prestress may be computed. The deformed and cracked shape of a loaded strengthened slab is shown in Fig. 3, where x stands for the depth of the compression zone in the concrete cross section, and ψ is the slab rotation. The strand elongation (Δlstrand) due to the slab rotation is given by Eq. (2).

$$\Delta \mathrm{l}_{\mathrm{strand}} = 2 \cdot \left(\psi \cdot \left(\mathrm{d}_{\mathrm{p}} - \mathrm{x}\right) - \Delta \mathrm{s}\right) = \frac{\Delta \mathrm{P}_{\mathrm{u}} \cdot l_{free}}{\mathrm{E}_{\mathrm{p}} A_p} \qquad (2)$$

where d_p represents the average effective depth of the strand, Δs represents the strand slip at the bonded anchorage due to ΔP_u (strand load increase) and lfree is the total free length of the strand. It is possible to compute Δs solving the governing equation of the bond phenomenon, using the local bond stress/slip law given by Eq. (1), as shown in Faria et al. (2011a) following Balázs (1987) work, allowing to compute the behaviour of a bonded strand being pulled-out, which is shown in Fig. 4 for several bonded lengths (l) up to the maximum possible load by bonding.

The presented behaviour (Fig. 4) may be represented by two branches: a common branch for all anchorage lengths up to a determined point, and a specific branch for each bond length (l_a). Taking into account Eq. (2), the specific behaviour of the bonded strand (Fig. 4) and the computed ψ using MC2010 (2012) methodology, it is possible to iteratively determine the strand force increment. This methodology is used to compute maximum prestress load at punching failure of the tested models. The average relation between the experimental and computed final prestress forces values is of 0.97 with a COV of 0.06, meaning that this methodology is adequate for the computation of strand load increase, and consequently the final deviation forces from prestress action. This allows an accurate prediction of the real punching capacity of the slab.

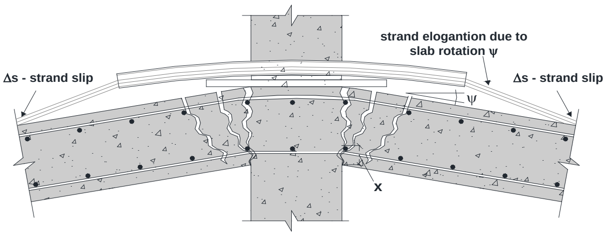

Fig. 3 – Strengthened slab deformed shape representation.

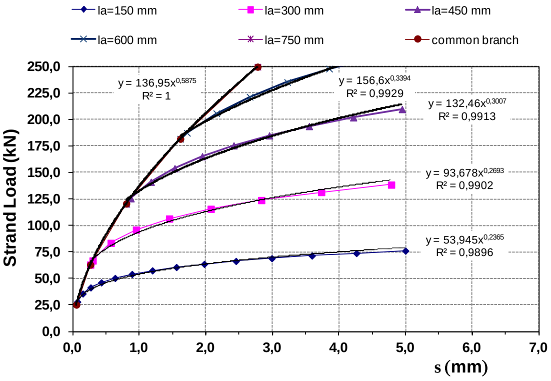

Fig. 4 – Strand pull-out behaviour.

5 Conclusions

The developed design proposal is able to correctly predict the bond behaviour of bonded steel strands during prestress transmission and pull-out of the strands, allowing the correct computation of the maximum capacity of the slab. The development of the design proposal was based in an extended investigation regarding the design, study and development of a new strengthening technique for flat slabs, consisting of post-tensioning with anchorages by bonding. It was shown that the strengthening technique is effective regarding ultimate and serviceability states, since it allowed a considerable increase in punching capacity and a considerable reduction of slab deformations

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