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Strengthening of flat slabs with post-tensioning using anchorages by bonding

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ABSTRACT

This work aims to study a new flat slab strengthening technique based on post-tensioning with anchorages by bonding using an epoxy adhesive. The main advantages of this technique over the traditional prestress strengthening systems that use mechanical anchorages are that it does not need external permanent anchorages, meaning that the forces are introduced into the concrete gradually instead of being localized, thereby preserving aesthetics and useable space. The seven tested slab models show that this technique meets its objective as it is able to reduce reinforcement strains at service loads by up to 80% if the strengthening technique is applied in two directions and slab deformations by up to 70%, consequently making crack widths smaller. It can also increase punching load capacity by as much as 51% when compared to non-strengthened slabs. The results are compared with the EC2 (2004) [20], ACI 318-08 (2008) [23] and MC2010 (2010) [21] provisions. The main conclusions are that this strengthening technique is effective regarding ultimate and serviceability states and that it represents an advance in RC slab strengthening techniques.

1. Introduction

The most common strengthening techniques used in slabs are related to increasing punching and/or flexural capacity and deformation control. The most widely used are the introduction of additional longitudinal reinforcement, with or without a section increase [1], strengthening by means of epoxy-bonded steel plates [2–4] or fibre reinforced polymers (FRP) [5–7], strengthening by replacing concrete with a higher grade concrete or fibre reinforced concretes [8,9], strengthening using concrete collars [10] or steel collars [8,10] and strengthening by introducing new shear reinforcements [8,10–14]. These techniques are known as 'passive' since the strengthening system is only mobilized when new deformations appear.

'Active' techniques reduce the existing deformations, cracking and stresses caused by bending and punching. Little research has been carried out on these techniques where steel strands are used, although they have already been used in practical applications [15,16]. More recently the use of prestressed FRP has become more popular as studies are being developed. The traditional active technique using prestressing steel strands and external permanent anchorages allows strengthening to flexure and punching simultaneously; deformation and cracking behaviour also improves. However, it also has some disadvantages that must be taken into account when deciding which technique to use. The technique described here sets out to eliminate some of the disadvantages of the traditional prestressing techniques.

This paper describes the experimental research conducted on a new reinforced concrete slab strengthening technique and presents the results obtained. This strengthening system consists of introducing post-tensioning using anchorages formed by bonding a prestressing steel strand to the concrete, using an epoxy adhesive agent for the purpose. Compared with the traditional strengthening using external prestressing, this technique does not need external permanent anchorages; it does not compromise aesthetics and useable space and, whereas in the traditional technique the anchorage forces are localized, in this system the anchorage forces are introduced gradually through bonding. This represents new knowledge and developments in the field of RC slab strengthening.

2. The system

2.1. Construction stages

The strengthening system proposed here consists of introducing post-tensioning using anchorages formed by bonding a prestressing steel strand and the concrete. The strengthening procedure is based on the following stages (Fig. 1): drilling the slab (Fig. 1(a)) and setting up the strands (Fig. 1(b)), prestressing the

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Nomenclature

Suffices

i	Individual
0	At the stage before transfer of prestress
initial and ini	Initial, after transfer
final and fin	Final, at maximum load in test
y and z	Directions of reinforcement

Notation

σ_{cp}	Average normal concrete stresses
ρ	Reinforcement ratio of bar reinforcement
ΔP	Prestress load variation
τ	Bond stress
$\tau_{\max}$	Average value for maximum bond stress
τ_{trans}	Average value for allowable transmission bond stress
d	Average effective depth
f_{ccm}	Concrete compression strength on $150 \times 150 \times 150$ mm^3 cubes
f_{ck}	characteristic concrete compression strength on 150×300 mm^2 cylinders
f_{cm}	concrete compression strength measured on 150×300 mm^2 cylinders
f_t	Ultimate strength of reinforcement
f_y	Yield strength of reinforcement
h	Slab depth
P	Prestress/strand load
u	Length of the perimeter control ($u = \Sigma c + 4\pi d$ in EC2, $u = \Sigma c + 4d$ in ACI 318-08, $u = \Sigma c + \pi d$ in MC2010)
c	Column side dimension
V	Load applied to the slab
V_{dev}	Vertical component of prestress forces crossing the control perimeter
V_{eff}	Effective punching load
V_{exp}	Experimental punching load
V_{Rm}	Mean value of punching resistance
E_s	Modulus of elasticity of steel
$F_{\text{trans}B}$	Transmitted force at B
F_{tB}	Force at the top in B
F_{bB}	Force at the base in B

steel with temporary anchorages (Fig. 1(c)), injecting with a bonding agent (Fig. 1(d)), releasing the provisional anchorages and transferring the prestress forces to the concrete (Fig. 1(e)).

Although the system represented in Fig. 1 is unidirectional, it can be bidirectional and have several strands on each column side, as long as certain restrictions (mentioned below) are respected regarding the prestress forces for effective punching calculation, which are limited by geometrical considerations (Section 6.2). If the problem is in the 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.

2.2. Equipment

Specific equipment is needed to apply the prestress. Most of this equipment is not required once the bonding agent has been cured and it can be reused in other prestressing operations. This equipment 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.

Steel struts, steel mechanical actuators and steel deviators were developed and built as described below. The steel strut was designed to be used in different lengths and to adjust to several prestress profiles. The strut is divided into two sections, one of which may be inserted into the other; it is adjusted by means of a thread and two screws used as a set. Fig. 2 illustrates the equipment.

As Fig. 2 shows, there are two parts in each end of the strut that connect to the mechanical actuators, described below. These parts give the strands the desired slope and are connected to the strut with bolts, for easier assembly The actuators are also shown in Fig. 2. These mechanical actuators are activated using a wrench and three bolts. This mechanical system allows the prestress forces to be maintained without loss while the epoxy adhesive is cured. The deviators give the appropriate curvature to the strand and are positioned above the slab, as shown in Fig. 2.

2.3. General considerations

As mentioned before this system allows strengthening to flexure and punching simultaneously and promotes an improvement regarding deformation and cracking behaviour. Normally these problems exist in slabs with relatively high slenderness and/or lack of reinforcement, or slabs with poor quality concrete due to construction and/or design errors. Relating to its installation we may say that two men took in average 2.5 h to drill the holes, assemble the system including the prestressing of the strands and injecting the bonding agent. As the steel struts are divided in two parts it is not difficult to lift them up, making its installation easy.

3. Background considerations

The bond between the steel strands and the concrete is important to this strengthening technique. An experimental programme of pull-out and push-in tests was developed to study it. These two types of test are 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. This experimental programme and its results have already been presented [17–19], and so, in this manuscript only a synopsis of the tests and its results is presented for better understating of the following developments.

Pull-out tests consist in pulling out the strands sealed with the bonding agent in a concrete block (Fig. 3). Five tests were performed for each embedment length, which were 100, 150 and 200 mm long. The experimental results from some pull-out tests are presented in Fig. 4. These figures show the relationship between the pull-out force and slip.

The push-in tests consisted in drilling a hole through a concrete block from one side to another and then inserting a high strength steel strand. Afterwards the strand was tensioned, with the help of a mechanical actuator, that allows the load to be maintained while the adhesive is injected and cured. After curing of the bonding agent the strands were de-stressed in the base end, and the load difference between both sides was borne by bond (Fig. 5). Afterwards the strand was pulled-out from the top side. Forces in each end were measured with load cells and slip was measured with the help of four displacement transducers diametrically opposed (two in each end of the strand). In each test, forces and