BOND BEHAVIOUR OF PRESTRESS STEEL STRANDS BONDED WITH AN EPOXY ADHESIVE AND A CEMENT GROUT FOR FLAT SLAB STRENGTHENING PURPOSES – EXPERIMENTAL STUDY

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ABSTRACT

In the last decades several types of connections between steel elements and concrete have been developed, namely those usually known as bonded anchors that employ as bonding materials, polymer adhesives, cementitious materials or a combination of the two. The objective of this study is to analyze the behaviour of 15.2 mm diameter prestress steel strands sealed with an epoxy adhesive and a cement grout. The understanding of this behaviour is essential for the development of a new kind of strengthening technique of reinforced concrete flat slabs applying prestress with anchorages by bonding herein described. To do so, it was developed an experimental study based in pull-out and push-in tests with different embedment length. Regarding pull-out tests the average values for τ_{el} *and* τ_{max} *were, respectively, 6.3 MPa and 13.4 MPa for the epoxy adhesive studied, and 1.7 MPa and 3.0 MPa, for the cement grout studied. From the push-in tests the average values for* τ_{piB} *were 5.4 MPa and 1.1 MPa for the epoxy adhesive studied and the cement grout, respectively. The pull-out test done after the push-in test also gave some useful information, since in this tests the average value obtained for* $\tau_{pull\text{-}out}$, *was 11.7 MPa. From these results it is clear that the cement grout, although is cheaper, has poor bond characteristics in relation to the epoxy adhesive.*

Keywords: Post-tensioning, Bond, Strands, Bonded Anchors, Strengthening, Reinforcement

INTRODUCTION

The main objective of this paper is to present the results of bond tests ("pull-out" and "push-in" tests), in order to characterize the bond behaviour of prestress steel strands sealed with an epoxy adhesive or a cement grout. The purpose is understand the bond behaviour of seven-wire strands of high strength steel with 15.2 mm nominal diameter, when sealed into concrete 18 mm diameter holes using an epoxy adhesive (the holes have a diameter 18% wider than the diameter of the strand), and when sealed into concrete 25 mm diameter holes using a cement grout (the holes have a diameter 64% wider than the diameter of the strand). The understanding of this behaviour is essential for the development of a new kind of strengthening of reinforced concrete flat slabs, using prestress with anchorages by bonding. The strengthening system proposed consists in the introduction of post-tension in reinforced concrete, with anchorages by bonding between a high strength steel prestress strand and the concrete. The strengthening system was already described in Faria[1].

BACKGROUND CONSIDERATIONS

The biggest issue of the proposed system is the bond behaviour of the strand embedded and sealed with an epoxy adhesive or a cement grout. As far as the authors are aware there hasn't been any research in strands embedded with an epoxy adhesive. Nevertheless there has been some research in the bonding of prestress steel strand sealed with cement grout[2,3]. An important reference is Walther's[3], who found that as less fine aggregates the grout has, less is the bond stress attainable. Values obtained for cement grout show that the bond strength of steel strands embedded in grout may be considerable less than in ordinary steel bars. In the pre-tension method used in concrete elements, Janney[4], in the mid 1950's, stated that the mechanisms that contribute to the bond transfer of the prestress are adhesion, friction and mechanical action. Nowadays these mechanisms are still accepted. In the bond behaviour of strands, after the adhesive component is lost, the bond stress increases with slip and the frictional component plays an important role, contrary to plain wires, where bond drastically drops after debonding[5]. The frictional component is also enhanced by some kind of mechanical action[5] due to the typical shape of the strand, characterized by helical outer wires around a straight centre wire.

Regarding the behaviour of steel anchors sealed with adhesives, it is important to mention the work of Cook et al.[6], who studied various design models for single adhesive anchors located away from concrete edges ($c \geq h_{ef}$) and compared to a worldwide test database of adhesive anchors. The results indicate that a model based on uniform bond stress along the anchorage length provides the best fit to that database and agrees with non-linear analytical studies (McVay et al.[7]) of the adhesive anchor system. The proposed uniform bond stress model by Cook et al.[1] is as follows:

$$N_u = \tau \cdot \pi \cdot d \cdot h_{ef} \qquad (1)$$

since the following limitations are met, $4.5 \leq h_{ef}/d \leq 25$, $13 \leq f_c \leq 68$ (MPa) and $1250 \leq A_b \leq 60000$. Where N_u represents the ultimate predicted load of the anchor, d stands for the diameter of the anchor, c for the edge distance, h_{ef} for the embedment length, τ is the bond stress associated with each product, f_c represents the concrete strength measured on 150 mm x 300 mm cylinders and A_b (mm^2) stands for the bonded area, calculated based on the anchor diameter (Eq. 2). Also the work by Zamora[8] on grouted anchors proved that the uniform bond model is able to correctly predict the ultimate load, although doesn't state explicit limits for its application.

$$A_b = \pi \cdot d \cdot h_{ef} \tag{2}$$

EXPERIMENTAL INVESTIGATION

"Pull-out" and "push-in" tests were executed for the characterization of bond behaviour. These two types of tests are intended to simulate the bond behaviour that may be found in the strengthening technique. 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 when the prestress force is released, and what is the maximum force that can be supported by the strand anchorage when it is pulled out.

MATERIALS PROPERTIES

To assess the strength of the concrete used in the production of the test specimens, compression tests on cubes of $150x150x150mm^3$ were carried out ($f_{cm,cube}$). These were tested at 28 days from the casting day and the average value obtained was of 25.7 MPa and 26.0 MPa for the "pull-out" and "push-in" models, respectively. The prestress strand was 15.2 mm diameter, 139 mm^2 cross section, with 273 kN of maximum force and 246 kN of proof force at 0.1%, average values. The epoxy adhesive used in this study is composed by an epoxy resin and a hardener. To assess the strength of the epoxy adhesive, both in bending and in compression, three prismatic specimens of 40x40x160 mm^3 were made. First the specimens were tested in bending[9] and after three half's of them were tested in compression[10]. The average results are presented in Table 1.

Table 1: Bending and compression tests results (epoxy adhesive)

Bending Tests			Compression Tests		
f_{pct} (MPa)	ε_{pct} (%)	E_f (GPa)	f_{pc} (MPa)	ε_{pc} (%)	E_{pc} (GPa)
49.10	2.39	2.06	108.79	4.60	2.37

Where f_{pct} represents the elastic tensile stress in bending, ε_{pct} the elastic tensile strain in bending, E_f the modulus of elasticity in bending, f_{pc} the maximum elastic compression stress, ε_{pc} the maximum elastic compression strain and E_{pc} the modulus of elasticity in compression.
The grout was composed by cement, a shrinkage controlling chemical and water. After the correct mixing, the grout was injected into the holes. To assess the strength of the cement

grout used in the bonding of the prestress steel strands, both in bending and in compression, six prismatic specimens of 40x40x160 mm^3 were produced. First these specimens were tested in bending[11] and after twelve half's of the specimens were tested in compression[12]. The average results are presented in Table 2.

Table 2: Bending and compression tests results (grout)

Bending Tests	Compression Tests
R_f (MPa)	R_c (MPa)
6.2	54.4

PULL-OUT TESTS

Models and Test Description

Pull-out tests consist of pulling out the strands sealed with the bonding agent in a concrete block (Fig. 1). The characteristics of the strand and the holes diameter were described above. An electro-pneumatic rotary-impact drill was used to drill the holes, which were afterwards cleaned through air blowing and brushing. The number and embedment depths tested were 5 for the 100 mm, 150 mm and 200 mm embedment depths for the epoxy adhesive, that results in the corresponding relations h_{ef}/d of 6.6, 9.8 and 13.2, respectively. Two tests with 250 mm embedment depths for the cement grout, results in h_{ef}/d of 16.4. The concrete blocks measured 600x600x800 mm^3, in order to have a concrete cover greater than h_{ef}.

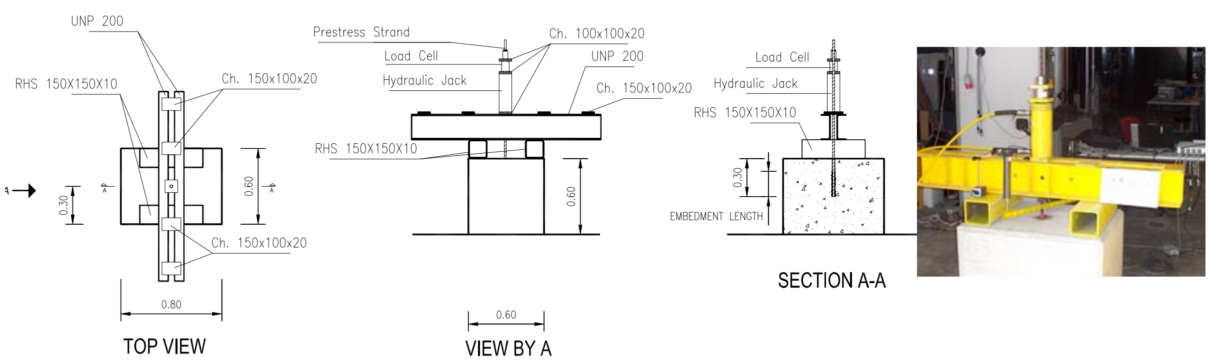


Fig. 1 - Pull-out test assembly

The force was measured with a load cell and the slipping with the help of two displacement transducers placed diametrically opposed. In the following, slip is the average of the measured displacements with the two displacement transducer deducting the elastic shortening of the strand along its length between the concrete surface of the measuring points. The strands were cleaned, in order to eliminate traces of rust, grease and dust. After this the epoxy adhesive or cementitious grout was injected or poured into the concrete hole, respectively, avoiding the formation of air bubbles. Right after, the strand was introduced with circular movements, in order to guarantee its full perimeter embedment. During the tests, the slipping of the strand in a rotating helical way, could be observed, always in the strand/bonding agent interface, corresponding to the shape of the surface of the strand.

Results Presentation and Discussion

Some results of the several pull-out tests are presented in Fig. 2, Fig. 3 and Table 3.

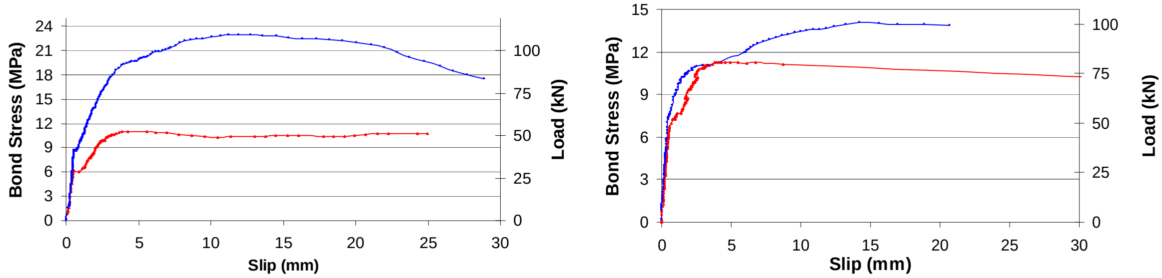


Fig. 2 Pull-out behaviour of two specimens for epoxy adhesive with 100 mm and 150 mm embedment depth

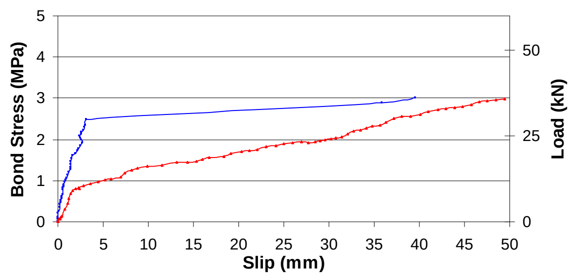
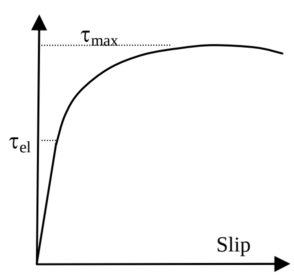


Fig. 3 Pull-out behaviour of two specimens for cement grout with 250 mm embedment depth

Table 3: Epoxy adhesive pull-out tests results

	Embedment Depth	τ_{el} Average (MPa)	τ_{el} Stand. Dev.	τ_{el} COV	τ_{max} Average (MPa)	τ_{max} Stand. Dev.	τ_{max} COV
Epoxy	200 mm	6.04	1.42	0.23	13.22	2.78	0.21
	150 mm	6.06	1.03	0.17	12.18	1.49	0.12
	100 mm	6.86	1.19	0.17	14.78	6.08	0.41
Cement	250 mm	1.70	1.10	0.67	3.00	----	----

Where COV = standard deviation/average of the values.

In Table 3, the average values of τ_{max} and τ_{el} are presented, where τ_{max} is the maximum bond stress and τ_{el} is the maximum elastic bond stress (at the end of the elastic behaviour), corresponding to the adhesion bond breaking. On the top left of Table 3 the typical behaviour in pull-out tests is represented. As in the case of reinforcing or threaded bars, it is reasonable to assume the uniform bond model when strands are used. From the results presented, it may be said that the cement grout presents poor bond properties related to the results obtained with the studied epoxy adhesive.

PUSH-IN TESTS

Models and Test Description

The push-in tests consisted in drilling a hole passing through a concrete block, from one side to the other, and introducing a high strength steel strand. Afterwards the strand was tensioned, with the help of a manual jack, that enables to maintain the load while the adhesive is injected, in the gap left between the strand and the walls of the hole, and cured. In the case of the cementitious grout, the holes were previously saturated with water for a minimum of 24 hours. The cementitious grout was injected in damp holes, and cured according to the manufactures procedures. After curing of the bonding agent the strand is unstressed gradually on the bottom end, and the difference in load between both sides is supported by bonding (Fig. 4). Afterwards the strand was pulled-out from the top side.

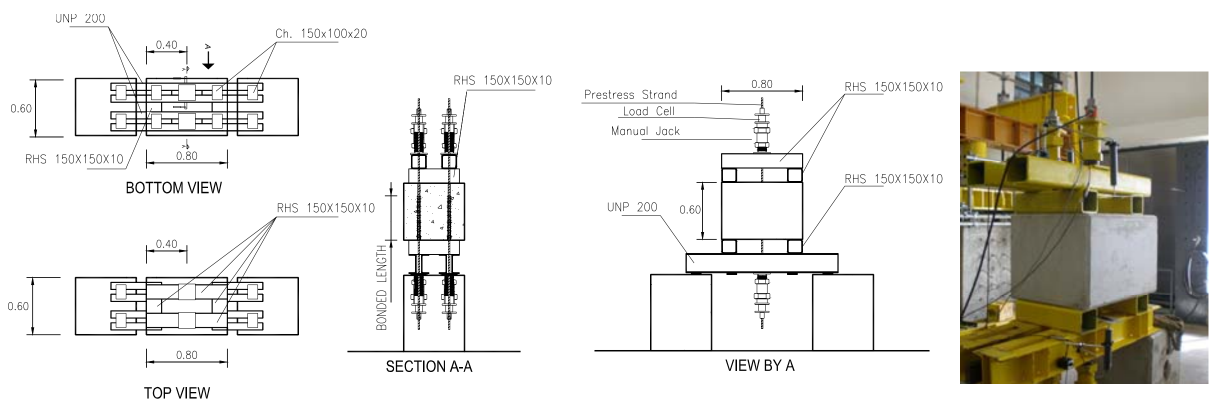


Fig. 4 Push-in test assembly

The drilling method and the diameter of the holes was the same as in the pull-out tests. Two tests were performed for each embedment length (from 250 mm, 350 mm, 450 mm, 550 mm, 650 mm and 800 mm), for the epoxy adhesive and two tests for an embedment length of 550 mm for the cement grout. The epoxy adhesive and the cementitious grout were injected throught an injection tube positioned in the sealed bottom of the hole, from bottom to top, avoiding the formation of air bubbles, until the adhesive was expelled from the top, and the excess was removed. Forces in each end were measured with load cells (Fig. 4) and slipping with the help of four displacement transducers diametrically opposed (two in each end of the strand) (Fig. 4). In the following, slip is the average of the displacements measured with the two displacement transducer deducting the elastic deformation of the strand, in each end (free end-bottom, fixed or dead end-top). During the tests the slipping of the strand in a rotating helical way could be observed, always in the strand/bonding agent interface, corresponding to the shape of the strand surface.

Results Presentation and Discussion

In each test, forces and displacements were measured continuously, making it possible to determine the bond stress and slip in each side. As Abrishami[13] suggested, a uniform distribution of the bond stresses along the bonded length was assumed. For its calculation the nominal diameter of the strand was used, since the bond failure occurred in the interface between the steel and the bonding agent .

$$\tau_{pi} = \frac{F_{fixed} - F_{free}}{\pi\, d\, h_{ef}} \qquad (2)$$

Where τ_{pi} represents bond stress, F_{fixed} represents the force measured in the fixed end (top), F_{free} represents the force measured in the free end (bottom). Some results of the several pull-out tests are presented in Fig. 5. The real h_{ef} was measured in order to compute τ_{piB} accurately. For each specimen three graphs were drawn, one that relates bond stress/transmitted force with slip in each end, another that relates free end slip with fixed end slip and at lasty one that relates F_{fixed} with F_{free}.

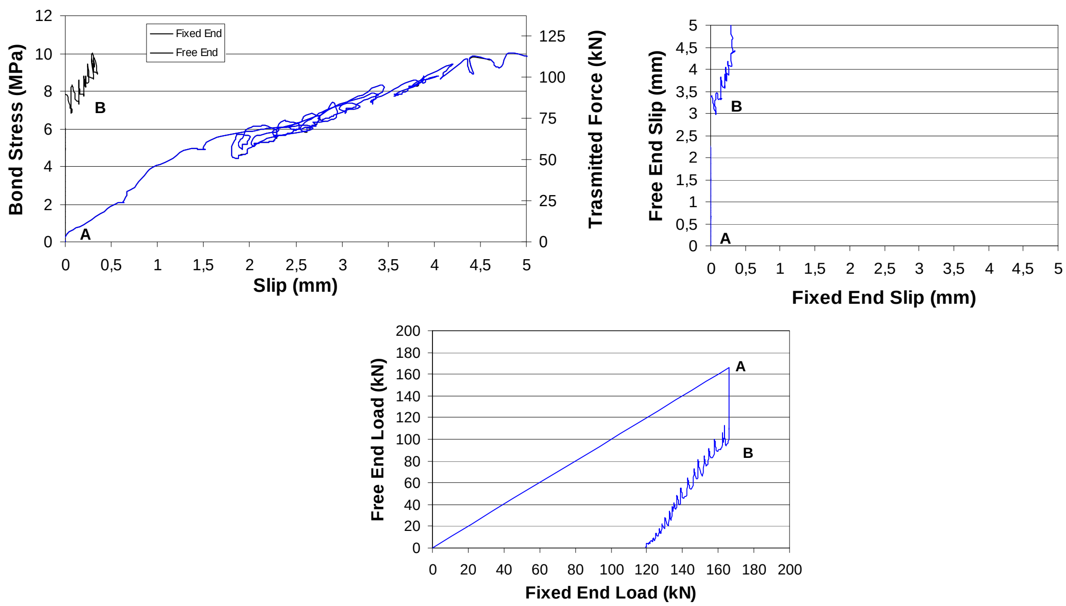


Fig. 5 Push-in test results, one specimen for epoxy adhesive with 250 mm embedment depth.

Point A refers to the beginning of the test, and point B refers to the point where fixed end load starts to be reduced and fixed end slip begins. Point B refers to the point where τ_{pi} is calculated, referring to the maximum bond stress that may be assumed to transmit a certain amount of load by bonding without force losses in the fixed end (τ_{piB}). The values of τ_{piB} are presented in Table 4.

Table 4: Epoxy adhesive and grout push-in tests results

	Specimen	Average Initial Load (A) (kN)	Average Load in(B) Free End (kN)	Average Slip in (B) Free End (mm)	Average τ_{piB} (MPa)
Epoxy	250 mm	165.5	104.5	1.6	5.4
	350 mm	169.5	84.8	0.7	5.2
	450 mm	172.5	41.1	1.1	6.3
	550 mm	176.0	57.1	0.7	4.6
	650 mm	178.0	10.7	2.0	5.5
	800 mm	171.5	0.0	0.2	---
Cement	550 mm	180.0	151.5	0.2	1.1

The average value for τ_{piB} is of 5.4 MPa for the epoxy adhesive and 1.1 MPa for the cement grout. From the results presented, we may say that the cement grout presents poor bond properties related to the results obtained with the studied epoxy adhesive. Epoxy adhesive allows the transfer of a certain load in a length about five times less than cement grout. The tests with the cement grout shows that it is not an adequate product to perform the anchorage technique proposed, and that the epoxy adhesive is clearly advantageous, as concluded, also, in the pull-out tests. As stated before, after this phase of the test, in the epoxy adhesive, the strands were pulled-out from the top . The maximum loads and bond stresses attained (calculated based on the bond uniform model, Eq. (1)) are presented in Table 5.

Table 5: After push-in, pull-out tests results, for the epoxy adhesive

Specimen	Average Pull-Out load (kN)	Average $\tau_{pull\text{-}out}$(MPa)
250 mm	136.0	11.9
350 mm	195.2	12.0
450 mm	236.0	11.3
550 mm	Strand Failure	---
650 mm	Strand Failure	---
800 mm	Strand Failure	---

Where $\tau_{pull\text{-}out}$ represents pull-out bond stress after the push-in test stabilization takes place. The average value for $\tau_{pull\text{-}out}$ is of 11.7 MPa with a standard deviation of 0.37 and coefficient of variation of 0.03. Comparing average values for $\tau_{pull\text{-}out}$ (11.7 MPa) with values obtained and presented in Table 3 (average of epoxy adhesive of 13.4 MPa), it may be stated that the injection in the push-in tests is not as effective as the injection in the pull-out tests Although the test with 450 mm does not meet the limitations for Eq. (1), the uniform bond model provided values of the same magnitude of the others (250 mm and 350 mm). As in the strengthening system the procedure for the installation of prestress follows the procedure used in the push-in tests, the values that should be kept in mind for the application of the epoxy adhesive are those from Table 4 and Table 5.

CONCLUSIONS

From the results obtained with the pull-out and push-in tests it is possible to state the following:

Regarding pull-out tests the average values for τ_{el} and τ_{max} were, respectively, 6.3 MPa and 13.4 MPa for the epoxy adhesive studied, and 1.7 MPa and 3.0 MPa, respectively, for the cement grout used. From these results it is clear that the cement grout, although is cheaper, has poor bond characteristics in relation to the epoxy adhesive.

From the push-in tests the average values for τ_{piB} were 5.4 MPa and 1.1 MPa for the epoxy adhesive and the cement grout, respectively. Once again it is seen that the cement grout has poor bond characteristics in relation to the epoxy adhesive, in the prestress transmission situation. Comparing these values to τ_{el} obtained from the pull-out tests, that were supposed to be similar since they correspond to the adhesion bond breaking, it is seen that the results from push-in tests are inferior. This may be explained by the fact that there is a considerable difference between the injection procedures in both tests. As in the push-in tests the bonding agent is injected after the insertion of the strand, is not as easy as it is in the pull-out tests to guarantee a total involvement of the bonding agent in the strand. The pull-out test done after the push-in test also gave some useful information, since in these tests the average value obtained for $\tau_{pull\text{-}out}$, was 11.7 MPa, somewhat inferior than the 13.4 MPa measured in the pull-out tests. This value (11.7 MPa) is approximately 13% less than the value measured in pull-out tests (13.4 MPa). Also the value for τ_{piB} measured in push-in tests (5.4 MPa) is approximately 14% inferior than the value measured in pull-out tests (6.3 MPa). This may lead to the conclusion that the injection procedure implies a reduction of efficiency in bond stress of 13.5%.in average

As in the normal situation, where strands are embedded in a concrete element, bond behaviour is based in adhesion, followed by the development of friction, and this friction is enhanced by some kind of mechanical action due to the the strand shape, characterized by helical outer wires around a straight centre wire. In this case, the adhesion component is significant, contrary to the normal situation (concrete). The Poisson effect is not important in both studied products since values obtained for τ_{piB} and τ_{el}, are similar. If that effect was significant values for τ_{piB} would be much different. This can be ascribed to the low stiffness of the epoxy adhesive, preventing the development of radial stresses, and to the low friction capabilities of the cement grout since, without good friction properties, there are no conditions to the development of the Poisson effect.

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