

The influence of hole surface treatment and confinement level in the connection capacity between RC footings and strengthening micropiles

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ABSTRACT

The building rehabilitation assumes presently great importance in construction. Retrofitting and strengthening of reinforced concrete (RC) buildings and bridges foundations is often required in this situation. One of the most used solutions is the application of micropiles.

In this context, the connection between the micropile and the existing RC footing is extremely important. An adequate understanding of the connection behaviour, namely bond and load transfer mechanisms, is crucial for structural design. One of the most used solutions in foundation retrofit with micropiles consists in applying micropiles through pre-drilled holes, which are filled with non-shrinking grout to ensure the bond between the micropile and the existing foundation. In this type of connection, the load transfer mechanisms depend on the bond stress at the steel / grout and grout / concrete interfaces.

The study herein presented describes the behaviour of grout / concrete interfaces. This study aims to assess the influence of the roughness of interface and the influence of different confinement levels in the connection behaviour. The conclusions are based in the observation of 26 specimens tested using 4 different types of hole surface treatment and 5 different confinement levels. Several recommendations are drawn to help designers in practice.

Key words: Micropile, foundation, concrete, retrofit, rehabilitation, building, bridge.

1. INTRODUCTION

The use of shear rings at micropile heads is currently used to increase the capacity in grouted connections between these and the existing concrete foundation. In this situation, the compression force at the micropile head is transmitted by compression struts to the concrete foundation.

In order to guarantee an adequate bond strength at the grout / concrete interface, the hole surface must be properly prepared. One of the solutions currently used, when textured micropiles are used, is to perform an indented surface in the pre-drilled hole of the existing foundation to prevent failure at grout / concrete interface since an active or passive confinement is assured. Another common procedure is to increase the surface roughness of the pre-drilled hole to achieve a better bond.

The study herein presented describes the behaviour of grout / concrete interfaces aiming to assess the influence of the roughness of interface and the influence of different confinement levels in the connection behaviour.

2. PAST STUDIES

In a previous research study recently conducted by Veludo (2013) several compression tests (by push-out) were performed using textured micropiles inserts grouted in RC footings ($450 \times 450 \times 500 \text{ mm}^3$) to study the influence of the following parameters on the bond strength at the steel/grout/concrete interfaces: (i) the hole diameter (D_h), adopting 82, 92, 102 and 122 mm; (ii) the embedment length (L_e), adopting 200, 275 and 350 mm; (iii) the surface roughness of the hole, adopting a wire-brushed and indented surface; and (iv) the level of active lateral confinement (P_e), adopting 240, 360 and 480 kN for the compression force.

In order to enable those different confinement levels of the RC footings, eight Dywidag bars were used, four in the longitudinal direction and four in the transversal direction. The micropile inserts were produced using 60 mm API N80 steel tube, grade 760/860 MPa (values obtained from tensile tests), with 6 mm thickness, reinforced with a 16 mm grade 500/600 MPa Dywidag bar. Steel shear rings were welded to each micropile. Four rings were adopted, with 75 mm spacing, a thickness of 5.5 mm and 5 mm height.

A concrete mix with a measured compressive strength of 32.5 MPa and a Young's modulus of 35 GPa, at 28 days, was used to produce the RC blocks that simulates the existing foundation. A grout with a measured compressive strength of 53.4 MPa and a Young's modulus of 14.2 GPa, at 28 days, and a water-cement ratio of 0.40 was adopted to bond the micropile to the RC block. In Figure 1 is presented the geometry of the specimens and the adopted test set-up.

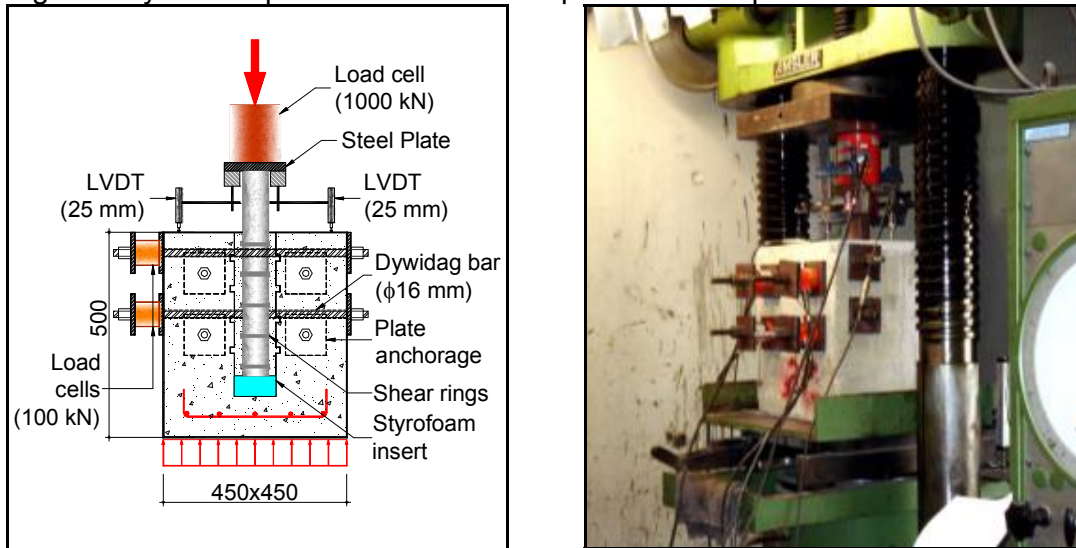


Figure 1 – Geometry of the specimens and test set-up (Veludo, 2013)

In tests performed with an indented hole surface and various levels of confinement three different failure modes were observed (see Figure 2):

- (1) Monolithic failure of RC blocks by internal crushing of the bulk (observed in specimens with an indented hole surface and without active confinement).
- (2) Bond failure at grout / concrete interface (observed in specimens with wire-brushed holes and active confinement);

- (3) A mixed bond failure at steel / grout and grout / concrete interfaces (observed in specimens with an indented hole surface and active confinement);

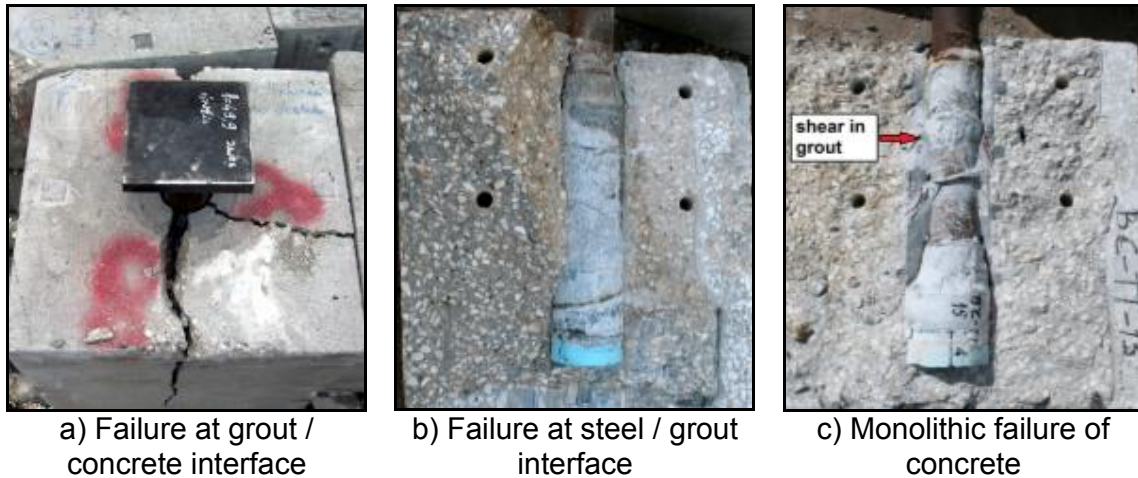


Figure 2 – Failure modes observed in compression tests performed with textured micropiles (Veludo, 2013)

The results obtained from tests performed with textured inserts are presented in Table 1 and Figure 3. In Figure 3a) are presented the average load / displacement curves; in Figure 3b) the load / displacement behaviour for tests performed with different hole surface treatment and the lowest level of confinement are compared; in Figure 3c) the results from tests with indented hole surface and with different levels of confinement are shown; and finally, Figure 3d) illustrates the variation in bond strength with the level of confinement.

Table 1 - The complete push-out test program.

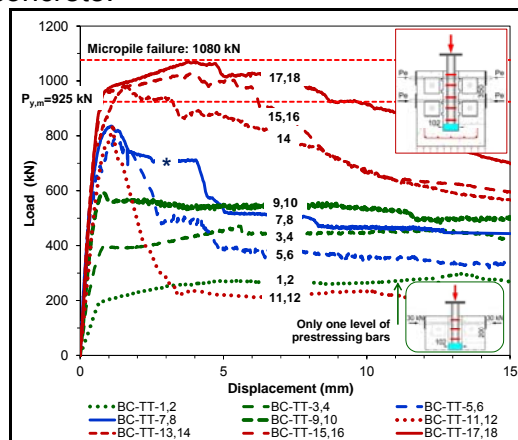
Test	Hole surface	D_h (mm)	L_e (mm)	P_e (kN)	P_u (kN)	f_b (MPa)	δ_u (mm)	K_0 (kN/mm)	δ_y (mm)	δ_u/δ_y
C 1,2	Wire brushed	102	200	120 (Level 1*)	301.8	4.71	13.55	275	1.09	12.4
C 3,4	Wire brushed	102	275	240 (Level 1)	486.3	5.52	8.38	775	0.66	12.6
C 5,6	Wire brushed	102	350	240 (Level 1)	802.6	7.16	1.33	1482	0.55	2.4
C 7,8	Wire brushed	92	350	240 (Level 1)	864.6	8.55	2.54	1548	0.56	4.5
C 9,10	Wire brushed	122	350	240 (Level 1)	638.4	4.76	4.61	1130	0.57	8.1
C 11,12	Grooved	102	350	0 (Level 0)	842.1	10.79	1.15	1075	0.78	1.5
C 13,14	Grooved	102	350	240 (Level 1)	980.5	12.56	1.58	1529	0.62	2.6
C 15,16	Grooved	102	350	360 (Level 2)	1040.4	13.33	4.54	1544	0.67	6.8
C 17,18	Grooved	102	350	480 (Level 3)	1097.6	14.06	5.66	1611	0.68	8.3

D_h – Hole diameter; L_e - Embedment length; P_e - Confinement level; * - only one layer of confinement P_u - Peak load; f_b - bond strength; δ_u - total displacement of micropile inside the grout at peak load; K_0 - initial stiffness; δ_y - displacement at yield; δ_u/δ_y – ductility

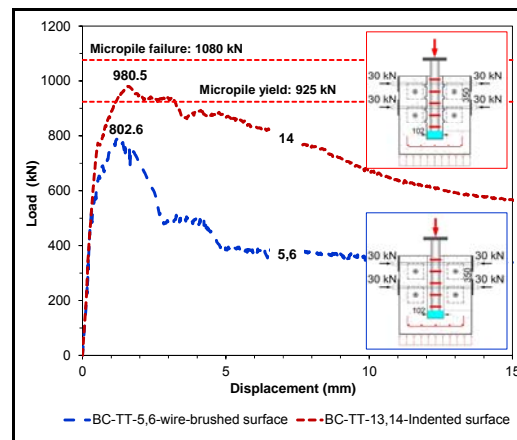
From Figure 3a) it is clear that a different behaviour is obtained for the connection when any of the keys parameters is modified (roughness of the hole surface; hole diameter; embedment length; and level of active confinement). According to Figure 3b) and the observed failure modes, the roughness of the hole surface has a significant influence on the behaviour of the connection when textured

micropiles are used. For specimens with wire-brushed holes, failure occurs at the grout / concrete interface, whereas for specimens with indented holes a mixed bond failure is observed. To prevent failure at the concrete / grout interface, the confinement must be effective along the entire embedment length of the insert and adequate indentation must be made at the hole surface. For long embedment lengths, brittle failure is observed in specimens with wire-brushed holes, whereas for specimens with indented holes, a ductile response is observed. Moreover, the latter always provides higher load capacity, reaching 20% capacity increase. In practice, if the reinforcement of the existing RC footings is insufficient, active lateral confinement must be provided to prevent monolithic failure. Moreover, this also reduces and distributes cracking, thus increases the ductility of the connection.

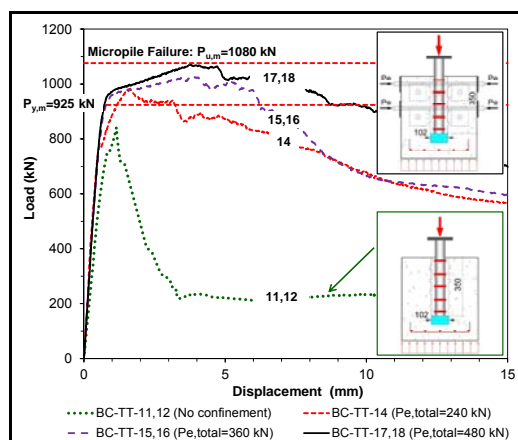
In the experimental study performed by Veludo (2013) it was concluded that for textured micro-piles the key parameters affecting the bond strength are: (1) the surface roughness of the hole; (2) the hole diameter; (3) the embedment length; (4) the level of active and passive confinement; and (5) the strength of the grout and concrete.



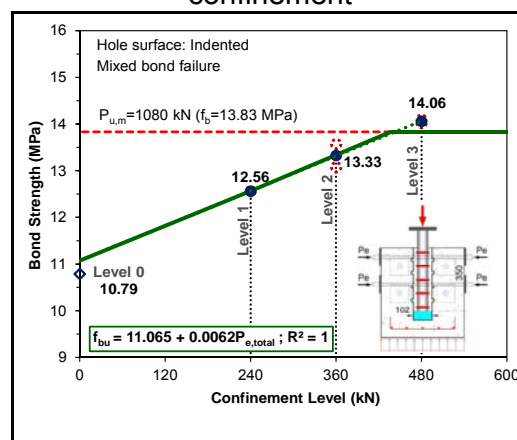
a) Average load / displacement curves for all the tests performed with textured inserts



b) Load / displacement curve for specimens with different hole surface treatment and lowest level of confinement



c) Load / displacement curves in specimens with an indented hole surface and different levels of confinement



d) Bond strength variation with confinement level

Figure 3 – Results from compression tests performed with textured inserts (Veludo, 2013)

One of the most relevant studies with micropiles grouted in existing RC footings was performed by Gómez et al. (2005), using compression tests to evaluate the connection capacity considering smooth and textured inserts. Holes were drilled using a jack hammer to guarantee sufficient bond at grout / concrete interface. The reinforcement represented approximately 1% by volume of the concrete footing. For textured inserts weld beads were created around the perimeter of two micropiles to simulate shear rings with 150 mm spacing and a width varying between 10 mm and 12.5 mm. The failure of the connection occurs at steel / grout interface. The connection capacity for textured micropile inserts is mostly controlled by frictional effects due to the dilation caused by the relative slip at the steel / grout interface. It was concluded that the use of textured micropiles increases both capacity and ductility of the connection. The authors states that the connection capacity can be estimate considering the confining force provided for the reinforcement during yield and the friction at steel/grout interface.

The results of the Load Transfer Mechanism in Rock Sockets and Anchors are presented in the EPRI Report EL-3777 (1984). In those systems four modes of failure are observed: 1) failure in steel; 2) failure is steel / grout interface; 3) failure at grout / rock interface; and 4) failure in rock mass. The study performed by the authors was focused on the two latest modes of failures. As the authors concluded, the third mode is the most prevalent one. The connection capacity depends on the resistance of this interface and is a function of the material strength, bond, friction and interlocking. The behaviour of such connection can be explained in three stages: 1) elastic with intact interface; 2) secondary after a relative slip at the interface; and 3) residual after large displacement. The roughness of the interface has a significant influence in the connection behaviour and its quantification is very important. A smooth surface leads to a brittle behaviour and a rough surface leads to a ductile behaviour.

Transverse reinforcement is a common practice used for concrete confinement. Figure 4 shows two different arrangements of transverse reinforcement. According to Model Code 2010 and Appleton (2012) the confining stress for circular cross-sections with circular hoops (see Fig. 4a) can be calculated with the expressions:

$$\sigma_2 = w_c \cdot f_{cd} \cdot \left(1 - \frac{s_c}{d_c}\right) \quad (1)$$

$$w_c = \frac{A_{sc} \cdot f_{yd}}{d_c \cdot s_c \cdot f_c} \quad (2)$$

and for rectangular cross-sections (see Fig. 4b) by the expressions:

$$\sigma_2 = w_c \cdot f_{cd} \cdot \left(1 - \frac{s_c}{a_c}\right) \cdot \left(1 - \frac{s_c}{b_c}\right) \cdot \left(1 - \frac{\sum b_i^2 / 6}{a_c \cdot b_c}\right) \quad (3)$$

$$w_c = \min \left\{ \frac{A_{sy} \cdot f_{yd}}{a_c \cdot s_c \cdot f_{cd}}; \frac{A_{sz} \cdot f_{yd}}{b_c \cdot s_c \cdot f_{cd}} \right\} \quad (4)$$

where w_c is the mechanical volumetric ratio of transverse reinforcement; f_{cd} is the design value of unconfined compression strength of concrete; s_c is centre-to-centre spacing of transverse reinforcement; d_c is the diameter of the confined area; A_{sc} is the total area of transverse reinforcement; f_{yd} is the design value of yield strength of transverse reinforcement; a_c and b_c is the sides of the confined area; b_i is the centre line spacing along the section parameter of longitudinal bars engaged by a stirrup

corner or across-tie; and A_{sy} and A_{sz} are the total area of transverse reinforcement in each direction.

The total confining force provided for each stirrup is given by the following expression:

$$F_t = 2A_{sc} \cdot f_{yd} \quad (4)$$

where A_c is the total area of transverse reinforcement; f_{yd} is the design value of yield strength of transverse reinforcement.

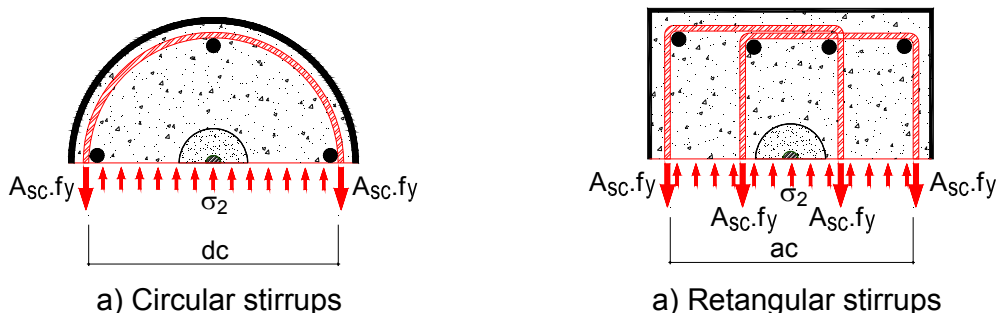


Figure 4 – Confinement provided by transverse reinforcement (Appleton, 2013)

As can be seen from the expressions above, the main parameters involved in the confinement are the ratio of transverse reinforcement (the ratio of volume of hoops to the volume of confined core of the member), the yield strength of transverse reinforcement, the compressive strength of concrete and the spacing of hoops.

3. EXPERIMENTAL PROGRAM

The experimental study herein presented was conducted to investigate the influence of both surface hole treatment and passive confinement. Different surface conditions and different amounts of transverse reinforcement were considered. The test specimens were composed by cylindrical concrete blocks with a centre hole where a reinforcing bar was grouted. Combining the studied parameters, eight different situations were defined and, for each one, three specimens were tested in compression (push-out) to evaluate the influence of the parameters previously referred to on the bond strength at grout / concrete interface. Besides these, all the remaining parameters were kept constant: grout type and strength; concrete type and strength; reinforcing steel bar; and loading.

3.1 Materials

A preliminary initial study was developed to define the grout mixture. Five mixtures with different water / cement ratio (0.40, 0.39, 0.38, 0.37 and 0.36) were considered. A Portland cement type I 42.5R and two admixtures, a high range water reducer and an expansive admixture, representing 1% of cement weight were adopted. The selected grout was the one corresponding to the mixture obtained with the lowest water/cement ratio, presenting the better mechanicals properties and also an adequate flowability for grouting.

The following mix proportions were adopted, per cubic meter: 1415.5 kg of Portland cement type I 42.5R; 509.6 l of water; 14.2 kg of modified polycarboxylate admixture (high range water reducer); and 14.2 kg of expansive admixture. The compressive strength at 28 days was evaluated, according to European standards NP EN 196-1 (2006), NP EN 445 (2008) and NP EN 446 (2008), considering the

average of three prismatic specimens ($40 \times 40 \times 160 \text{ mm}^3$) tested in bending. The Young modulus was determined according to standard E 397 (1993), considering also the average of another set of three prismatic specimens ($40 \times 40 \times 160 \text{ mm}^3$). The adopted grout presented, at 28 days, a compressive strength of 71.7 MPa and a Young modulus of 15.2 GPa.

The specific gravity of the grout was 19.2 kN/m^3 . The following properties were also measured, according to European standards NP EN 445 (2008) and NP EN 446 (2008): a flowability of 16 s and an air content of 1.0%. According to European standard NP EN 447 (2008), these results were considered acceptable.

The adopted concrete was a ready-mix with a compressive strength of 20.0 MPa at 28 days of age. According to European standards NP EN 12350-1 (2002), NP EN 12390-1 (2003), NP EN 12390-2 (2003) and NP EN 1008 (2003), twelve cubic specimens of 150 mm were produced to evaluate the compressive strength at 7 and 28 days of age. These tests were performed according to European standards NP EN 12390-3 (2003) and NP EN 206-1 (2007). A slump test was performed to measure the consistency of the fresh concrete according to European standard NP EN 12350-2 (2002), presenting a slump class S3.

The micropile inserts were comprised by a S500 steel bar with a diameter of 25 mm. For the passive confinement, stirrups were provided adopting S400 steel bars with a diameter of 6 mm.

3.2 Test Specimens

The geometry adopted for the specimens tested under compression (push-out) is presented in Figure 5. Each specimen comprises a cylindrical concrete block with a diameter of 303 mm and a height of 300 mm obtained by cast against a PVC formwork. The centre hole presents a diameter of 75 mm, obtained using a central PVC tube as formwork, where a concentric reinforcing bar is placed and grouted.

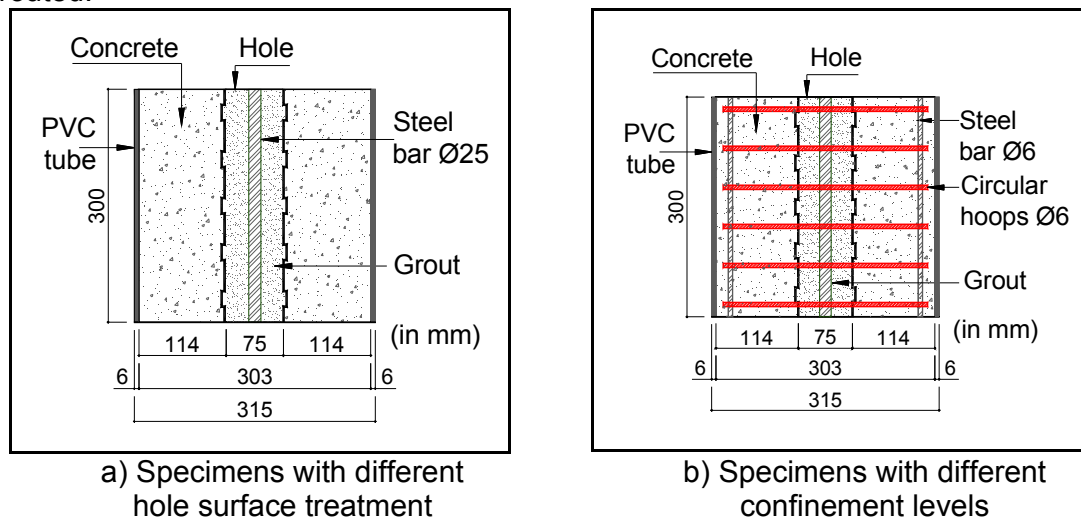


Figure 5 – Geometry of the specimens

Eight different situations were presented (Table 2). Four treatments were adopted for the hole surface of specimens without transverse reinforcement: (1) Left as drilled; (2) Sandblasted; (3) Helical (spiral indentation); and (4) Indented. The left as drilled surface condition was obtained by cast against the PVC formwork without further treatment. The sandblasted surface condition was simulated by glued sand on

the formwork. The indented surfaces were obtained by creating an irregular shape in the hole surface. The grooves for the indented and helical hole surfaces were of 1,25 cm height and 1 cm depth.

Assuming that the indented surface gives the highest bond strength, another four situations were considered adopting an indented hole surface but with variations in the transverse reinforcement: (1) 3 stirrups; (2) 4 stirrups; (3) 5 stirrups; and (4) 6 stirrups. Therefore, four different confinement levels were considered.

Table 2 – The complete test program

Specimen	Hole Surface Treatment	Transverse Reinforcement
L1 - L3	Left as drilled	No confinement
R1 - R3	Sandblasted	No confinement
H1 - H3	Helical	No confinement
A1 - A3	Indented	No confinement
C3.1 - C3.3	Indented	3 stirrups (s=130 mm)
C4.1 – C4.3	Indented	4 stirrups (s=87 mm)
C5.1 – C5.3	Indented	5 stirrups (s=65 mm)
C6.1 – C6.3	Indented	6 stirrups (s=52 mm)
T1-T2	Indented	6 stirrups (s=52 mm)

s = spacing of the transverse reinforcement

Figure 6 presents the main five stages of the test specimens production: stage (1) - PVC tubes with 315 mm, 75 mm diameter and 300 mm height were used for formwork (Fig. 5a); stage (2) - the hole surface treatment was prepared on the internal formwork tubes (75 mm diameter), prior of the concrete cast (Fig. 5b). The sandblasted treatment was simulated with glued sand on the tube surface (Fig. 5c). For the spiral indented surface, a rope sealed with silicone was place around the tube in a spiral shape (Fig. 5d). For the indented surface, polystyrene rings were made and glued around the tube (Fig. 5e); stage (3) - concrete was cast and vibrated (Fig. 5f); stage (4) - after one week of indoor curing the inside formwork was removed and the steel reinforcing bar was positioned into the holes and the sealed with grout (Fig. 5g); and stage (5) - finally, the top of grout pocket was capped with high adhesive strength to ensure a parallel and smooth surface (Fig. 5h).

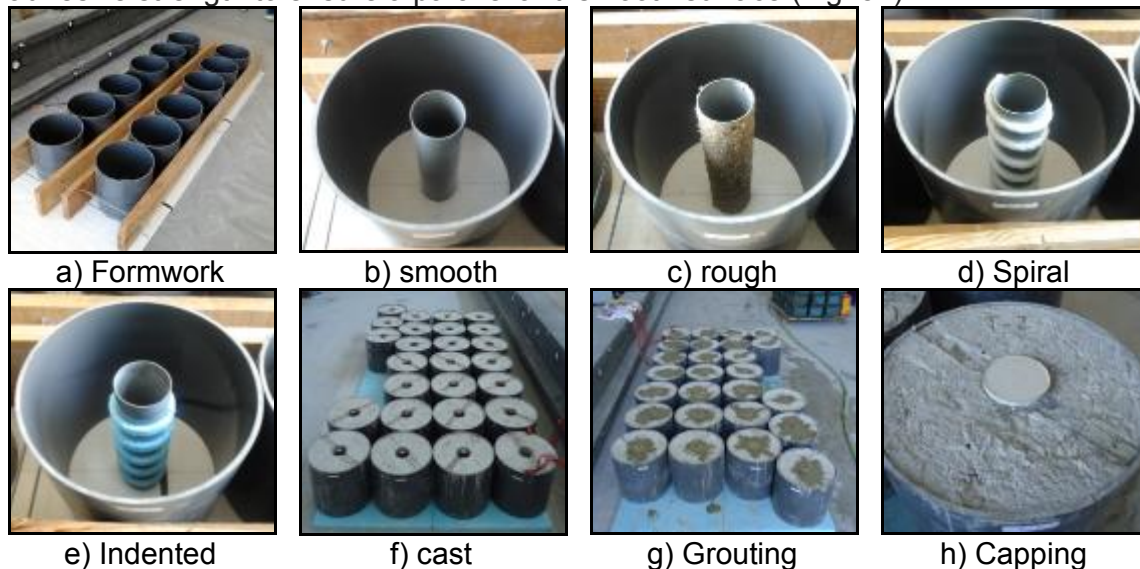


Figure 6 – Preparation of the test specimens

3.3 Test set-up and procedures

A hydraulic actuator of 1000 kN, attached to a loading frame, was used to apply the compression load on the top of each specimen. The relative displacement between the grout pocket and the concrete top surface was measured with two linear variable differential transducers (LVDTs) placed between the loading plate and the surface of the block. The applied load was monitored using the load cell installed in the actuator and an external load cell TML CLC-50 placed under the hydraulic actuator plate, between two steel plates with 75 mm of diameter. A steel plate with a hole in the centre was placed on the bottom of the specimens as base support. The test set-up is shown in Figure 7.

A TML TDS 303 data logger was used to record data from the load cells and from the LVDTs. All tests were conducted with displacement control. It was adopted a displacement rate of 0.025 mm/s until reach 25 mm of displacement, in order to also obtain the residual connection capacity.

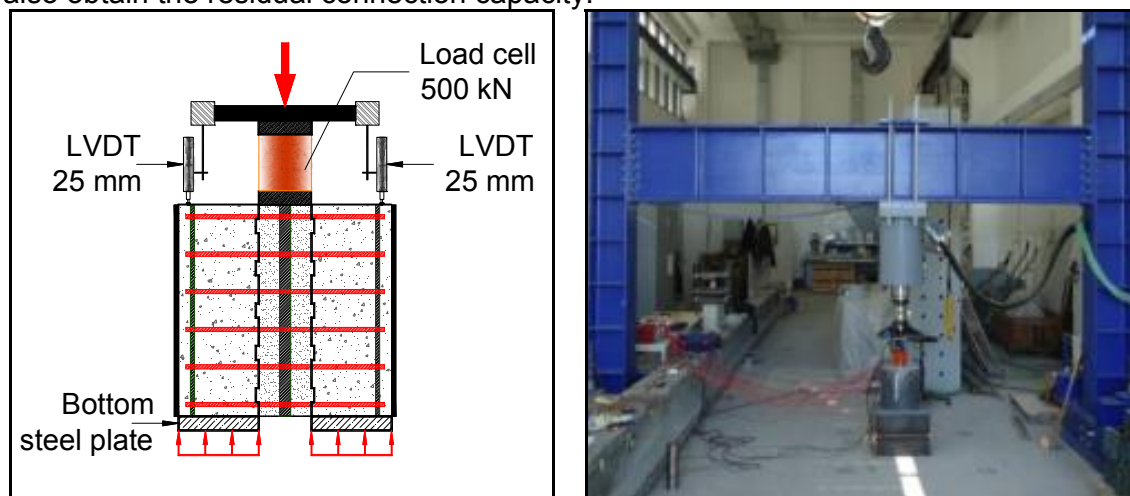


Figure 7 – Test set-up

3.4 Internal instrumentation of the specimens

One of the test specimens (test C6-3: hole indented surface and the highest level of confinement Level 4: six stirrups spaced 52 mm) was instrumented to monitor axial strain in the steel bar and tangential strains in transverse reinforcement. The axial strain gauges were used to evaluate the load transfer between the grout and the reinforcing steel bar and the horizontal ones to evaluate the tensile stress of the stirrups and the level of passive confinement.

Two TML PFL-10-11 (120 Ω) strain gauges were bonded in the surface of each stirrup (each pair in opposite sides) in horizontal direction (twelve in total) and two were mounted in vertical direction on the opposite sides in the centre of the reinforcing steel bar. Figure 7 shows instrumentation details for specimen with the higher confinement level.

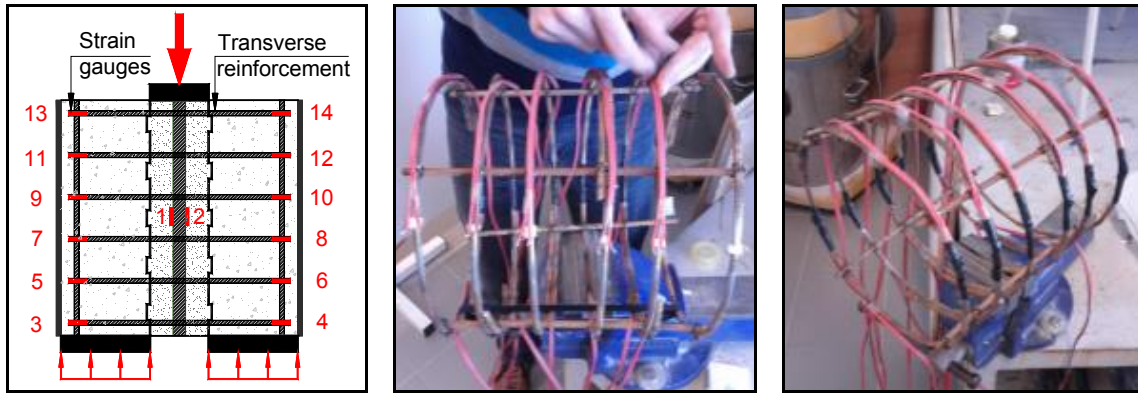


Figure 7 – Instrumentation details

4. RESULTS AND DISCUSSION

In Figure 8, the results obtained in the instrumented specimen are shown. The load / displacement curve in Figure 8a) shows a ductile behaviour of the connection. The response is almost linear until the value of 400 kN is reached. At this stage, the load / displacement curve shows a drop in the capacity followed by an increase of the load capacity with a reduction in stiffness. As the applied load increases, longitudinal cracks propagate along the depth of the concrete cylinder, resulting in a reduction of concrete confinement and a sudden drop in stiffness.

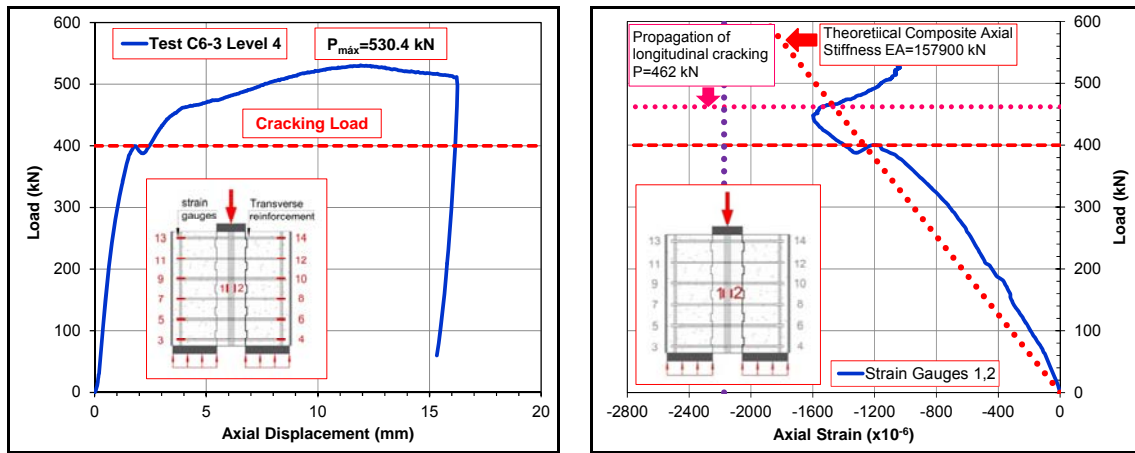
The axial strain plotted in Figure 8b) is the results of the average reading of two axial gauges mounted in the steel bar, while the axial load plotted represents the readings of the load cell. Figure 6d) also include the composite axial stiffness, EA , of the grout and steel, which is calculated according to the following expression:

$$EA = E_s A_s + E_g A_g \quad (5)$$

where E_s and E_g are the Young's modulus of steel and grout; and A_s and A_g are the area of steel and grout respectively. E_g was taken as 15.3 GPa based on the results from laboratory tests, while E_s is assumed to be 200 GPa. The value considered for EA was 157900 kN. Considering strain compatibility between steel and grout, the load supported by the bar is about 60% of the total load.

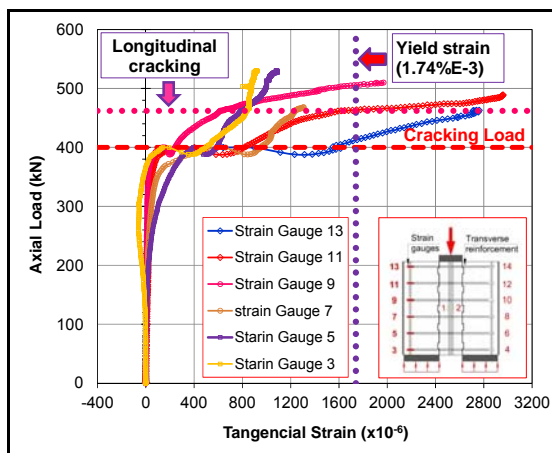
Strain records indicate that radial and longitudinal cracking occurred as shown in Figure 8c) and in Figure 8d). After the radial and longitudinal cracking of the concrete, the tensile strain in transverse reinforcement increases. The variation in tangential strain differs in the strain gauges mounted on the opposite sides of the transverse reinforcement. This difference is in line with the non-uniform observed cracking pattern in different sections along the height of the test specimen (see Figure 8e).

The vertical lines in Figures 8b), 8c) and 8d) represents the axial and tangential strains at the yield of the vertical and horizontal reinforcement, respectively. The lower values of tensile strains in the transverse reinforcement, near the bottom of the specimens, are due to the effect of base confinement.

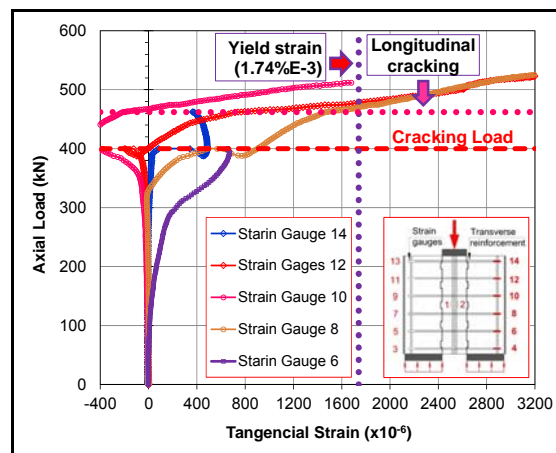


a) Load / Displacement

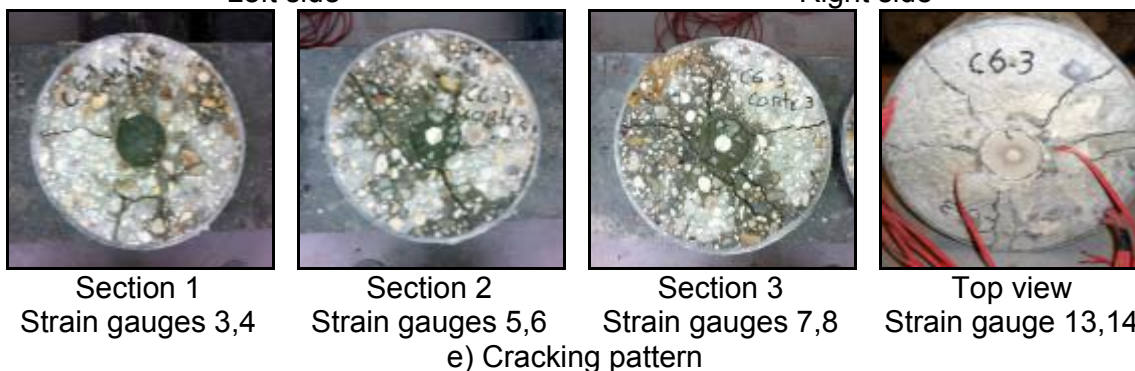
b) Displacement / Time



c) Load / Tangential Strain variation: Left side



d) Load / Tangential Strain variation: Right side



e) Cracking pattern

Figure 8– Results of instrumented test

Figure 9 illustrates the failure modes observed in tests. In all the specimens splitting radial cracks are visible at the surface of the concrete, three or four cracks in each specimen. The cracks propagate along the entire length of the concrete cylinder. For the specimens with indented hole surface the failure occurs by shearing in the grout in the grooves and shear in concrete.

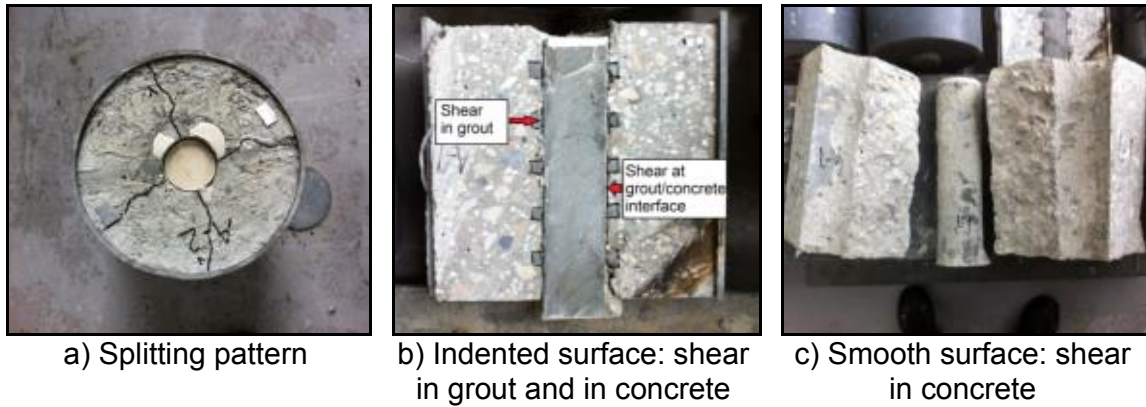


Figure 9– Failure modes

Table 3 presents the average values of the peak load, bond strength, axial displacement at peak load, initial stiffness, final stiffness, axial displacement at yield, and ductility. The bond strength was calculated at the concrete / grout interface and for design proposes it is assumed that there is a uniform distribution of bond along the interface. The initial stiffness was defined as the stiffness in the elastic stage. The final stiffness is the relation between peak load and the corresponding displacement. The ductility is defined as the ratio between the displacement at peak load and the slip at yield. The yield point was defined assuming the initial stiffness up to the failure load.

Table 3 - Summary of results

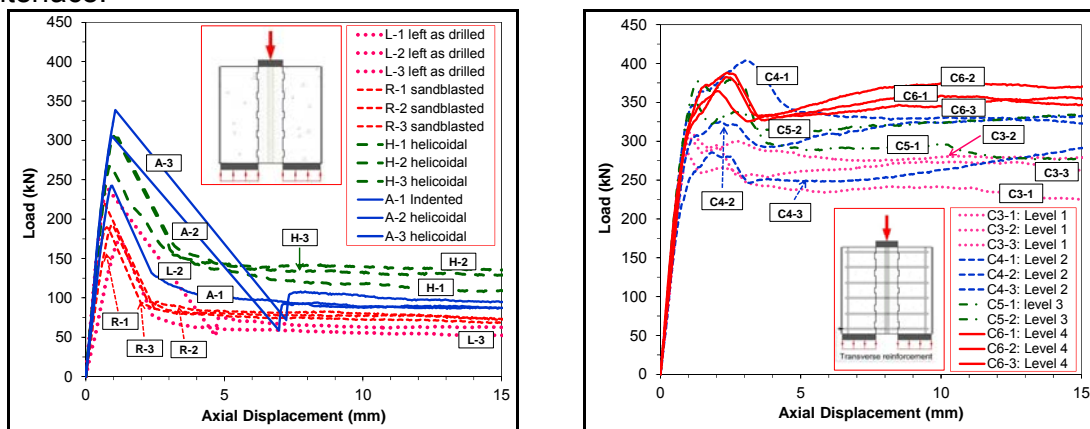
Test	Hole surface treatment	Transverse Reinforcement.	$L_g^{(1)}$ (mm)	P_{max} (kN)	$\delta_{P_{max}}$ (mm)	P_r (kN)	f_{bu} (MPa)	K_0 (kN/mm)	$K_{P_{max}}$ (kN/mm)	δ_y (mm)	μ_g
L1	Left as cast	No	290	237.2	0.731		3.47	380.2	324.5	0.624	1.17
L2	Left as cast	No	293	241.3	0.697	62.6	3.50	382.3	346.2	0.631	1.10
L3	Left as cast	No	295	178.3	1.217	52.5	2.57	163.4	146.5	1.091	1.12
R1	Sandblasted	No	296	192.8	0.935	72.8	2.77	246.1	206.2	0.783	1.19
R2	Sandblasted	No	293	221.0	0.67	73.1	3.20	383.9	329.9	0.576	1.16
R3	Sandblasted	No	294	189.7	0.754	68.3	2.74	317.0	251.6	0.598	1.26
H1	Spiral	No	292	269.2	0.887	109.4	3.91	367.5	303.5	0.733	1.21
H2	Spiral	No	292	305.5	0.967	135.5	4.44	385.1	315.9	0.793	1.22
H3	Spiral	No	297	303.8	0.945	129.0	4.34	356.7	321.5	0.852	1.11
A1	Indented	No	292	242.3	0.953	87.1	3.52	301.7	254.2	0.803	1.19
A2	Indented	No	295	305.2	0.947	87.2	4.39	379.4	322.3	0.804	1.18
A3	Indented	No	292	338.5	1.067	94.9	4.92	378.7	317.2	0.894	1.19
C3.1	Indented	3 Stirrups	294	285.5	0.921	225.3	4.12	334.1	310.0	0.855	1.08
C3.2	Indented	3 Stirrups	296	311.3	1.055	278.7	4.47	335.5	295.1	0.928	1.14
C3.3	Indented	3 Stirrups	295	305.0	0.963	262.3	4.39	401.2	316.7	0.760	1.27
C4.1	Indented	4 Stirrups	294	403.7	3.031	323	5.83	381.9	133.2	1.057	2.87
C4.2	Indented	4 Stirrups	294	325.3	2.135	332.5	4.70	333.4	152.4	0.976	2.19
C4.3	Indented	4 Stirrups	296	285.5	1.851	291.1	4.10	301.0	154.2	0.949	1.95
C5.1	Indented	5 Stirrups	296	351.0	1.205	277.7	5.04	374.8	291.3	0.936	1.29
C5.2	Indented	5 Stirrups	295	379.4	2.458	333.1	5.46	395.3	154.4	0.960	2.56
C6-1	Indented	6 Stirrups	293	387.9	2.347	346.7	5.62	393.4	165.3	0.986	2.38
C6-2	Indented	6 Stirrups	296	364.4	2.035	370.0	5.23	353.1	179.1	1.032	1.97
C6.3	Indented	6 Stirrups	296	382.7	2.339	354.6	5.49	361.5	163.6	1.059	2.21
T 1 ⁽⁶⁾	Indented	6 Stirrups	296	328.7	8.533	317.1	4.72	172.4	38.5	1.907	4.48
T 2	Indented	6 Stirrups	298	382.7	2.339	354.6	5.45	361.5	163.6	1.059	2.21

L_g - Embedment length of the grout pocket; P_u - Peak load; f_{bu} - bond strength; $\delta_{P_{max}}$ - total displacement of grout pocket at peak load; K_0 - initial stiffness; $K_{P_{max}}$ ~ final stiffness; δ_y - displacement at yield; δ_u/δ_y - ductility

All average load / displacement curves are shown in Figure 9: Figure 9a) contains the results from tests performed without transverse reinforcement and with different hole treatment surfaces; whereas Figure 9b) shows the results from tests with transverse reinforcement (with different levels of confinement) and an indented hole surface. Results show that specimens without confinement and with an indented hole surface provides the highest connection capacity, when compared to those specimens with the others hole's surface treatment. Also, the results show that specimens with transverse reinforcement and indented hole surface provide a higher connection capacity, when compared to those specimens without confinement and with same indented hole surface. It can also be stated that higher confinement levels provides higher connection capacities.

A brittle failure was observed in all tests performed in specimens without transverse reinforcement (Figure 9a). Each curve exhibits two different stages. First, a linear elastic branch is identified, presenting similar values of tangent stiffness, until the failure of the connection. After the failure of the connection, due to tension, failure of the concrete cylinder occurs resulting in the decrease of the confinement provided by the concrete cover and in a sudden loss of the connection capacity down to a residual value of 30 to 40% of the maximum load. The initial stiffness is observed to be independent of the hole surface treatment. The axial displacement at the peak load range from 0.670 to 1.217 mm. The connection capacity depend on the hole treatment surfaces used in each specimens. Specimens with indented surfaces provide the highest load capacities.

A ductile failure was observed in tests performed on specimens with transverse reinforcement (Figure 9b). Each curve exhibits three different stages. First, a linear elastic branch is identified, presenting similar values of initial stiffness, until the appearance of the first splitting cracks in concrete top surface. Then, the response becomes non-linear at 80-90% of the peak load. At this stage, the effectiveness of the confinement is reduced as further splitting cracks appear, propagate, and extend from the concrete surface to the entire height of the concrete cylinder. This results in a nonlinear response of the connection, accompanied with the observed softening and failure of the connection. After the peak load is reached the confinement provides by transverse reinforcement guarantee a high capacity and ductility of the connections due to confining pressure acting at grout / concrete interface.



a) Specimens without transverse reinforcement and different hole surface treatments

b) Specimens with transverse reinforcement and an indented hole surface

Figure 9 – Load / displacement curves

In Figure 10 is presented the influence of the surface preparation method, namely the roughness of the hole surface, on the bond strength of specimens without transverse reinforcement. The bond strength obtained for specimens prepared by sandblasting is lower than the initially expected value due to a deficient preparation of the specimens since the excessive use of release agents modified the surface characteristics. Specimens with helical and indented hole surface lead to an increase in the bond strength of approximately 35%. Aforementioned, in specimens without transverse reinforcement the observed failure mode was brittle with a sudden loss in the connection capacity. In practice, an indented surface must be used to guarantee adequate bond stress at the grout / concrete interface when textured micropiles are adopted. If this method is used, the existing concrete footing must have sufficient reinforcement (existing or adding) to provide an adequate confinement to assure ductile connection behaviour.

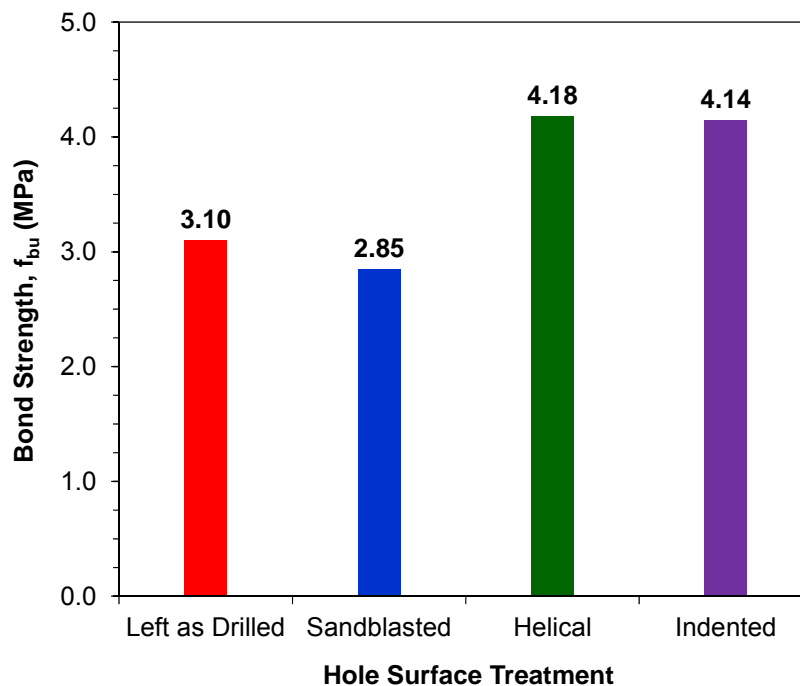


Figure 10 – Bond strength variation with the hole surface treatment

Figure 11 shows the relationship between bond strength and confining pressure. In this figure, nominal (blank bullets) and average values (solid filled bullets) are presented. The values of the confining pressure were obtained by expression 1. It can be seen that the bond strength increase with the confining pressure provided by passive reinforcement. A high correlation coefficient is observed (0.94). Furthermore, this relationship seems to be linear and follows a Mohr–Coulomb criterion. These results are consistent with those obtained by Veludo (2013) in tests performed with textured micropiles grouted in predrilled holes in RC footings with active confinement.

The volumetric ratio of transverse reinforcement ($\rho_w = \omega_w \cdot f_{cd} / f_{yd}$), in percentage, for each specimen obtained is: 0.34 for Level 1; 0.51 for Level 2; 0.68 for Level 3; and 0.85 for Level 4. The latter provides an increase in the bond strength of 27%.

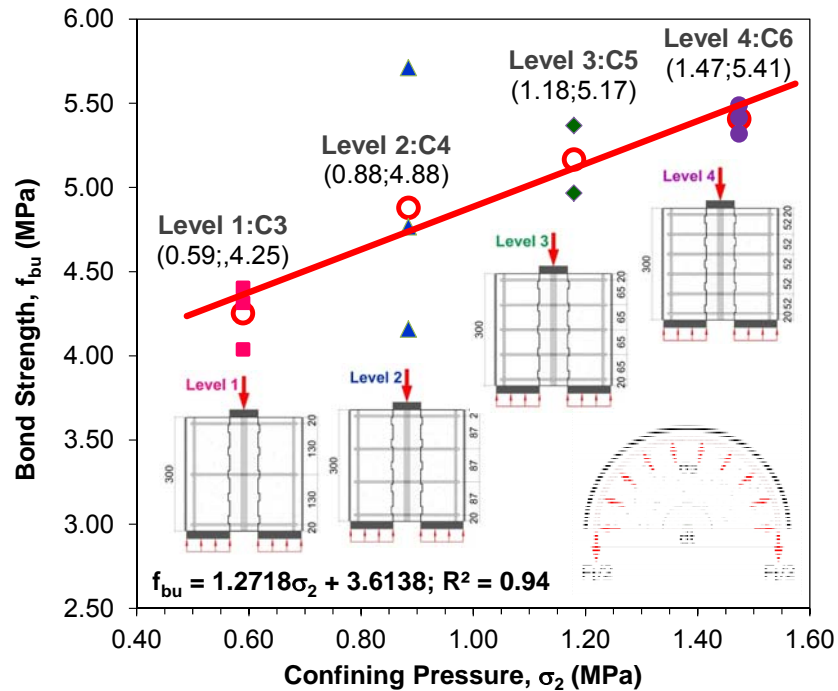


Figure 11– Relationship between bond strength and confining pressure

5. CONCLUSIONS

From previous studies it can be stated that confinement of the micropile-to-footing connection is the most relevant parameter in the load capacity of the connection. Active confinement has a notable increasing effect in ductility and in the load capacity of the connection.

From the research study herein described, it was concluded that:

- i) specimens without transverse reinforcement shows a brittle failure and in specimens with transverse reinforcement a ductile behaviour was observed;
- ii) the use of an indented hole surface leads to the highest bond strength at the grout / concrete interface;
- iii) the use of an indented hole surface in grouted connections provides an adequate load capacity and ductility of the connection if the concrete specimen has sufficient reinforcement to provide the necessary level of confinement. In this situation, by increasing the volumetric ratio of transverse reinforcement the bond strength at grout / concrete interface increases. An increase of two and half times the volumetric ratio of transverse reinforcement ensures a 27% increase in the bond strength at grout / concrete interface.

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