Compressive strength of micropile-to-grout connections

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ABSTRACT

Strengthening foundations with micropiles is progressively being used, due to the major advantages that this technique presents. Nevertheless, the influence of some relevant parameters in the overall behavior of the retrofitted foundations has not yet been studied. Generally, micropiles are installed in holes drilled through the existing RC footing, which are then filled with grout. The efficiency of the load transfer mechanism depends on the bond strength of both the micropile–grout and the concrete–grout interfaces.

This paper describes an experimental study performed to specifically study the influence of the following parameters on the bond strength between micropile–grout interface: hole diameter; embedment length of the micropile; and level of confinement of the grout mass. Thirty micropile–grout specimens were submitted to monotonic push-off tests, until failure. Bond strength was found to increase with a decrease of the hole diameter and with an increase of the confinement level.

1. Introduction

RC footing strengthened with steel micropiles is today a widespread method. However, in practice, it is empirically applied. In reality, although the parameters that influence the connection capacity are identified, these have not been quantified in a comprehensive way. In general, micropiles are applied to the existing RC footings through predrilled holes. After the micropile is installed, the hole is filled with non-shrink grout. It is known that the efficiency of the connection depends on the bond strength of both the micropile–grout and the concrete–grout interfaces but this has not been characterized so far.

To increase the bond strength of the micropile–grout interface, it is common practice to weld steel rings or a steel spiral around the perimeter of the casing. To improve the bond strength of the grout–concrete interface, sometimes grooves are chipped into the wall of the hole. Detailing depends mainly on the required capacity [1–3]. Attention must also be paid to the reinforcement of the existing concrete footing since this can be inadequate for the strengthened situation. In this case, the lateral and the axial confinement of the existing footing should be increased to improve the connection capacity.

As mentioned, few experimental studies have been conducted on this subject. Gómez et al. [4] performed push-off tests to study the connection capacity of smooth micropiles, grouted in reinforced concrete footings through holes drilled using a jack hammer. The authors concluded that the connection capacity is controlled by adhesion and friction at the micropile–grout interface and that the residual capacity of the connection is entirely frictional and dependent on the confinement provided by the footing reinforcement. It is also concluded that the connection capacity increases with the decrease of the hole diameter and that the embedment length has little influence on the bond strength.

Contrarily to micropile–footing connections, the bond mechanism between reinforcing bars and concrete is well studied and it is generally accepted that it is controlled mainly by three different parameters: (1) chemical adhesion between concrete and steel; (2) friction between concrete and steel; and (3) bearing of the rebar ribs on the surrounding concrete [5–8]. Two different bond failure mechanisms can be observed: splitting failure or pull-out failure.

Various studies have also been performed in grouted ribbed rebar or cable bolts. Moosavi et al. [9] studied the bond of cement grouted reinforcing bars under constant radial pressure. These authors state that the properties of both grout and confinement play an important role in developing the bond capacity.

Hyett et al. [10] performed several pull-out tests of grouted cable bolts using a modified Hoek cell and concluded that the bond strength at the cable bolt–grout interface is more related to friction rather than to chemical adhesion. The authors also state that the
bond strength depends on the pressure generated at the cable bolt–grout interface caused by dilatancy during bond failure. In a previous study, Hyett et al. [11] indicate that the parameters with a major influence in cable bolt capacity are: the grout properties (w/c ratio); the cable bolt embedment length; and the radial confinement acting on the outer surface of the grout mass. Yahia et al. [12] studied the bond strength of cement grout anchors cast in rock under dry and submerged conditions. These authors concluded that the main mechanism to mobilize the bond strength is the friction developed at both grout–rebar and grout–rock interfaces. It is also concluded that friction depends on: the mechanical properties of both rock and grout; the geometry of the hole and of the bar; and the roughness of the drilled hole surface. Malvar [13] and Noghbabai [14] performed pull-out tests with deformed bars cast in concrete cylinders under different radial confinements. Both authors conclude that the confinement is the most important factor at the slip phase and observed the increase of bond stress with the growth of the level of confinement.

From the studies previously referred to, it can be assumed that the load transfer mechanism between a strengthening steel micropile and the existing reinforced concrete footing is controlled by three different parameters: (1) chemical adhesion at the steel–grout and the grout–concrete interfaces; (2) friction at the steel–grout and the grout–concrete interfaces; and (3) bearing of the welded steel rings/spirals at the steel–grout interface and of the concrete grooves at the grout–concrete interface.

Design codes for RC structures, namely ACI 318 [15], EuroCode 2 [16] and the CEB-FIP ModelCode 1990 [6], specify expressions for the design of the bond strength and development length of bars embedded in concrete. However, none of these codes presents expressions to compute the development and the bond stress of bars grouted in holes predrilled in concrete. Furthermore, using current codes expressions to determine the development length of a smooth micropile in a predrilled hole filled with grout would be too conservative. Moreover, this would require having a significantly deep foundation, which is not observed in practice.

The study herein described focuses specifically the behavior of the steel–grout interface with smooth micropile inserts aiming to quantify the influence of the following parameters: the hole diameter, the embedment length; and the confinement of the grout mass.

2. Research significance

Strengthening existing RC footings with grouted steel micropiles is currently one of the most used retrofitting techniques of foundations. However, in practice, this is performed empirically since the behavior of the micropile–footing connection has not been characterized so far. The experimental study herein described contributes to the knowledge of the behavior of the micropile–grout interface. It is demonstrated that: the capacity of the micropile–footing connection increases with the decrease of the hole diameter; and the bond strength strongly depends on the radial confinement; but it is not significantly influenced by the insert embedment length.

3. Experimental investigation

Aiming to study the influence of the insert embedment length, the hole diameter and the confinement of the grout mass, 15 different situations were defined and, for each one, two specimens were tested in compression. In order to enable different radial confinement levels of the grout mass, steel tubes, PVC tubes and RC blocks were used. First, 30 smooth inserts were positioned inside 10 steel tubes, 10 PVC tubes and 10 holes predrilled in RC footings. Then, an unreinforced mass of grout was used to seal the void between the inserts and the walls of the tubes/holes. Afterwards, these specimens were tested in compression until failure, to evaluate the influence of the parameters referred to on the bond strength of the micropile–grout interface. Besides these, the remaining parameters were kept constant, such as: grout type and strength; concrete type and strength; micropile insert; and loading procedure. In the following paragraphs, the materials adopted in this study, the different situations considered, the geometry adopted for the specimens, the production of the specimens; and the tests set-up are described.

3.1. Materials

The micropile inserts were produced using smooth 60 mm API N80 steel tube grade 562/703 MPa, with 6 mm thickness. In tests performed with concrete specimens, the tube was reinforced with a 16 mm grade 500/600 MPa bar which was first welded to the center of a 150 × 150 × 20 mm³ steel plate. Finally, the insert was fully grouted. An average roughness of 1 mm for the tube surface was measured with a laser roughness analyzer [17].

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. The mix proportions per cubic meter are the following: 1327 kg of type I:42.5 R Portland cement, 530 l of water, 13.27 kg of modified polycarboxylate admixture (high range water reducer); and 13.27 kg of expansive admixture. At each age, a set composed by six specimens obtained from the flexure test performed on three prismatic specimens with 40 × 40 × 160 mm³ were used to evaluate the corresponding Young’s modulus [20]. Other set composed by three prismatic specimens with the dimensions previously referred to were used to evaluate the corresponding Young’s modulus [20] (see Fig. 1a). The specific gravity of the grout was 19.2 kN/m³. The following properties were measured, according to European standards [19]: a flowability of 11 s; a volume change of 0%; a bleed of 0.45%; and an air content of 2%. These results were considered acceptable, also according to European standards [21].

Fig. 1. Mechanical properties of concrete and grout: (a) unconfined compressive strength and (b) Young’s modulus.
Table 1
The complete push-off test program.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Diameter of grout (Dc) (mm)</th>
<th>Embedment length (Lc) (mm)</th>
<th>Confinement</th>
<th>Dext (mm)</th>
<th>t (mm)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1-P2</td>
<td>101</td>
<td>200</td>
<td>PVC</td>
<td>110</td>
<td>4.5</td>
<td>PVC</td>
</tr>
<tr>
<td>P3-P4</td>
<td>101</td>
<td>275</td>
<td>PVC</td>
<td>110</td>
<td>4.5</td>
<td>PVC</td>
</tr>
<tr>
<td>P5-P6</td>
<td>101</td>
<td>350</td>
<td>PVC</td>
<td>110</td>
<td>4.5</td>
<td>PVC</td>
</tr>
<tr>
<td>P7-P8</td>
<td>81</td>
<td>350</td>
<td>PVC</td>
<td>90</td>
<td>4.3</td>
<td>PVC</td>
</tr>
<tr>
<td>P9-P10</td>
<td>119</td>
<td>350</td>
<td>Steel</td>
<td>130</td>
<td>5.5</td>
<td>Steel</td>
</tr>
<tr>
<td>S1-S2</td>
<td>100</td>
<td>200</td>
<td>Steel</td>
<td>110</td>
<td>5.0</td>
<td>Steel</td>
</tr>
<tr>
<td>S3-S4</td>
<td>100</td>
<td>275</td>
<td>Steel</td>
<td>110</td>
<td>5.0</td>
<td>Steel</td>
</tr>
<tr>
<td>S5-S6</td>
<td>100</td>
<td>350</td>
<td>Steel</td>
<td>110</td>
<td>5.0</td>
<td>Steel</td>
</tr>
<tr>
<td>S7-S8</td>
<td>80</td>
<td>350</td>
<td>Steel</td>
<td>90</td>
<td>5.0</td>
<td>Steel</td>
</tr>
<tr>
<td>S9-S10</td>
<td>120</td>
<td>350</td>
<td>Steel</td>
<td>130</td>
<td>5.0</td>
<td>Steel</td>
</tr>
<tr>
<td>C1-C2</td>
<td>102</td>
<td>200</td>
<td>Concrete</td>
<td>450</td>
<td>174</td>
<td>Concrete</td>
</tr>
<tr>
<td>C3-C4</td>
<td>102</td>
<td>275</td>
<td>Concrete</td>
<td>450</td>
<td>174</td>
<td>Concrete</td>
</tr>
<tr>
<td>C5-C6</td>
<td>102</td>
<td>350</td>
<td>Concrete</td>
<td>450</td>
<td>174</td>
<td>Concrete</td>
</tr>
<tr>
<td>C7-C8</td>
<td>82</td>
<td>350</td>
<td>Concrete</td>
<td>450</td>
<td>184</td>
<td>Concrete</td>
</tr>
<tr>
<td>C9-C10</td>
<td>122</td>
<td>350</td>
<td>Concrete</td>
<td>450</td>
<td>164</td>
<td>Concrete</td>
</tr>
</tbody>
</table>

Dext – external diameter; t – thickness.

For the PVC confinement, a P100 pressure class tube with three different diameters (see Table 1) was used, presenting according to the manufacturer a Young’s modulus of 3.0 GPa and a Poisson ratio of 0.3. For the steel confinement, a S t 52 BK + S grade 520/600 MPa tube with three different diameters was used (see Table 1). For the RC blocks, 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. The following mix proportions per cubic meter of concrete were adopted: 280 kg of type II:42.5 R Portland cement, 180 l of water, 250 kg of washed siliceous sand with 3.56 fine-ness modulus, 710 kg of siliceous sand with 3.71 fineness modulus, 880 kg of lime-stone crushed aggregates with 6.35 fineness modulus and 2.8 kg of a water reducing admixture. Three cubes with 150 mm were produced to evaluate the average compressive strength [22,23] at each of the following ages: 1, 3, 7, 14, 21, 28, 56 and 90 days (see Fig. 1a). The corresponding Young’s modulus was also measured [20], using 150 × 150 × 600 mm³ specimens (see Fig. 1b). The concrete blocks were reinforced at the bottom face with an 8 mm S400 grid, with five bars in each direction, and presenting a 50 mm of nominal cover.

3.2. Test specimens

In Fig. 2 is presented the geometry of the specimens adopted for the push-off tests: (a) specimens confined using steel/PVC tubes and (b) specimens confined using RC blocks. In Table 1 the different 15 situations considered are presented, including the diameter of the grout mass, the insert embedment length, and the type and geometry (steel, PVC or concrete) of the confinement of the grout mass. This is part of a wider experimental program aiming to assess the most significant parameters related to the connection capacity between micropiles and existing RC footings. For few set-ups, the load applied to the RC blocks could exceed the strength of the steel tubes, thus justifying the rebar represented in Fig. 2b. Since expected failure occurs at the steel–grout interface, their influence is neglected.

One of the main objectives of this investigation was to compare the bond strength at the micropole–grout interface using different confinement levels of the grout mass. The PVC tube represents the lowest confinement level and was mainly used to prevent splitting of the grout mass during the hardening process. The steel tube was adopted to apply a moderate confinement. For the highest confinement level, a concrete block with dimensions 450 × 450 × 500 mm³ was adopted.

The radial stiffness (Kr) of the different types of confinement considered can be estimated from the ‘thick wall cylinder theory’, according to the following equation [24]:

\[ K_r = \frac{2E}{(1 + v)} \left( d_i^2 - d_o^2 \right) \left( 1 - 2v \right) \left( d_i^2 - d_o^2 \right) \]

where E is the Young’s modulus and v is the Poisson ratio of tubes, and di and do are inside and outside diameters of the tubes, respectively. Computed values of K_r for PVC tubes, steel tubes and RC footings are listed in Table 2.

In Fig. 3 are shown the different stages of the production of the 20 specimens confined using steel and PVC tubes: (a) each micropile insert was first glued to a steel formwork in the center of the respective steel/PVC confinement tube and (b) then, the micropile inserts and the holes between these and the confinement tubes were filled with grout.

In Fig. 4, four stages of the production of the 10 specimens confined with RC blocks are presented: (a) first, steel and wooden formwork were assembled to execute the 450 × 450 × 500 mm³ RC blocks; (b) then, concrete was cast and vibrated; (c) after 28 days of indoor curing, the blocks were drilled using a diamond coring system for insert application and (d) lastly, the prefabricated micropiles inserts were positioned into the holes and these were sealed using grout.

Table 2
Wall stiffness of the confining tubes and RC footings used in tests.

<table>
<thead>
<tr>
<th>Confinement</th>
<th>K_r (GPa)</th>
<th>v</th>
<th>d_i (mm)</th>
<th>d_o (mm)</th>
<th>K_r (MPa/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>3</td>
<td>0.3</td>
<td>90</td>
<td>81</td>
<td>8.2</td>
</tr>
<tr>
<td>PVC</td>
<td>3</td>
<td>0.3</td>
<td>110</td>
<td>101</td>
<td>5.4</td>
</tr>
<tr>
<td>Steel</td>
<td>200</td>
<td>0.3</td>
<td>90</td>
<td>80</td>
<td>613.4</td>
</tr>
<tr>
<td>Steel</td>
<td>200</td>
<td>0.3</td>
<td>110</td>
<td>100</td>
<td>401.3</td>
</tr>
<tr>
<td>Concrete</td>
<td>37.1b</td>
<td>0.2</td>
<td>450</td>
<td>82</td>
<td>714.8</td>
</tr>
<tr>
<td>Concrete</td>
<td>37.1b</td>
<td>0.2</td>
<td>450</td>
<td>102</td>
<td>557.9</td>
</tr>
<tr>
<td>Concrete</td>
<td>37.1b</td>
<td>0.2</td>
<td>450</td>
<td>122</td>
<td>449.7</td>
</tr>
</tbody>
</table>

a Values assumed according to manufacturer.
b At time of tests (107 days after casting concrete blocks).

Specimens confined with steel/PVC tubes were tested using a compressive testing machine with a capacity of 60 tons (Fig. 6a and b). Specimens confined with RC blocks were tested using a compressive testing machine with a capacity of 500 tons (Fig. 6c). In both situations, the relative displacement between the insert and the grout mass was measured with two displacement transducers (LVDT) placed between the loading plate and the surface of the grout mass. The applied load was monitored using the machine pressure gauge as well as an external load cell placed on top of the loading plate. A data logger was used to record data from the load cell and from the LVDTs. All tests were conducted until failure with displacement control, considering a load rate of 0.025 mm/s, in order to also obtain the residual connection capacity.

4. Results and discussion

In Table 3, the average values of the peak load, the corresponding bond strength and the axial displacement, obtained with the push-off tests, are presented. The average bond strength, f_b (MPa), is the peak load, P_u (N), divided by the nominal surface area of the embedment length, l_e (mm), of the micropile insert.

Two different types of failures were observed. For tests performed with PVC confinement, failure occurred by radial fracturing...
with radial displacement of grout wedges. For higher confinement levels (steel/concrete confinement), a mixed failure mechanism was registered, consisting of splitting-induced push-off of the insert. In both cases, three to four resulting splitting wedges were observed which is also in agreement with Malvar [13]. Furthermore, in tests performed in RC footings no visible cracks were observed in the concrete block. In these cases the mechanical properties of the grout, the micropile surface and the diameter of the grout mass are the critical parameters.

The load–displacement curves obtained in the tests are shown in Fig. 7a–c for each confinement situation considered. It can be stated that the obtained load–displacement responses have similar shape for all the tests. In fact, each curve consists of a linear branch until 70–80% of the failure load is reached, followed by a non-linear branch from this point onwards. A sudden drop of the load carrying capacity appears just after reaching the peak load followed by a ductile post-failure response. In all tests, significant residual bond stress after a slip of 15 mm is identified, representing approximately 50% of the bond strength (at peak load). This results corroborate those obtained by Gómez et al. [4].

From Fig. 7d, it can be seen that for the same diameter of grout mass, 100 mm, and the same embedment length, 350 mm, the connection capacity increases with the confinement level. It can also be observed that the beginning of non-linearity also depends on this parameter, increasing with the level of confinement. In addition, the initial stiffness increases with the increase of the radial confinement. After the peak load, for different radial confinement, the curves gradually evolve towards a similar rate, revealing the same friction mechanism.

The bond strength at the micropile–grout interface for smooth micropile inserts depends on two components: chemical adhesion and friction mechanism. The effect of chemical adhesion is transitory since it is destroyed immediately after slippage of the
micropile insert in the beginning of the push-off test. After this stage the insert starts to slip relatively to the grout mass and from this point onwards the bond strength is controlled by friction. Simultaneously, the shear displacement causes normal dilatation and consequently normal stresses are developed. The dilatation is dependent on the confinement level and grout quality. The mechanical properties of the grout and of the confinement material, the surface irregularities of the insert, and the diameter of the grout mass, influence the magnitude of these stresses. According to Moosavi et al. [9] grouts with lower quality generate smaller dilatation and, consequently, reduced bond strength at micropile–grout interface.

In all push-off tests performed, the failure of the connection was observed after a deflection of less than 2.0 mm of the insert head has occurred (see Table 3). In Fig. 8 the relationship between embedment length of the insert and the displacement at the peak load is shown for specimens with the same diameter of the grout mass, 100 mm. It can be seen that for the same confinement level, the displacement at peak load increases with the increase of the embedment length of the insert. Furthermore, the displacement at the peak load seems to be proportional to the embedment length of the insert. For specimens with the same type of failure mechanism (steel/concrete confinement) the displacement at peak load decreases with the increase of the level of confinement. In the case of PVC confinement, the displacement is lower due to the longitudinal cracking of the grout allowed by the radial deformation of the confinement tube.

Based on the results of push-off tests performed with smooth micropiles inserts grouted in predrilled holes in RC footings, Gómez et al. [4] presented the following relationship for the average bond strength, $f_b$ in MPa, related to the width of grout-filled annular space around the insert, $a$ in mm:

$$4.14 - 0.054 \times a \leq f_b \leq 4.83 - 0.054 \times a$$  \hspace{1cm} (2)$$

This expression is valid for values of $a$ between 6.35 mm and 50.8 mm, a cement grout with a compressive strength higher than 27.6 MPa at 28 days of age, a Young’s modulus higher than 6.9 GPa and it considers the confinement provided by the grout-filled annular space around the insert (parameter $\alpha'$) for a constant high steel reinforcement of 1% of volume of the concrete block. A thorough discussion of Eq. (2), including an approximate procedure to estimate the effect of the reinforcing of the concrete block on the confinement, can be found in [4].

In Fig. 9, the results of the research herein described are shown, in terms of the relationship between the bond strength and the confinement level. A high correlation coefficient is observed (0.96). Furthermore, this relationship seems to be linear and follows a Mohr–Coulomb criterion [13,14].

Based on this, the authors propose the following relationship to estimate the bond strength at micropile–grout interface, $f_b$ in MPa:

$$f_b = 0.0101K_r + 1.0214$$  \hspace{1cm} (3)$$

where $K_r$ is the radial stiffness in MPa/mm, given by Eq. (1). It must be stated that Eq. (3) is valid for smooth micropiles, grouted in holes.
drilled in existing RC footings, using a cement grout with a compressive strength higher than 53 MPa at 28 days of age, a Young’s modulus higher than 14 GPa and it assumes that the concrete block has a very low steel reinforcement ratio (most common situation in rehabilitation works).

To estimate the bond strength at micropile–grout interface using Eq. (3), the radial stiffness needs to be computed first using Eq. (1). For this purpose, both $E$ and $v$ need to be measured. This can be done either through cores extracted from the existing footing or non-destructive testing (NDT). In case the existing foundation is found to be cracked, external prestress must be provided. It should also be mention that, to use Eq. (3) for design purposes, a suitable safety factor must be adopted.

For identical hole’s geometry and materials mechanical properties, Eqs. (2) and (3) give similar results. This can imply that, for smooth micropiles and uncracked footings (situation observed both in tests herein discussed and in tests performed by Gómez et al. [4]), the contribution of the footing’s reinforcement for the confinement level is not relevant.

Table 3

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Peak load ($P_u$) (kN)</th>
<th>Bond strength ($f_b$) (MPa)</th>
<th>Displacement at peak load (mm)</th>
<th>Confinement</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1-P2</td>
<td>40.3</td>
<td>1.07</td>
<td>0.301</td>
<td>PVC</td>
</tr>
<tr>
<td>P3-P4</td>
<td>46.5</td>
<td>0.90</td>
<td>0.346</td>
<td>PVC</td>
</tr>
<tr>
<td>P5-P6</td>
<td>70.5</td>
<td>1.07</td>
<td>0.528</td>
<td>PVC</td>
</tr>
<tr>
<td>P7-P8</td>
<td>45.8</td>
<td>0.69</td>
<td>0.868</td>
<td>PVC</td>
</tr>
<tr>
<td>P9-P10</td>
<td>91.8</td>
<td>1.39</td>
<td>0.609</td>
<td>PVC</td>
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<tr>
<td>S1-S2</td>
<td>160.7</td>
<td>4.26</td>
<td>0.952</td>
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<tr>
<td>S3-S4</td>
<td>244.9</td>
<td>4.72</td>
<td>1.092</td>
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<tr>
<td>S5-S6</td>
<td>345.4</td>
<td>5.23</td>
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<td>6.01</td>
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<tr>
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<td>7.46</td>
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<tr>
<td>C3-C4</td>
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<td>1.886 (1.011)</td>
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<td>7.36</td>
<td>1.287</td>
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<tr>
<td>C7-C8</td>
<td>549.8</td>
<td>8.33</td>
<td>1.341</td>
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</tr>
<tr>
<td>C9-C10</td>
<td>410.9</td>
<td>6.23</td>
<td>1.184</td>
<td>Concrete</td>
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</table>

$a$ Discarded values – Instrumented inserts. Very low peak load.  
$b$ Load and displacement at the onset of failure (see Fig. 7c).

Fig. 7. Results of tests performed with different radial confinement: (a) PVC confinement, (b) steel confinement, (c) RC footings and (d) comparison of results.
In Fig. 10, the relationship between the diameter of the grout mass and the bond strength at the micropile–grout interface is illustrated. It can be observed that, for specimens confined with PVC tubes, the bond strength increases with the diameter of the grout mass around the insert. In this situation, the grout cover provides itself confinement through tensile hoop stresses prior to cracking. On the contrary, for specimens confined with steel tubes and for specimens grouted in RC footing, it can be observed that the bond strength decreases with the increase of the diameter of the grout mass around the insert. In this situation, the bond strength depends on the mechanical properties of the grout and on the confinement materials.

The bond strength at the micropile–grout interface versus the embedment length is presented in Fig. 11. The bond strength seems to vary slightly with the embedment length for specimens with steel confinement, whereas no variation is detected for specimens confined with PVC tubes or RC footings. These results are consistent with those obtained by Gómez et al. [4] with smooth casing inserts grouted in predrilled holes in RC footings.

**5. Conclusions**

From the experimental study herein presented, the following conclusions can be drawn. In all tests, immediately after reaching the peak load, a sudden decrease on the load carrying capacity of the specimens is observed, followed by a ductile post-failure response. In this phase, the connection capacity gradually decreases until an almost constant value is reached. This residual bond strength represents approximately 50% of the maximum bond strength, which is still significant.

The connection capacity is first controlled by chemical adhesion at the micropile–grout interface and then by friction, being the latter proportional to the radial confining. However, after the peak load, the load–displacement diagrams tend to similar rates, indicating that the post-peak phase is controlled by the same friction mechanism, independently of the level of confinement.

The stiffness of the confinement materials has a major influence on the bond strength when the Young's modulus of the confinement material is smaller than that of the grout. In this case, failure occurs by radial fracturing with radial displacement of grout wedges. On the contrary, for higher confinement levels, the mechanical properties of the grout and the diameter of the grout mass are the critical parameters.

The variation of the bond strength at micropile–grout interface is shown to be strongly related with the confinement level (correlation coefficient of 0.96), therefore being this one of the most important parameters.

In the case of micropiles grouted in holes predrilled in existing RC footings and for steel confinement, the bond strength increases
with the decrease of the hole’s diameter. Consequently, increasing the hole’s diameter is not an option to improve the connection capacity.

Finally, for RC footings, the bond strength does not vary significantly with the embedment length.

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References


