INJECTED ANCHORS FOR THE SEISMIC RETROFIT OF HISTORICAL MASONRY BUILDINGS: EXPERIMENTAL STUDY ON BRICK MASONRY

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Abstract. The paper reports the results of a research on the behaviour of injected anchors in historical masonry under cyclic loads. Tests in laboratory with masonry specimens (bricks and mortar with low characteristics to replicate a real historical masonry) were conducted to analyse the response of steel anchors injected with a special sock and with different sorts of mortar (cement and lime based).

The test benches replicate the real condition of the use of these anchors: to connect masonry panels (T and L connections) or to anchor steel ties to contrast the arch thrust. Monotone and cyclic pull out tests were conducted on short and long anchors (injected orthogonally and lengthwise to the masonry main plane) to compare the results and to define the loss of strength under cyclic loads for different situations.

The results allowed to obtain: 1) construction of load-displacement graphs, up to the maximum load value (maximum strength) of each anchor and the related displacement; 2) steel bar deformation graphs on the length of the anchors (thanks to the strain gauges installed on steel bars) at different values of load and under cyclic loads; 3) qualitative bond stress curve derived from the steel bar strains, which allowed to investigate the behavior of the anchors along the bar length under cyclic loads.
1 INTRODUCTION

In recent years the interest on anchors in historic masonry is increasing, especially with regard to existing buildings’ seismic improvement. In masonry buildings, the first-order (out of plane) mechanisms represent the main cause of collapse, where wood slabs does not guarantee effective diaphragm effect or where central walls are not tied to the perimeter ones. Against these well-known failure mechanisms, perimeter ties, placed along the masonry walls (at horizontal elements level) are a classical solution.

However external anchor plates are not usable in the presence of valuable elements (paintings or decorations) or of geometric constraints, that do not allow pass-through perforations. In these situations anchors in the thickness of the masonry, realized by a steel bar placed in a borehole then grouted, is the best solution. Moreover, using a special "sock" to contain the bar and the injected grout it is possible to ensure that mortar remains confined within the borehole (fig. 1), thus realizing a "bulb" whose outer surface is in contact with the masonry substrate along the entire length, conforming to asperities and holes, creating a mechanical interlocking and, at the same time, ensuring a less invasive intervention.

This technology has been studied in recent years, but needed new efforts to assess the behaviour in the presence of seismic actions [1] [2] [3] [4] [5], thus under cyclic loads.

With these premises the laboratory experiments were carried out in order to assess:
- the influence of vertical confinement on anchor capacity;
- the tensions’ trend along the anchor length;
- the anchor capacity under cyclic loads, even varying the injection grout typology;
- the differences between superficial (or short anchors, injected orthogonally to the main wall plane) and deep (or long anchors, injected in the main plane of the wall).

The laboratory experimental campaign consisted of the following tests:

1) monotone pull-out tests on anchors injected orthogonally to the masonry plane and loaded with different vertical loads, in order to assess the influence of axial stress (induced by the presence of overhanging masonry) on the anchor performance;

2) cyclic pull-out tests on "short" anchors injected orthogonally to the main wall plane and with three different types of grout;

3) cyclic and monotone pull-out tests on "long" anchors injected in the main wall plane and with three different types of grout.

The aim of the three experiments was to replicate the real situations in using these anchors to connect, for example, masonry panels (T and L connections) or to anchor steel tie to contrast the arch thrust. The real conditions in fact may include: different vertical loads due to the presence (or not) of upper floors; holes to be provided orthogonally to the wall plane with high lateral confinement, but with length conditioned by the thickness of the wall; holes to be provided longitudinally to masonry plane, with high lengths, but low lateral confinement.
2 TEST BENCH

The test benches were brick masonry wallets with poor mechanical properties in order to replicate a real historical masonry, with the same weakness points, but at the same time avoiding voids and cavities, typical of real stone masonry which would otherwise influence the stress distribution along the interface and the adhesion between bulb and masonry substrate. It was chosen to build a solid brick masonry wall with four heads, with lime-based mortar whose mix-design has been properly tuned on the basis of previous studies [6], particularly "poor" in lime content to best recreate the conditions of a degraded masonry (mechanical characteristics illustrated in table1).

Table 1: Mechanical characteristics of mortar test bench

<table>
<thead>
<tr>
<th>Average compressive strength</th>
<th>Average tensile strength in bending</th>
<th>Young’s Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
</tr>
<tr>
<td>0.42</td>
<td>0.20</td>
<td>131</td>
</tr>
</tbody>
</table>

The anchoring system consists of a 20 mm diameter threaded stainless steel bar inserted in a 60 mm diameter borehole (see Table 2). The connection of the bar to the masonry substrate takes place by means of a grout injected in a special fabric sock wrapped to the anchor over the entire length (fig. 1). The anchors, once injected, were tested after a 28 days maturation of the mortar.

Table 2: Geometrical and mechanical characteristics of steel bar

<table>
<thead>
<tr>
<th>Material</th>
<th>Bar Diameter</th>
<th>Area</th>
<th>Failure tensile stress</th>
<th>Yeld point stress</th>
<th>Minimum tensile failure load</th>
<th>Minimum yeld point load</th>
</tr>
</thead>
</table>

It was defined a minimum anchor length of 400 mm. The bulb has been sunk for about 50 mm from the outer surface of the wall, in order to increase the surface area of the cone breakup, thus preventing its formation, and to be sure that the maximum tangential stresses $\tau$ would not occur near the masonry surface where the vertical confinement is minimal.

Figure 2: a) Anchors position in the masonry test bench and their interference areas; b) Strain gauges position: Type A anchor with 5 strain gauge (central anchors)

The width of the masonry walls was equal to 500 mm. It was chosen a length of 2000 mm and a height of 1000 mm with the aim of creating a set of three anchor for each wallet, ensuring a distance between the drilled holes in order to avoid the interaction between rupture
cones (Fig. 2). The confinement structure, symmetrically arranged at the top and at the base of the test bench, was realized by two beams HEB140 welded together by steel plates. In order to recreate a state of stress comparable to that obtained by the loads imposed by the upper floors of a building, a pre-stressing system has been organized, placing on the top another steel beam, loaded by two hydraulic jacks (Maximum force 60 ton ~ 576 kN), with two DYWIDAG bars passing through the cylinders, fixed to the ground (Fig. 3).

For the anchor extraction the following equipment was used:

- perforated hydraulic jack positioned in line with the anchor and orthogonal to the masonry surface (Maximum force of 30 ton ~ 326 kN)(fig. 3);
- position spring transducers (stroke 50 mm) for the measurement of the displacement, fixed to the ground in order to have an absolute reference system, at the free head of the steel rod (later purified by the elongation of the free bar) and at the mortar bulb;
- digital data acquisition system composed by a personal computer (PC) connected to the control unit of acquisition/conversion A/D (analog/digital) with 16 channels.

3 PULL-OUT TESTS WITH DIFFERENT VERTICAL AXIAL LOADS

The first aim of the experimental tests was to investigate the behavior of the anchors when preloaded with different vertical axial forces. To this end 4 wallets were made, each with a set of three holes orthogonal to the main wall plane, with anchors injected with sock length of 400 mm (plus 50 mm of sinking) and mortar currently used by the supplier (BCM Presstec, cement-based, see tab. 5). In order to better understand the anchor behavior along its length, strain gauges were glued (5 for the central anchors and 3 for the others) to the steel bar. After 28 days of curing, the walls were preloaded with different axial compressive loads:

- 0.05 MPa, comparable to a state of stress obtained from the load imposed by a bricks masonry single-storey (about 3-3.5 meters in height);
- 0.1 MPa comparable to the presence of two -storeys (about 6-7 meters);
- 0.2 MPa comparable to the presence of up to four floors (about 12-13 meters) or in the presence of high walls (such as in churches).

A pull-out load was imposed up to "collapse" by means of a hydraulic jack.

3.1 Experimental results and considerations

The failure of each tested anchor occurred on the masonry side (table 3), with extraction of a limited portion of bricks in contact with the bulb. It can be noted that with higher vertical axial stress (0.2 MPa) the portion of the extracted masonry was larger, up to two or three bricks. The rupture of the bricks or the extraction of a masonry cone was never observed, showing that the weak part of the system was the mortar, leading to bricks slippage.
Figure 5: Failure mechanisms observed in wall A after the tests.

Figure 5 shows the typical failure mechanism observed during the tests, with the different behavior between central (extraction and rotation of bricks) and lateral anchors (only extraction of bricks). Table 3 and 4 summarize the failure mechanisms, the max load at collapse, the relative displacement at the head of the mortar bulb and on the bar at the same point, the average tangential stresses on the steel bar surface (τ_bar) and on the mortar bulb surface (τ_hole).

Table 3: Monotone tests results for each of the 3 anchors in each wall (maximum load, failure mode) and average results for each wallet (maximum load and bond stresses on bar and bulb surfaces)

<table>
<thead>
<tr>
<th>WALL ID</th>
<th>VERTICAL AXIAL STRESS</th>
<th>Anch. ID</th>
<th>Max load</th>
<th>Failure mechanism</th>
<th>Anch. ID</th>
<th>Max load</th>
<th>Failure mechanism</th>
<th>Anch. ID</th>
<th>Max load</th>
<th>Failure mechanism</th>
<th>MAX LOAD</th>
<th>AVER. τ HOLE</th>
<th>AVER. τ BAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.20</td>
<td>b.6</td>
<td>54.84</td>
<td></td>
<td>b.1</td>
<td>90.01</td>
<td></td>
<td>b.7</td>
<td>77.00</td>
<td></td>
<td>73.95</td>
<td>0.98</td>
<td>2.94</td>
</tr>
<tr>
<td>B</td>
<td>0.10</td>
<td>b.8</td>
<td>37.58</td>
<td></td>
<td>b.2</td>
<td>85.15</td>
<td></td>
<td>b.9</td>
<td>42.93</td>
<td></td>
<td>55.22</td>
<td>0.73</td>
<td>2.20</td>
</tr>
<tr>
<td>C</td>
<td>0.05</td>
<td>b.11</td>
<td>40.78</td>
<td></td>
<td>b.3</td>
<td>77.04</td>
<td></td>
<td>b.10</td>
<td>53.88</td>
<td></td>
<td>57.23</td>
<td>0.76</td>
<td>2.28</td>
</tr>
<tr>
<td>D</td>
<td>0.10</td>
<td>b.12</td>
<td>55.08</td>
<td></td>
<td>b.4</td>
<td>62.30</td>
<td></td>
<td>b.13</td>
<td>50.69</td>
<td></td>
<td>56.02</td>
<td>0.74</td>
<td>2.23</td>
</tr>
</tbody>
</table>

Table 4: Monotone tests results for each of the 3 anchors in each wall: maximum load at collapse, bar and bulb displacement, bond stresses at bar and hole interfaces.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.20</td>
<td>b.6</td>
<td>54.84</td>
<td>1.21</td>
<td>1.14</td>
<td>0.73</td>
<td>2.18</td>
<td>b.1</td>
<td>90.01</td>
<td>1.87</td>
<td>1.19</td>
<td>3.58</td>
<td>b.7</td>
<td>77.00</td>
<td>1.14</td>
<td>0.95</td>
<td>1.02</td>
<td>3.06</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.10</td>
<td>b.8</td>
<td>37.58</td>
<td>2.43</td>
<td>2.24</td>
<td>0.50</td>
<td>1.50</td>
<td>b.2</td>
<td>85.15</td>
<td>3.94</td>
<td>2.50</td>
<td>3.39</td>
<td>b.9</td>
<td>42.93</td>
<td>0.79</td>
<td>NP</td>
<td>0.57</td>
<td>1.71</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.05</td>
<td>b.11</td>
<td>40.78</td>
<td>1.46</td>
<td>0.81</td>
<td>0.54</td>
<td>1.62</td>
<td>b.3</td>
<td>77.04</td>
<td>1.79</td>
<td>1.81</td>
<td>3.07</td>
<td>b.10</td>
<td>53.88</td>
<td>0.96</td>
<td>0.93</td>
<td>0.71</td>
<td>2.14</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>0.10</td>
<td>b.12</td>
<td>55.08</td>
<td>1.39</td>
<td>0.67</td>
<td>0.73</td>
<td>2.19</td>
<td>b.4</td>
<td>62.30</td>
<td>NP</td>
<td>2.48</td>
<td>b.13</td>
<td>50.69</td>
<td>1.29</td>
<td>0.88</td>
<td>0.67</td>
<td>2.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6 shows the load-displacement graph at the head of the mortar bulbs for each anchor. It is possible to observe that there is no clear proportionality with the increase of vertical axial stress, and great variability concerning both the peak value and the post-peak behavior also in
anchors in the same position and with same confinement. This shows that the response of the anchor with vertical axial stress varying between 0.05 and 0.1 MPa does not depend proportionally by the vertical axial action, probably due to other factors, for example the anchor position with respect to the courses of bricks and mortar and the execution of the holes.

![Figure 6: Load - Displacement graphs for: a) central anchors, b) lateral anchors](image)

This appear even clearer by looking at the average values for each wall (Table 3, values in blu): the average strength values for anchors of the walls B, C and D (confinement between 0.05 MPa and 0.1 MPa) are substantially equal. It is however noted that in the case of greater confinement (0.2 MPa) the average ultimate strength values is higher (+30%).

With these results, it was appropriate to design the subsequent cyclic tests in the most critical detected condition, using a realistic value of 0.06 MPa (comparable with the stress value obtained with one bricks masonry upper storey with wooden floor).

4 CYCLIC PULL-OUT TESTS ON “SHORT” ANCHORS PLACED ORTHOGONALLY TO THE MAIN WALL PLANE

The second purpose of the test was to investigate the anchors behavior under cyclic loads, to better understand their performance during seismic event, when injected with different types of mortar. Tab. 5 illustrates the characteristics of the 3 used grouts (two cement-based, one already on the market and one of new formulation, and one based on natural hydraulic lime).

Table 5: Mechanical characteristics of injection grout used during laboratory tests

<table>
<thead>
<tr>
<th>Injection mortar tyology</th>
<th>Average compressive strength</th>
<th>Average tensile strength in bending</th>
<th>Young’s Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
</tr>
<tr>
<td>BCM Presstec (cement based)</td>
<td>40,90, 45,30, 49,20</td>
<td>4,60, 6,30, 7,60</td>
<td>24,796</td>
</tr>
<tr>
<td>BCM Ms (cement based)</td>
<td>39,30, 48,00, 59,10</td>
<td>5,00, 10,60, 10,80</td>
<td>27,851</td>
</tr>
<tr>
<td>BCM Ls (lime based)</td>
<td>0,80, 2,00, 9,30</td>
<td>0,40, 0,90, 3,10</td>
<td>9,484</td>
</tr>
</tbody>
</table>

For the purpose, 3 new wallets were built for this experimental phase, and 3 anchors were placed (with the same characteristics illustrated in topic 3), in each of the 3 walls where different types of injection mortar were used.

The cyclic tests were conducted in a quasi-static mode with a limited number of cycles (aimed at evaluating the decay of the resistance – oligocyclic Fatigue Tests, fig. 7) , under force control and applying increasing load values until collapse (increasing displacements in
presence of stable or decreasing load), with 3 cycles of loading and unloading for each value of applied force (fig. 7). There was no load inversion, since the anchors were made of bars not subject to withstand significant compression actions.

![Loading history for cyclic tests on "short" anchors](image)

**Figure 7**: Loading history for cyclic tests on “short” anchors

### 4.1 Experimental results and considerations

Table 6 shows that the failure, for each tested anchor, was masonry side, with extraction of a limited portion of brick blocks slid on weak mortar joints.

Table 6: Cyclic tests results for each of the 3 anchors in each wall (maximum load, failure mode) and average results for each wallet (maximum load and bond stresses on bar and bulb surfaces)

<table>
<thead>
<tr>
<th>WALL ID</th>
<th>INJECTION GROUT</th>
<th>Anch. ID</th>
<th>Max load</th>
<th>Failure mechanism</th>
<th>Anch. ID</th>
<th>Max load</th>
<th>Failure mechanism</th>
<th>Anch. ID</th>
<th>Max load</th>
<th>Failure mechanism</th>
<th>MAX AV. LOAD</th>
<th>AV.  HOLE</th>
<th>AV.  BAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>kN</td>
<td>kN</td>
<td></td>
<td>kN</td>
<td>kN</td>
<td></td>
<td>kN</td>
<td>kN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-PR</td>
<td>BCM Presstec (cement)</td>
<td>B1</td>
<td>35,01</td>
<td>A1</td>
<td>45,75</td>
<td>B2</td>
<td>37,27</td>
<td>39,34</td>
<td>0,52</td>
<td>1,57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BCM Hs (cement)</td>
<td>B3</td>
<td>32,52</td>
<td>A2</td>
<td>44,55</td>
<td>B4</td>
<td>36,60</td>
<td>37,89</td>
<td>0,50</td>
<td>1,51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BCM Ls (lime)</td>
<td>B5</td>
<td>27,22</td>
<td>A3</td>
<td>45,90</td>
<td>B6</td>
<td>29,36</td>
<td>34,16</td>
<td>0,45</td>
<td>1,36</td>
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<td></td>
</tr>
</tbody>
</table>

Compared to the monotonic tests, and regarding anchors injected with cement-based mortar, the break affected a larger part of the masonry. In anchors injected with lime-based mortar
the damage was less evident and limited to a small portion of masonry. It can be observed that the cement-based injected anchors performances are very similar, both for central and lateral anchors, while the lime-based injected lateral anchors show smaller resistance values (max load is 20% lower than the average of the values reported for cement-based lateral anchors).

For each anchor the force displacement graph was obtained under the execution of cyclic loading, in which the hysteresis loop showed for all investigated points (the starting point of the steel bar and of the mortar bulb) an increase in the residual displacement both at the increasing of the applied load and at the increasing of the number of cycles at the same load.

Even more interesting is to analyze the response of the anchor along its length: Fig. 8. illustrates (as an example for the bulb A1) the deformation pattern along the bar up to a maximum load (collapse), while fig. 8. b) illustrates the evolution of shear stresses along the bar at increasing load, calculated as average values along the sections between two strain gauges.

From fig. 8.a) it can be observed that for very low load values at the end of each step the strains are the same (with a superposition of the obtained curves). Starting from 20 kN load, it can be observed that at the end of the third step there are greater deformations, especially in areas closer to the loading end, thus indicating that the axial stress $\sigma$ transferred from one point to another is greater, index of damage in the system. Close to the max load this phenomenon is more evident.

At the same time, from fig. 8.b) it can be observed that for low load values the average $\tau$ trend shows a peak in the first section, closer to the load end, and with increasing load we observe a peak recession, due to a possible damage of the masonry near the load end. With further load growth (near the maximum load), the peak shows a further recession and a more regular trend, showing that a damage, and therefore a slippage of the blocks, has incurred also in the anchor’s central part, with a probable bulb cracking or breaking in that area.

Comparing the results and graphs obtained for each anchor, the average resistance values obtained for each wallet (tab 6, values in blu), and also comparing results obtained during cyclic tests with those obtained during monotone tests (fig. 9), it is possible to note that:

- cyclic loads accelerated the system damage, with a peak recession in the curve of the tangential stresses (even with low load values) and with maximum load value at failure (or collapse) lower by approximately 35% (compared to monotonous tests results);
- in general, anchorage length of 400 mm was not sufficient to transfer the stresses in the deeper area to compensate the damage in the areas closest to the load end;
- with regard to the two cement-based mortars their behavior is rather similar;
• in anchors injected with lime-based mortar the average resistance values are slightly smaller than those obtained with the two cement-based mixtures (approximately 13%);
• in the comparison between monotonic and cyclic tests (fig. 9) with the same injected grout (Presstec) and same confinement value (0.05 and 0.06 MPa, wall A_PR and wall C) the maximum load is reduced, in the case of cyclic tests, by 32%.
• in the comparison between monotonic and cyclic tests (fig. 9) with the two cement-based injected grout (Presstec and Hs) and comparable confinement value (from 0.05 to 0.1 MPa), the maximum load is reduced again, in the case of cyclic tests, by 32%.

<table>
<thead>
<tr>
<th>WALL ID</th>
<th>INJECTION GROUT</th>
<th>VERT. AXIAL STRESS MAX AVER. LOAD</th>
<th>AVER.  HOLE</th>
<th>AVER.  BAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-PR</td>
<td>BCM Presstec (cement)</td>
<td>0.06</td>
<td>39.34</td>
<td>0.52</td>
</tr>
<tr>
<td>B-HS</td>
<td>BCM Hs (cement)</td>
<td>0.06</td>
<td>27.99</td>
<td>0.50</td>
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<tr>
<td>AVERAGE VALUES</td>
<td></td>
<td></td>
<td>38.61</td>
<td>0.51</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WALL ID</th>
<th>INJECTION GROUT</th>
<th>VERT. AXIAL STRESS MAX AVER. LOAD</th>
<th>AVER.  HOLE</th>
<th>AVER.  BAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>BCM Presstec (cement)</td>
<td>0.10</td>
<td>55.22</td>
<td>0.73</td>
</tr>
<tr>
<td>C</td>
<td>BCM Presstec (cement)</td>
<td>0.09</td>
<td>57.23</td>
<td>0.76</td>
</tr>
<tr>
<td>D</td>
<td>BCM Presstec (cement)</td>
<td>0.10</td>
<td>56.02</td>
<td>0.74</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td></td>
<td></td>
<td>56.16</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Figure 9: Comparison between monotone and cyclic tests results in anchor injected with cement base mortar

5 CYCLIC AND MONOTONE PULL-OUT TESTS ON “LONG” ANCHORS PLACED LONGITUDINALLY TO THE MAIN WALL PLANE

To investigate the behavior of greater length anchors, injected longitudinally, it was chosen a length that, considering a cement-based injection grout, could reach, by monotone pull-out tests, the bar yield strength, thus equal to 900 mm [1] [2], placed with 50 mm sinking.

The test bench is represented by 9 walls (7 already used for the illustrated experiments and 2, E and F walls, made of ungrounded bricks and without vertical joints). In each wall one anchor (9 anchors to test) was placed, all of the same size and same steel bar, but with three types of injection mortar. For each injection mortar it was possible to test 3 different anchors: one (with 3 strain gauges) for the monotonous pull-out test; two (one with 3 strain gauges and another with 6) for the cyclic-pull out tests.

The monotone pull-out tests were conducted increasing the applied load up to “collapse”, under force control. The cyclic tests were conducted in a quasi-static mode with a limited number of cycles, aimed at assessing the resistance decay (oligocyclic fatigue tests, fig. 10), under force control, with 3 cycles of loading and unloading for each applied load up to failure.

Figure 10: Loading history for cyclic tests on "long" anchors
5.1 Experimental results and considerations

Tab. 8 illustrates each anchor characteristics, the observed failure mechanisms, the maximum load at collapse and the relative displacement and average bond stress, both along hole and bar surface.

Table 8: Cyclic tests results for each of the 3 long anchors: maximum load at collapse, bar and bulb displacement, bond stresses at bar and hole interfaces, failure mode

<table>
<thead>
<tr>
<th>ANCH. ID</th>
<th>WALL TYPOLOGY</th>
<th>INJECTION GROUT</th>
<th>TEST TYP.</th>
<th>MAX LOAD [kN]</th>
<th>Bar disp. [mm]</th>
<th>Bulb disp. [mm]</th>
<th>τ hole [Mpa]</th>
<th>τ bar [Mpa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-PR-4</td>
<td>UNGRIND BRICKS - NO VERTICAL JOINTS</td>
<td>BCM Presstec (cement)</td>
<td>Monotone</td>
<td>126,27</td>
<td>2,84</td>
<td>2,21</td>
<td>0,74</td>
<td>2,23</td>
</tr>
<tr>
<td>A-PR-8</td>
<td>VERTICAL JOINTS</td>
<td>Cyclic</td>
<td>118,19</td>
<td>2,51</td>
<td>1,69</td>
<td>0,70</td>
<td>2,09</td>
<td></td>
</tr>
<tr>
<td>C-PR-3</td>
<td>VERTICAL JOINTS</td>
<td>Cyclic</td>
<td>138,13</td>
<td>6,84</td>
<td>6,25</td>
<td>0,81</td>
<td>2,44</td>
<td></td>
</tr>
<tr>
<td>D-HS-6</td>
<td>VERTICAL JOINTS</td>
<td>Monotone</td>
<td>183,78</td>
<td>5,47</td>
<td>2,69</td>
<td>1,08</td>
<td>3,25</td>
<td></td>
</tr>
<tr>
<td>F-HS-7</td>
<td>UNGRIND BRICKS - NO VERTICAL JOINTS</td>
<td>BCM Hs (cement)</td>
<td>Cyclic</td>
<td>98,13</td>
<td>6,21</td>
<td>4,44</td>
<td>0,58</td>
<td>1,74</td>
</tr>
<tr>
<td>B-HS-2</td>
<td>VERTICAL JOINTS</td>
<td>Cyclic</td>
<td>131,29</td>
<td>4,54</td>
<td>3,70</td>
<td>0,77</td>
<td>2,32</td>
<td></td>
</tr>
<tr>
<td>A-LS-9</td>
<td>VERTICAL JOINTS</td>
<td>BCM Ls (lime)</td>
<td>Monotone</td>
<td>110,82</td>
<td>5,69</td>
<td>4,73</td>
<td>0,65</td>
<td>1,96</td>
</tr>
<tr>
<td>B-LS-5</td>
<td>VERTICAL JOINTS</td>
<td>Cyclic</td>
<td>57,96</td>
<td>0,91</td>
<td>0,34</td>
<td>0,34</td>
<td>1,02</td>
<td></td>
</tr>
<tr>
<td>C-LS-1</td>
<td>VERTICAL JOINTS</td>
<td>Cyclic</td>
<td>100,29</td>
<td>15,99</td>
<td>10,97</td>
<td>0,59</td>
<td>1,77</td>
<td></td>
</tr>
</tbody>
</table>

It is possible to observe the following points:

a) anchors injected into masonries without vertical joints (E-PR-4 and F-HS-7) showed resistance values 25% lower than the ones obtained by comparable specimens in masonries with vertical joints (D-HS-6 and B-HS-2);

b) in analyzing the data related to cement-based grout injected anchors, and only relating to walls with vertical joints, comparing the monotonous test max load (in D-HS-6, which led to the bar yield strength, nominally 170 kN) with the average of max loads achieved in cyclic tests (A-PR-8, C-PR-3, B-HS-2), it can be observed a reduction of 24%;
c) in analyzing the data related to lime-based mortar injected anchors, it can be observed that the average of the maximum load obtained during cyclic tests (B-LS-5 and C-LS-1) is reduced by 28% compared to that obtained during the monotonic test (A-LS-9);

d) concerning the failure mode, it was observed a large masonry breakup (with the extraction of a masonry cone from the depth of the anchor, by blunt dissection of vertical joints and blocks slip on horizontal joints) in the anchors injected with cement based mortar, while in those injected with lime-based mortar the breakup was only of few blocks around the anchor. As a matter of fact in these anchors there has been an in depth stresses diffusion (which justifies the high values of the reached maximum load), anyway with an overrun of the mortar resistance in some points, causing breaks in the bulb: in the breaking points a localization of deformation (elongation) in the steel bar led to the extraction of the anchor with bricks in its surroundings (see also Fig. 12. b);

e) comparing only the results of monotone tests, the lime based mortar injected anchor reached a maximum value of 35% lower than the one reached in cement base anchor (considering the yield point at 170 kN);

f) comparing only the results of cyclic tests, the lime based mortar injected anchors reached,
in average, a maximum value of 38% lower than the average related to the maximum loads reached in cement base anchors.

It is interesting to observe the trend of bond stresses along the bar at increasing applied loads comparing monotone to cyclic test for anchor injected with cement mortar (an example in fig. 11) and with lime mortar (an example in fig. 12).

For anchors injected with cement-based mortar, it can be observed that during monotonic test (Fig. 11.a) the trend of bond stresses is regular, with a recession of the peak only at high values of the applied load (from 90 kN). In the case of cyclic tests (Fig. 11.b) the trend in the bond stresses curve is regular with cycles up to 30 kN. From 50kN it can be observed a highly irregular pattern along the bulb length, and over 100 kN also a peak recession. This irregular pattern is indicative of a system damage, a probable slippage of the blocks, even when the first part of the anchor is still able to sustain high shear stresses.

Regarding anchors injected with lime-based mortar, it was observed that for the monotonic test (fig. 12.a) until the application of a 60 kN load the curve has a fairly regular trend, over it was observed a peak recession, indicating that the first part of the anchor was no longer able to sustain higher shear stress values, compensating by a deeper anchor part. Looking at the results of cyclic test (Fig. 12.b) it can be noticed a highly irregular trend starting from 30-50 kN load, demonstrating a strong system damage, for slippage of the blocks and breakage of the mortar bulb, compensated by the undamaged parts of the anchor (given the long distribution) which allowed to reach up to high final resistance value (100.27 kN). The graph shows
the stresses diffusion in depth, however with an overrun of the strength of the mortar, causing a break in the bulb in two central points of the anchor (around 150 mm and 350 mm).

In general it can be also observed that the greater anchor length allowed to better exploit the bond phenomenon, due to the possibility of transferring stresses from the damaged to undamaged areas.

6 CONCLUSION AND REMARKS

As a conclusion of the present research work it is possible to observe that:

a) the response of anchor injected in a brick masonry of poor quality (with the test bench characteristics) and with length equal to 400 mm, is not closely depending on the vertical axial confinement for fairly low value (0.1 MPa), while the dependence increase at the increasing of confinement (0.2 MPa);

b) cyclic pull-out test, when compared to monotonic tests, have led to a maximum value of applied load at failure reduced between 25 and 35%, both in short and long anchor, both with lime based and cement based mortar, even if with different behavior and failure mode.

7 REFERENCES


