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

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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. Laboratory tests with masonry specimens (bricks and mortar with low characteristics to replicate real historical masonry) were conducted to analyse the response of steel anchors injected using a special sock and with different types of mortar (cement and lime based).

The test benches replicate the real condition of the use of these anchors: they allow to simulate the connection of masonry panels (T and L connections) or the anchor of steel ties to contrast the arch thrust. Monotonic and cyclic pull out tests were conducted on short and long anchors to define the loss of strength under cyclic loads for different situations.

The results allowed to obtain: load-displacement graphs; steel bar deformation graphs on anchors' length; a qualitative bond stress curve; comparison among maximum strengths obtained under several conditions.

Running Head: INJECTED ANCHORS in HISTORICAL masonry buildings

Keywords: Masonry, Anchors, Seismic behaviour, Pull-out test, Reinforcement, Injection

INTRODUCTION

In recent years interest in the use of anchors in historic masonry is increasing, especially with regard to existing buildings' seismic improvement and retrofit. In masonry buildings subjected to earthquakes, the first-order mechanisms (wall overturning or out of plane mechanisms) represent the main cause of collapse, where wooden slabs are often used and do not guarantee any effective diaphragm effect or where central walls are not tied to the perimeter ones. A classical retrofitting solution, against these well-known failure mechanisms [1-6], is made by perimeter ties placed along the masonry walls at the level of the horizontal elements and at the T nodes between orthogonal walls.

External anchor plates are not usable in the presence of elements of value (paintings or decorations) or of geometric constraints that do not allow pass-through perforations. In these situations, anchors in the thickness of the masonry, made by a steel bar placed in a borehole grouted by means of mortar, is the best solution. Different studies have been carried out on this technology.

In 1997 the study of the local behaviour of steel dowels used to transfer horizontal shear loads between concrete slabs and stone masonry walls had been carried out [7].

At the same time a research project investigated the bond strength of supplementary injection anchors as a repair method in historic masonry, consisting of a tensile element inserted into the slightly larger borehole with the annulus grouted with cement. Field pull-out tests have been performed at different historic monuments during the research program, reflecting on the evaluation of bond strength considering different methods [8]. Investigating the loadbearing characteristics of these injection anchors and considering the lack of codes dealing with admissible bond stresses, design recommendations for injection anchors, based on the results of 500 pull-out tests in the laboratory and in-situ, were given [9] and latest results about the influence of restraint to free transverse deformations were provided [10].

A number of recommendations for the formulation of mineral injection grouts in historical buildings have been also provided [11–12].

Recently, in order to better understand the seismic performance of masonry wall-to-half-timbered wall and timber elements connections, tests were carried out in representative real scale specimens in which injected anchors were installed in an irregular stone masonry wall in order to improve the seismic response of the connection. Monotonic and cyclic pull-out tests were performed on representative connections in order to assess their performance and allow their characterization [13-14].

Another research has studied two typologies of dissipative devices that can be integrated in traditional steel anchors and installed within the masonry at the joints of perpendicular walls: pull-out tests aimed to analyse the behaviour of the hysteretic prototype in respect to traditional steel anchors in masonry panels have been carried out [15] and procedures specific to the strengthening of structural connections of historic buildings thus have been developed [16].

Moreover, the present research is addressed to the study of anchors injected using a special "sock" to contain the bar and the injected grout, to ensure that the mortar remains confined within the borehole (**Fig. 1**), thus realising 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.

A past research on the behaviour of injected anchors with sock in historical masonry had foreseen several preliminary tests in laboratory and a first series of in situ tests on different types of masonry. The tests allowed the definition of the strength of the anchors and the collapse mechanisms, developing a methodology to be used as a preliminary design stage for structural interventions. A standard set up test to perform extraction tests was also defined [17].

With these premises, and considering that this technology needed more investigation and new efforts to assess the behaviour in the presence of seismic actions, thus under cyclic loads, 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) anchors.

Since the anchors are subjected to axial forces, the laboratory experimental campaign consisted of the following tests:

1) monotonic pull-out tests on “short” anchors injected orthogonally to the masonry plane and loaded with different vertical loads, in order to assess the influence of transverse normal 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 monotonic pull-out tests on "long" anchors injected in the main wall plane and with three different types of grout.

4) monotonic pull-out tests on anchors with the same characteristics and conditions in 1), but injected in a masonry with improved quality, in order to deeper investigate the influence of the masonry quality on the anchor behaviour;

The aim of the four experimental series 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 normal loads due to the presence or not of upper floors; holes to be provided orthogonally to the wall plane and so with high lateral confinement, but with anchor length conditioned by the thickness of the wall; holes to be provided along the masonry plane and so with the possibility of high anchor lengths, but low lateral confinement.

Table 1 illustrates the full testing programme, described in the following, and **Figure 2** illustrates the different types of anchors.

TEST BENCH

The test specimens were brick masonry wallets with poor mechanical properties in order to replicate a real historical masonry, thus 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.

Masonry typology

A solid brick masonry wall with four heads was built, as shown in **Fig. 3**, with lime-based mortar whose mix-design has been properly tuned on the basis of previous studies [18], particularly "poor" in lime content to best recreate the conditions of a degraded masonry. **Table 2** illustrates the lime-based mortar composition and mechanical characteristics obtained with laboratory test on 7 specimens, after 28 days of curing, applying standard “EN 1015-11, 2006, Methods of test for mortar for masonry. Part 11: Determination of flexural and compressive strength of hardened mortar” and on one specimen, after 28 days of curing, applying standard “EN 6556, 1976, Determination of static modulus of elasticity in compression”.

Anchor’s characteristics

The anchoring system consists of a 20 mm diameter threaded stainless steel bar (commercialized and suggested by Bossong spa) inserted in a 60 mm diameter borehole (**Table 3** illustrates the Geometrical and Mechanical characteristics in the Supplier technical data sheet). Only in one wall (wall E in the following), 24 mm diameter bars were used, since they were used in a real in situ case study and it was useful to obtain some new data [19]. 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 its entire length (**Fig .1**). The sock plays a triple role: to confine the mixture, avoiding uncontrollable leakage of grout inside the masonry, to allow an effective expansion of the sock as it molds to the cavity and contributes to the anchor adherence itself, to allow the leakage of liquid residues.

The anchors, once injected, were tested after 28 days of curing of the mortar.

Wallets dimensions

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

The width of the masonry walls was equal to 500 mm. A length of 2000 mm and a height of 1000 mm were chosen with the aim of creating a set of three anchors for each wallet, for tests series with "short" anchors injected orthogonally to the main masonry plane, ensuring a distance between the drilled holes to prevent the interaction between rupture cones (**Fig. 4**).

Confinement structure and vertical pre-stressing system

The confinement structure, symmetrically arranged at the top and at the base of the test wallets, was made by two beams 2100 mm long HEB140 welded together by 20 mm thick steel plates, spaced from the wall by polystyrene and plywood sheets, which provide the laying surface of the masonry. This casing is able to exert a uniform pressure on the masonry. 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 organised, by 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 and fixed to the ground (**Fig. 5**). It's important to underline that this pre-stressing system is applied only during the pull-out tests, i.e. in test conditions, the imposed loads by this pre-stressing system are leading to a vertical (transversal) compression on the “injected anchors” executed before. In real conditions, when the “injected anchors” are executed, the walls have already installed the loads imposed by the upper floors of building, i.e. the “injected anchors” are not subjected directly to a vertical (transversal) compression in correspondence to those loads. Thus it’s evident that the real conditions are not perfectly replicated (with natural consequences on the results), nonetheless it was important to differentiate the imposed loads to verify the most critical conditions in laboratory to design the subsequent cyclic tests.

The imposed load has been monitored during the tests by a pressure transducer connected to the two jacks.

Test Layout and instrumentation

The extraction contrast structure was provided by a steel beam placed directly on the wall, to create a self-balanced system. The distance between the support points was chosen to not inhibit the possible extraction of a masonry cone (**Fig. 6**).

For the anchor extraction, the following equipment was used:

- a perforated hydraulic jack positioned in line with the anchor and orthogonal to the masonry surface (Maximum force of 30 ton ~ 326 kN) (**Fig. 6**);
- position spring transducers (stroke 50 mm) for the measurement of the displacement (fixed to the ground in order to have an absolute reference system) placed one at the free head of

the steel rod (later purified by the elongation of the free bar) and one at the head of the mortar bulb;

- a 16 channels digital data acquisition system composed by a computer connected to the control unit of acquisition/conversion A/D (analog/digital).

MONOTONIC PULL-OUT TESTS WITH DIFFERENT VERTICAL AXIAL LOADS

The first aim of the experimental tests was to investigate the behaviour of the anchors when preloaded with different normal axial forces.

First phase: wallets A, B, C, D

With this purpose 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 **Table 4,** standards applied in tests “EN 1015-11, 2006. Part 11” and “EN 6556, 1976”). In order to better understand the anchor behaviour along its length, strain gauges were glued on the steel bar after machining (5 for the anchor placed in the centre and 3 for those placed laterally). Although the application of strain gauges might affect the bond behaviour, nonetheless 3 (or 5) strain gauges were applied by removing the threads for less than 20 mm around each gauge. Being the anchorage length equal to 400 mm, the overall bond behaviour may be assumed to be unaffected by the strain gauges. The distance between the strain gauges was chosen to better observe, in particular, the adhesion stresses closer the load end, where they present a peak, then with increasing distances away from such point (**Fig. 7**)

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 brick 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.

Experimental results of first phase

The failure of each tested anchor occurred on the masonry side (**Table 5**), with extraction of a limited portion of bricks in contact with the bulb. With higher normal axial stress (0.2 MPa) the portion of the extracted masonry was larger, up to two or three bricks. In particular, when the anchor was installed in one brick only, with low confinement values up to 0,1 MPa, only the brick in which the anchor was installed was pulled-out and for a confinement value equal to 0,2 MPa more bricks were involved in the anchor pull-out (both in the case that the anchor was inserted in a brick, and between bricks). Being the wallet made of 4 heads, the fact that more bricks were involved in the pull-out implies that with higher confinement values the anchorage failure occured deeper in the wall thickness. The rupture of the bricks or the extraction of a masonry cone never occurred, showing that the weak part of the system was the mortar, leading to brick slippage.

Fig. 8 shows the typical failure mechanism observed during the tests, with the different behaviour between central and lateral anchors. In the case of lateral anchors, where the hole was in header course bricks, there was the extraction of the bricks adherent to the bulb, while in the case of central ones, where the hole was in stretcher course bricks, there was the outward rotation of the two bricks adjacent to the bulb.

Table 5 and **6** summarise the failure mechanisms, the max load at collapse and the relative displacement at the head of the mortar bulb and on the steel bar at the same point, the average tangential stresses on the steel bar surface (τ_bar) and on the mortar bulb surface (τ_hole). The average tangential stresses are calculated, starting from the measured max load, with the following:

$\tau\_bar = L_{max} / (l_b \pi \emptyset_s)$ $\tau\_hole = L_{max} / (l_b \pi \emptyset_h)$

where:

l_b is the anchor lenght

$\emptyset_s$ is the bar diameter

$\emptyset_h$ is the hole diameter

L_{max} is the max load at collapse.

Fig. 9 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 behaviour, also in anchors in the same position and with same confinement. This shows that the response of the anchor with normal axial stress varying between 0.05 and 0.1 MPa does not depend proportionally on the normal stress. This can be caused by other factors, like the anchor position in respect to the courses of bricks and mortar or the execution of the holes.

This appears even clearer by looking at the average values for each wall (**Table 5**, values in blue): 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. However, it is noted that in the case of greater confinement (0.2 MPa) the average ultimate strength value is higher by a factor of 1.31 (+31%).

Second phase: wallets E, F without vertical joints

To further investigate the behaviour, it was decided to build other 2 wallets (wall E and F), with poorer characteristics. They were made by unrectified bricks, using the same mortar but without vertical joints. In wallet E were injected 3 anchors consisting of a 20 mm diameter threaded stainless steel bar inserted in a 60 mm diameter borehole, and grout injected in the special fabric sock with the same mechanical characteristics, both for steel bar and injected grout (BCM Presstec, cement-based, see **Table 4**), used for wallets A,B,C and D. In wallet F were injected 3 anchors using the same grout, but consisting of 24 mm diameter threaded stainless steel bars inserted in a 72 mm diameter boreholes (mechanical characteristics illustrated in **Table 3**). After

28 days of curing, the walls were preloaded with an axial compressive loads of 0,2 MPa and pull-out loads were imposed up to "collapse" by means of a hydraulic jack.

Experimental results of second phase

Table 5 and **6** (in the bottom, rows in grey) summarise the failure mechanisms for these new tests. Comparing the results obtained in wall E with the ones obtained in wall A, which was preloaded with the same value of vertical axial stress, and in particular observing the average value (**Table 5**, values in blue), it’s possible to note that the average ultimate strength of the anchor decreases from 73.95 kN to 60.75 kN, thus by a factor 0.82 (– 18%).

The differences in values of ultimate strength between the results obtained in wall E (with 20 mm bar) and wall F (with 24 mm bar), under the same conditions, are also shown: with a 20 mm bar it’s observed an average value of 60.75 kN, and with a 24 mm bar an average value of 37.36 kN, decreased by a factor 0.61 (-39%).

Final consideration on monotonic pull-out test on “short” anchors

The results of this first series of experimental tests lead to argue that:

- the response of anchor injected in a brick masonry of poor quality and with length equal to 400 mm, is not closely depending on the vertical transverse confinement for fairly low confinement values (0,1 MPa), while the dependence increase at the increasing of confinement (0,2 MPa). This consideration is valid with reference to the actual laboratory conditions (pre-stressing system is applied only during the pull-out tests) and it can only partially transferred to real conditions (when the walls have already installed the loads imposed by the upper floors of building)

- the lower load capacity of this sort of injected anchors depends on the masonry quality, for example the load capacity of anchors injected in a masonry without vertical joints appears to decrease by about 1/5 if compared to the one of anchors injected in masonries with vertical joints.

Following the results, the subsequent cyclic tests have been designed, considering the most critical detected condition with reference to the normal axial load, thus defining a realistic value of 0.06 MPa (comparable with the stress value obtained with one bricks masonry upper storey with wooden floor).

CYCLIC PULL-OUT TESTS ON "SHORT" ANCHORS PLACED ORTHOGONALLY TO THE MAIN WALL PLANE

The second purpose of the tests was to investigate the anchors behaviour under cyclic loads, in order to better understand their performance during seismic events when injected with different types of mortar. **Table 4** illustrates the characteristics of the 3 grouts used (two cement-based, one already on the market and one of new formulation, and one based on natural hydraulic lime).

Cyclic tests: wallets A-PR, B-HS, C-LS

For this purpose, 3 new wallets were built. Three anchors were placed (with the same characteristics illustrated in section 3) in each of the 3 walls and different types of injection mortars were used. The cyclic tests were conducted in a quasi-static mode with a limited number of cycles. This was aimed to evaluate the decay of the resistance, under force control, applying increasing load values up to collapse, with 3 cycles of loading and unloading for each value of applied force. Since the anchors were made of bars not subject to withstand significant compression actions, there was no load inversion. **Fig. 10** illustrates the loading history for each anchor until the last cycle it underwent (since they failed at different loads).

Experimental results

Table 7 shows that the failure, for each tested anchor, was on the masonry side, with extraction of a limited portion of brick blocks sliding on weak mortar joints.

Compared to the monotonic tests and regarding anchors injected with cement-based mortar, the failure 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.

Table 7 and **8** summarise the failure mechanisms, the max load at collapse and 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).

It has been 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 under cyclic loads was obtained; 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 of the number of cycles at the same load (**Fig. 11**).

Even more interesting is to analyse the response of the anchor along its length: **Fig. 12.a** illustrates for the bulb A1 the deformation pattern along the bar up to a maximum load (collapse), while **Fig. 12.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. 12.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 σ transferred from one point to another is greater, indicating damage in the system. Close to the max load this phenomenon is more evident.

At the same time, from **Fig. 12.b** it can be observed that for low load values the average τ trend shows a peak in the first section, closer to the load end. With increasing load a peak recession is observed, due to possible damage of the masonry near the load end. With further load growth (near the maximum load), the peak shows a further recession and also an irregular trend, showing that damage has incurred (and therefore a slippage of the blocks) also in the anchor's central part, with a probable bulb cracking or breaking in that area.

Final consideration on cyclic pull-out tests on short anchors

Comparing the results and graphs obtained for each anchor, the average resistance values obtained for each wallet (**Table 7**, values in blue) and also comparing results obtained during cyclic tests with those obtained during monotonic ones (**Fig. 13**), 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 30-35% (compared to monotonic tests results);

- in general, an anchorage length of 400 mm was not sufficient to transfer the stresses in the deeper area to compensate the damage in the areas closer to the load end;

- with regard to the two cement-based mortars their behaviour is rather similar, while in anchors injected with lime-based mortar the average resistance values are slightly lower than those obtained with the two cement-based mixtures. These results lead to say that in “short” anchor its behaviour depends on the grout, but not in relevant measure, since there are other factors that influence more the behaviour, considering the short length, such as the quality of the masonry or the anchor position. Considering grouts, whose mechanical characteristic are similar (like the two cement based, that have comparable Young’s modulus and the mechanical characteristics differ for 20-40%) the response is not really influenced, while considering grouts whose mechanical characteristics presents relevant differences (like lime based : cement based) the influence is shown (even if not relevant as observed and commented above).

- in the comparison between monotonic and cyclic tests (**Fig. 13**) 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 by 32% in the case of cyclic tests. In the comparison between monotonic and cyclic tests (**Fig. 13**) 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 by 32%, in the case of cyclic tests, confirming also that, in "short" anchors, the behaviour is not influenced by the grout type when the mechanical characteristic of the grouts are comparable.

Moreover, about the behaviour during cyclic test, the results substantially confirm what was previously observed by authors during the in situ tests campaign on real historical stone masonry, where it was noted that the application of load cycles leads to a 27% reduction of the maximum strength (maximum applied load on 320 mm length anchors submitted to 0,08 MPa vertical confinement) compared to the result of monotonic pull-out test [20], leading to argue that the load capacity in cyclic pull-out test on "short" anchors, when compared to monotonic tests, decrease approximately by 30%.

CYCLIC and monotonIC PULL-OUT TESTS ON "long" ANCHORS PLACED longitudinally ALONG THE MAIN WALL PLANE

To investigate the behaviour of longer anchors, a 900 mm length was chosen, with 50 mm sinking, that could reach the bar yield strength by monotonic pull-out tests in the case of cement-based injection grout [8-10] [17] [19].

Cyclic and monotonic pull-out tests

The test bench is represented by 9 walls (already used for the illustrated experiments, and with wallets E and F, made of unrectified bricks and without vertical joints). In each wall only one anchor (9 anchors to test) was placed, all made of the same steel and with the same diameter but with three different types of injection mortars. In a second phase, only in the wallet where the steel bar reached the yield point after test (wallet D, thus with no damages to the masonry), it was possible to place a second anchor (D-PR-3). For each injection mortar it was possible to test 3 different anchors (4 for BCM Presstec grout), as illustrated in **Table 1,** instrumented with 3 or 6 strain gauges. The monotonic 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 to assess the resistance decay (**Fig. 14**), under force control, with 3 cycles of loading and unloading for each applied load up to failure.

Experimental results and considerations

Table 9 illustrates each anchor characteristics, the observed failure mechanisms, the maximum load at collapse and the relative displacement and average bond stress, both along the hole and bar surfaces.

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 20-25% lower than the ones obtained by comparable specimens in masonries with vertical joints (D-PR-3 and B-HS-2);

b) a reduction of 23% was observed in analysing the data related to BCM HS cement-based grout injected anchors (only with reference to walls with vertical joints) comparing the monotonic test maximum load (D-HS-6, which led to the bar yield strength, nominally 170 kN) with the max loads achieved in cyclic test (B-HS-2). A reduction of 20% was observed in analysing the data related to BCM Presstec cement-based grout injected anchors, comparing the monotonic test maximum load (D-PR-3) with the average of max loads achieved in cyclic tests (A-PR-8, C-PR-3).

c) in analysing 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, a large masonry breakup was observed in the anchors injected with cement based mortar (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), 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 stress 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 localised deformation (elongation) in the steel bar led to the extraction of the anchor with bricks in its surroundings (see also **Fig. 15.b**);

e) the results obtained with BCM HS and BCM Pressetc cement-based mortars are not exactly the same, but they differ only by 6% in monotonic tests (D-HS-6:D-PR-3) and by 2% in cyclic tests (B-HS-2:A-PR-8 and C-PR-3).

f) comparing only the results of monotonic tests, the lime based grout injected anchor reached a maximum value of 33% lower than the average maximum load reached in cement base anchors;

g) comparing only the results of cyclic tests, the lime based grout injected anchors reached, in average, a maximum value of 38% lower than the average maximum load reached in cement base anchors.

It is interesting to observe the trend of bond stress along the bar at increasing applied loads comparing monotonic to cyclic tests for anchors injected with cement mortar (**Fig. 16**) and with lime mortar (**Fig. 15**). For anchors injected with cement-based mortar, during monotonic test (**Fig. 16.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. 16.b**) the trend in the bond stresses curve is regular with cycles up to 50 kN. From 70 kN a highly irregular pattern along the bulb length was observed. This irregular pattern is indicative of system damage, a probable slippage of the blocks and breakage of the mortar bulb, even when the first part of the anchor is still able to bear high shear stresses.

Regarding anchors injected with lime-based mortar, it was observed that for the monotonic test (**Fig. 15.a**) the curve has a fairly regular trend until the application of a 60 kN load. Beyond a peak recession was observed indicating that the first part of the anchor was no longer able to bear high shear stress values. Looking at the results of cyclic tests (**Fig. 15.b**) a highly irregular trend can be noticed starting from 30-50 kN load. This demonstrates strong system damage, caused by slippage of the blocks and breakage of the mortar bulb, compensated by the undamaged parts of the anchor which allowed to reach a high final strength value (100.27 kN). The graph shows the stress diffusion along the bar, overcoming the strength of the mortar, causing a break in the bulb in two central points of the anchor (around 150 mm and 350 mm).

Final considerations on monotonic and cyclic tests on “long” anchors

The comparison between results obtained in wallets without vertical joints and the ones obtained in wallets with vertical joints shows, once again, that the masonry quality influences the anchor behaviour. Furthermore, the results obtained with different type of grouts show that the best performance are obtained with the grout with the best mechanical characteristics, thus the grout type highly influences the anchor behaviour with reference to “long” anchors.

Cyclic pull-out test, when compared to monotonic tests, have led to a maximum value of applied load at failure generally between 20 and 28% smaller, where the bigger difference is obtained with lime-based grout.

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

MONOTONIC PULL-OUT TESTS in wallets built with improved mortar

The last aim of this laboratory tests campaign was to analyse and quantify the behaviour of the anchors, when injected in masonry with better mechanical characteristics. Since the weak point was found to be in the mortar, it was decided to produce new wallets, with the same dimension illustrated in section 2, but using a mortar still with low mechanical characteristic (to replicate a historical mortar), but improved with respect to the one indicated in **Table 2**.

Test on wallets with improved mortar: G,H,I

A lime mortar with mechanical characteristics illustrated in **Table 10** (standards applied in tests “EN 1015-11, 2006. Part 11” and “EN 6556, 1976” on 30 specimens) [21] was used to build the 3 new wallets. The aim was to compare the failure mechanism and the strength of the anchor with the results illustrated in section 3, thus with 3 different value of normal confinement.

To this end 3 wallets were made, each with a set of three 60mm holes orthogonal to the main wall plane, with anchors injected (steel bar diameter 20mm, mechanical characteristics illustrated in **Table 3**) with sock length of 400 mm and 50 mm of sinking, and mortar currently used by the supplier (BCM Presstec, cement-based, see **Table 4**). After 28 days of curing, the walls were preloaded with different axial compressive loads, the same applied during the tests reported in section 3.

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

Experimental results

The failure of each tested anchor occurred on the masonry side, but with a different behaviour as compared to what was observed during the test illustrated in section 3: the breaking of the bricks in contact with the bulb was generally observed and also an extraction of a consistent portion of bricks with the creation of a sort of cone of rupture, showing that the weak part of the system was not anymore limited to the mortar, leading to bricks slippage, but was the whole masonry (**Fig. 17**).

Table 11 and **12** summarise the results.

Final considerations and comparison on monotonic pull-out tests

It’s immediately evident (**Table 13**), comparing the results obtained during the tests illustrated in section 3, that a consistent increase of ultimate strength has occurred. In particular, comparing the results obtained in the tests carried out on walls A, D, C with the ones obtained in walls G, I, H, it’s possible to note that the strength increase is relevant, by at least 30% with low normal axial stresses and even double the value with higher transverse confinements (from 27% to 117%). Once again this highlights that the quality of the masonry greatly influences the response of this sort of anchor and therefore a deep evaluation of the masonry quality is strongly recommended before proceeding to any on-site intervention.

CONCLUSION and remarks

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

a) the response of short anchor injected in a brick masonry of poor quality is not closely dependent on the vertical transverse confinement for fairly low confinement values, while the dependence increase with high confinement values;

b) cyclic pull-out test, when compared to monotonic tests, have led to a maximum value of applied load at failure generally between 25 and 35% smaller, both in “long” and “short” anchors, both with lime based and cement based mortar, even if with different behaviour and failure modes.

c) the tests show that the influence of grout type on the anchors behaviour is more evident at the increasing of the length anchor.

d) the improvement of the masonry mortar’s quality leads to much increased values in the ultimate anchor strength, highlighting that the quality of the masonry greatly influences the response of this sort of anchor.

Aknowledgements:

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Fig. 1: Injected anchor with fabric sock system

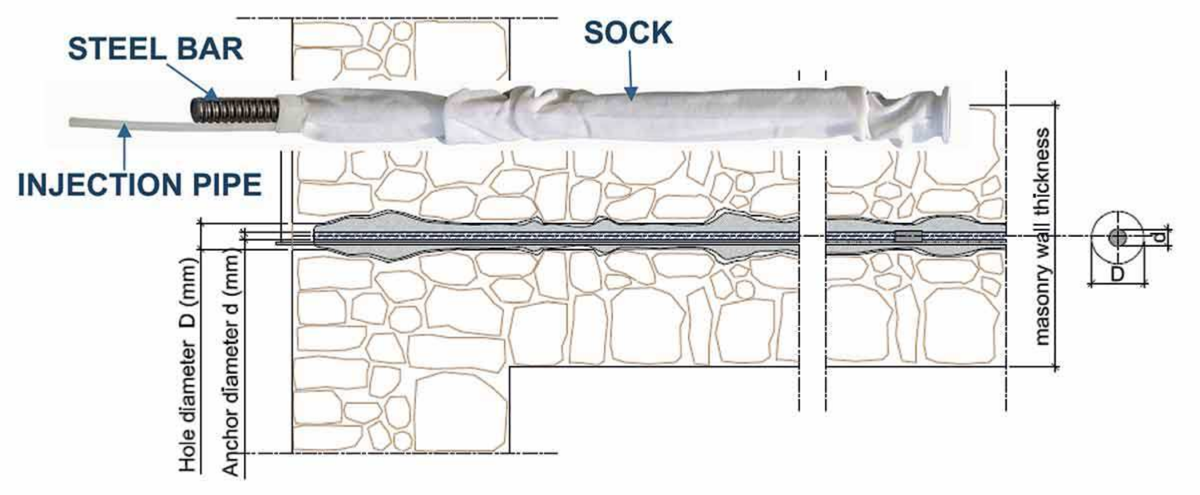


Fig. 2: Anchors dimensions and position in the wallets a) “Short” anchors; b) “Long” anchors

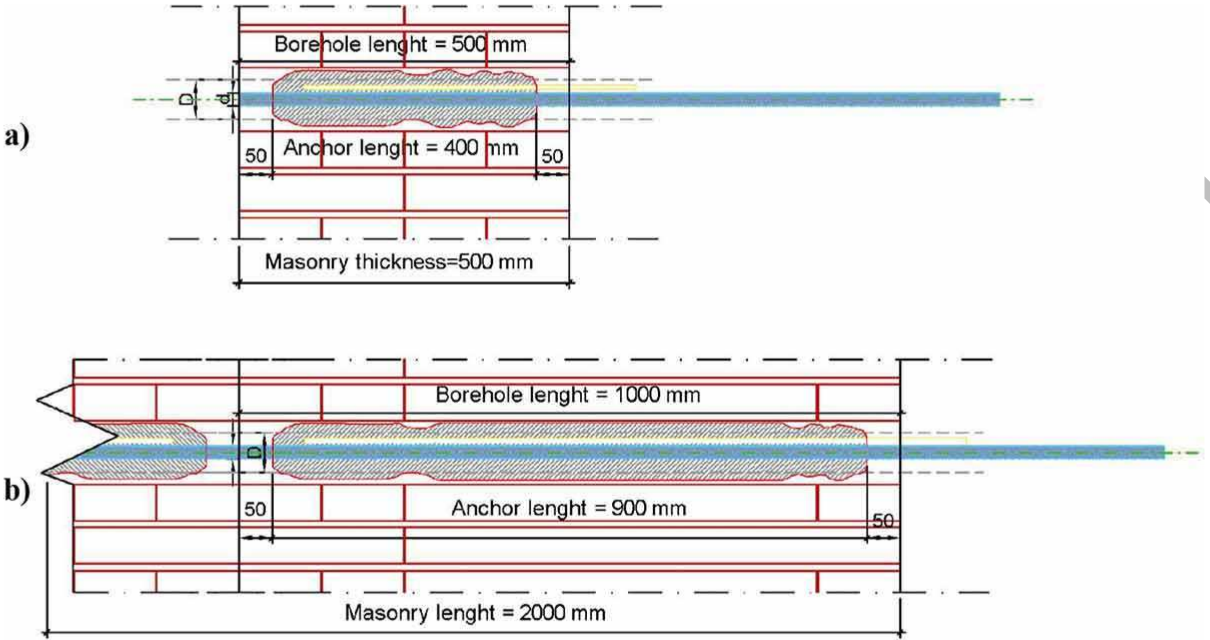


Fig. 3: Masonry texture for the realization of test wallets

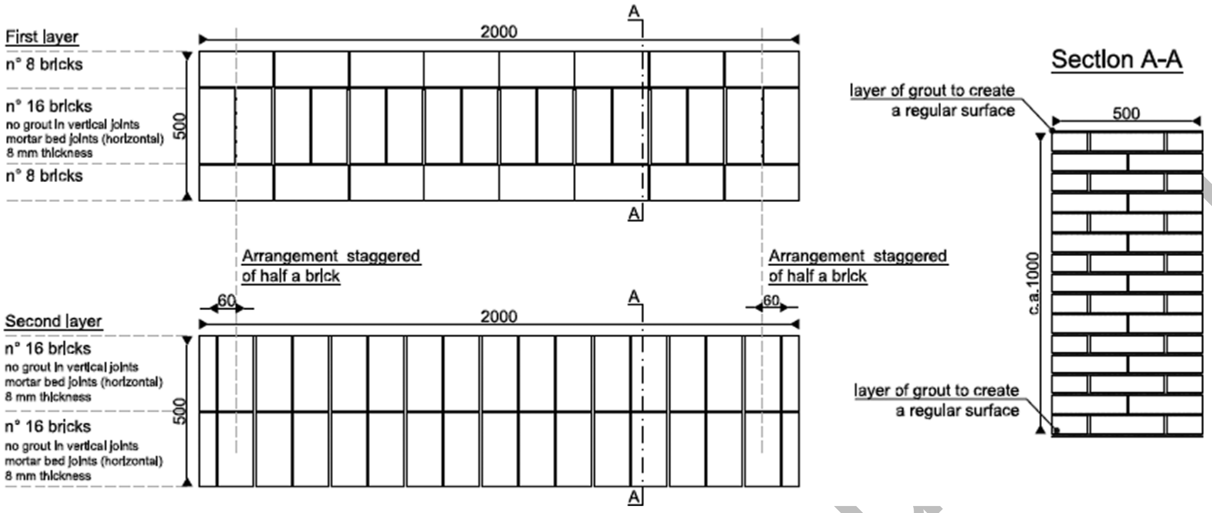
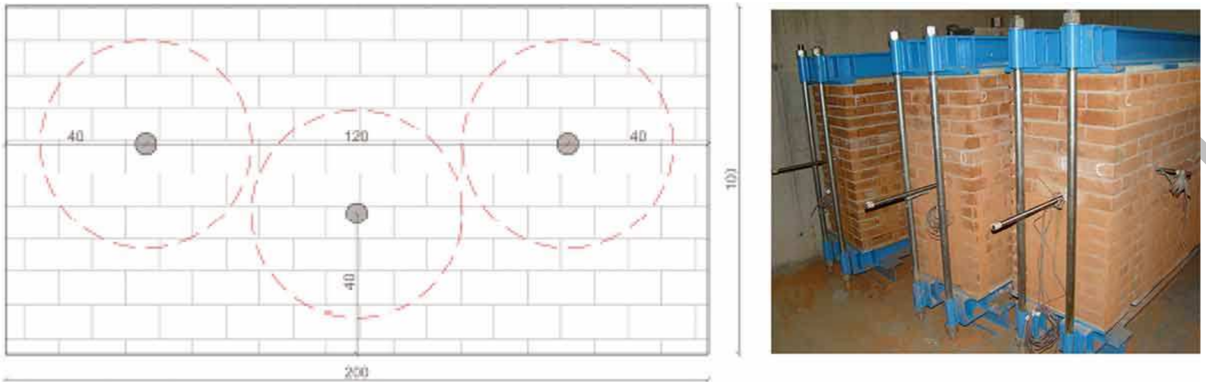


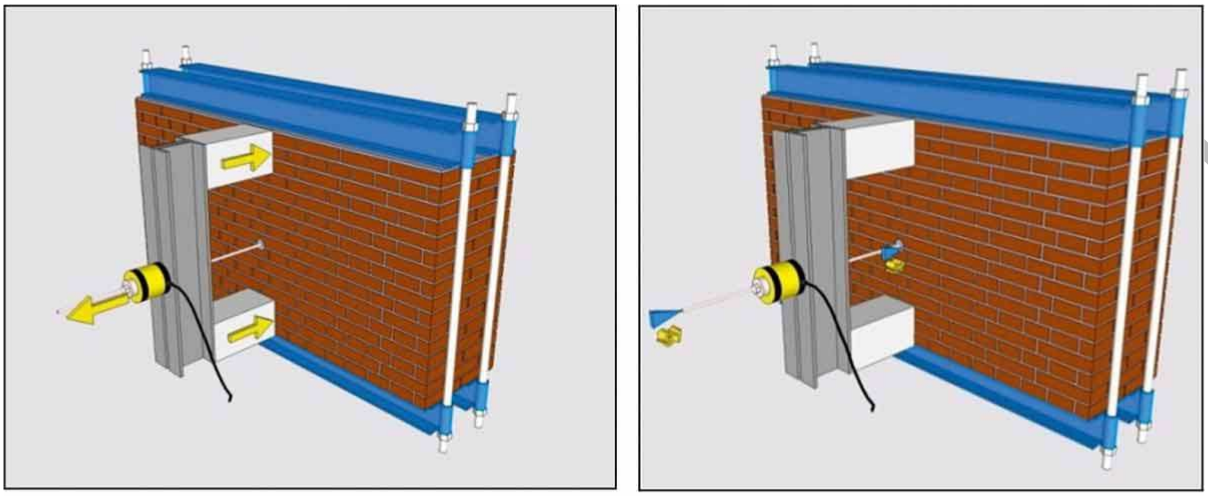
Fig. 4: Anchors position in the masonry test wallet a) “short” anchors and their interference areas, b) “long” anchors



a) b)

Fig. 5: Test layout with vertical pre-stressing system

Fig. 6: Test bench scheme with the application of contrast structure and showing: a) the loading point; b) the displacement reading points



a) b)

Fig. 7: Strain gauges positioning scheme and machining details: Type A anchor with 5 strain gauge (central anchors) and Type B with 3 strain gauges (lateral anchors)

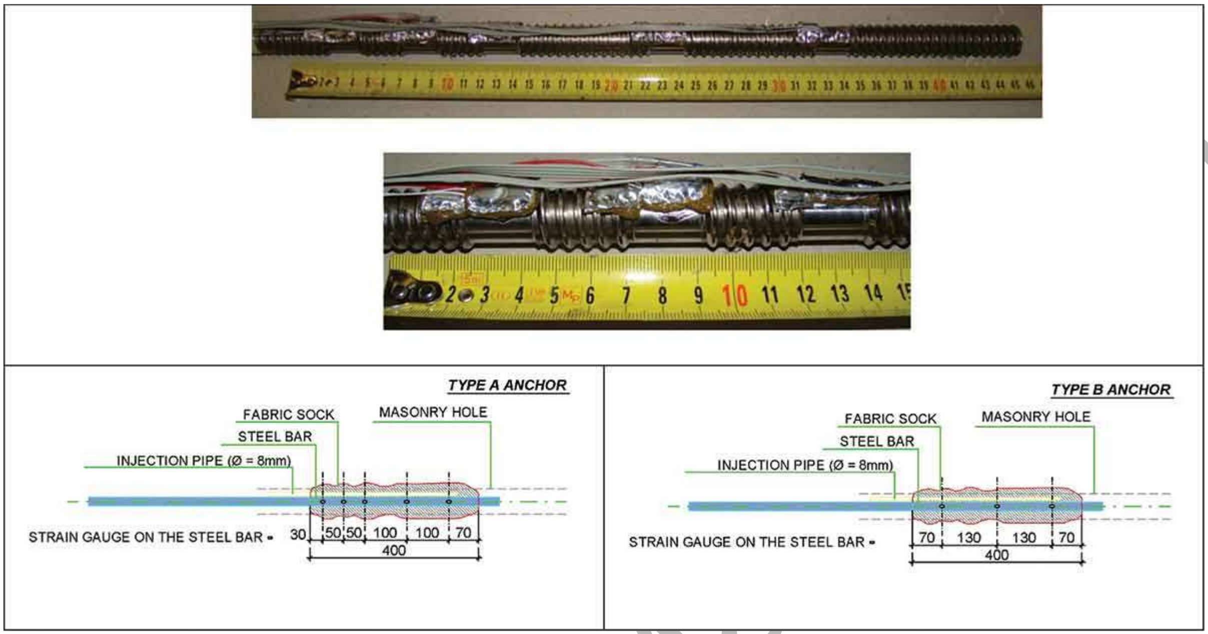


Fig. 8: Failure mechanisms observed in wall A after the tests

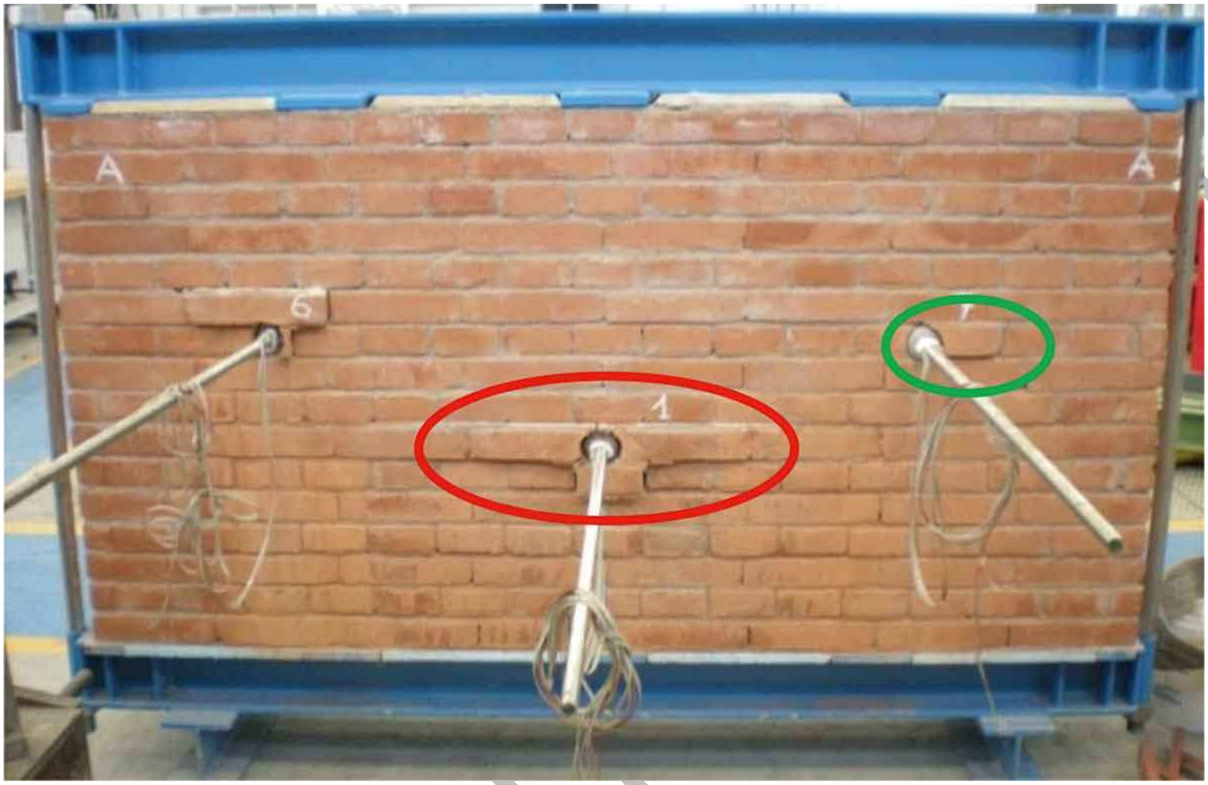
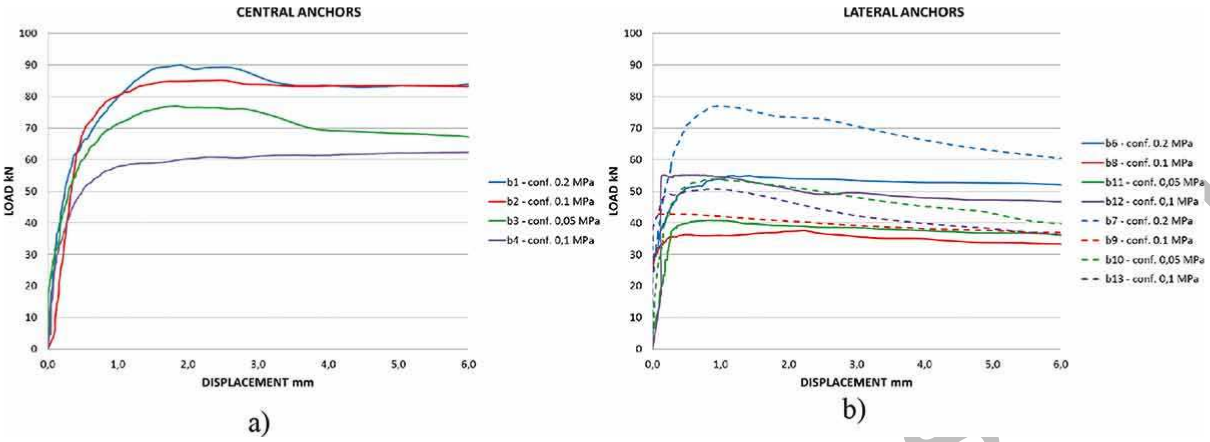


Fig. 9: Load - Displacement graphs on front bulb for: a) central anchors, b) lateral anchors



a)

b)

Fig. 10: Loading history for cyclic tests on "short" anchors

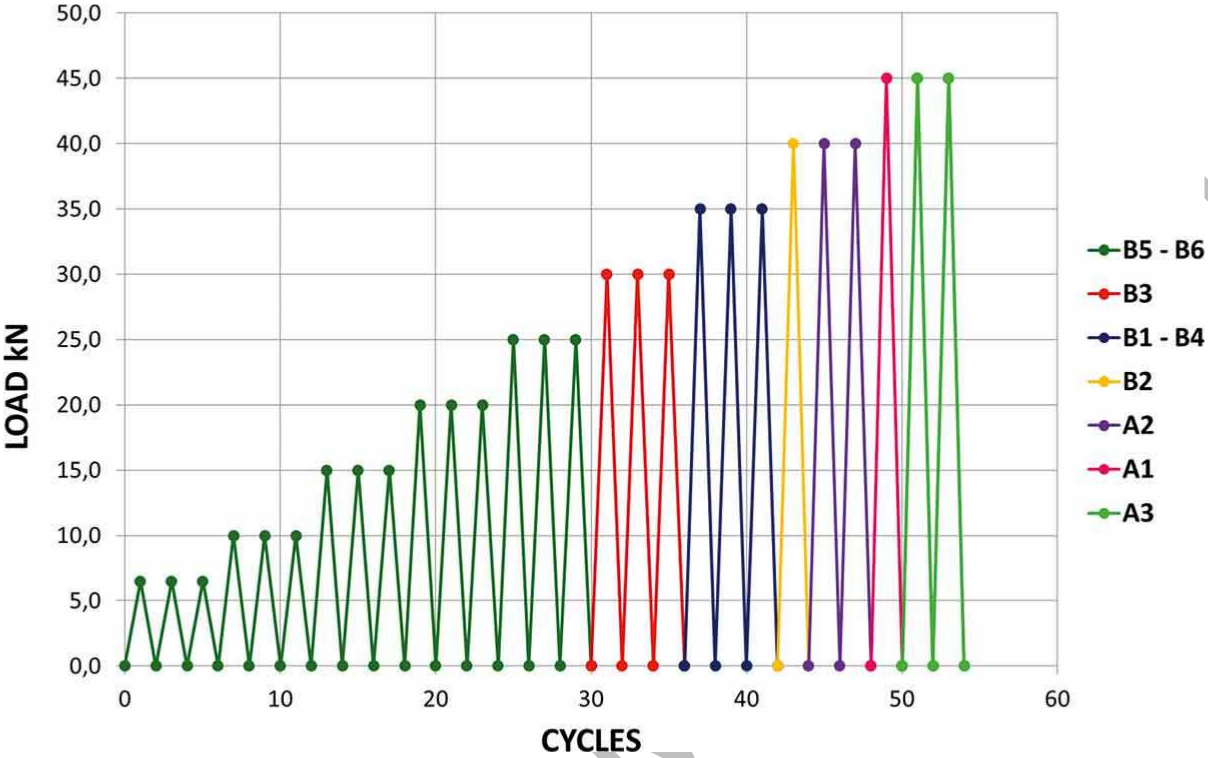


Fig. 11: Load – displacement graph during cyclic pull-out test for anchor B4

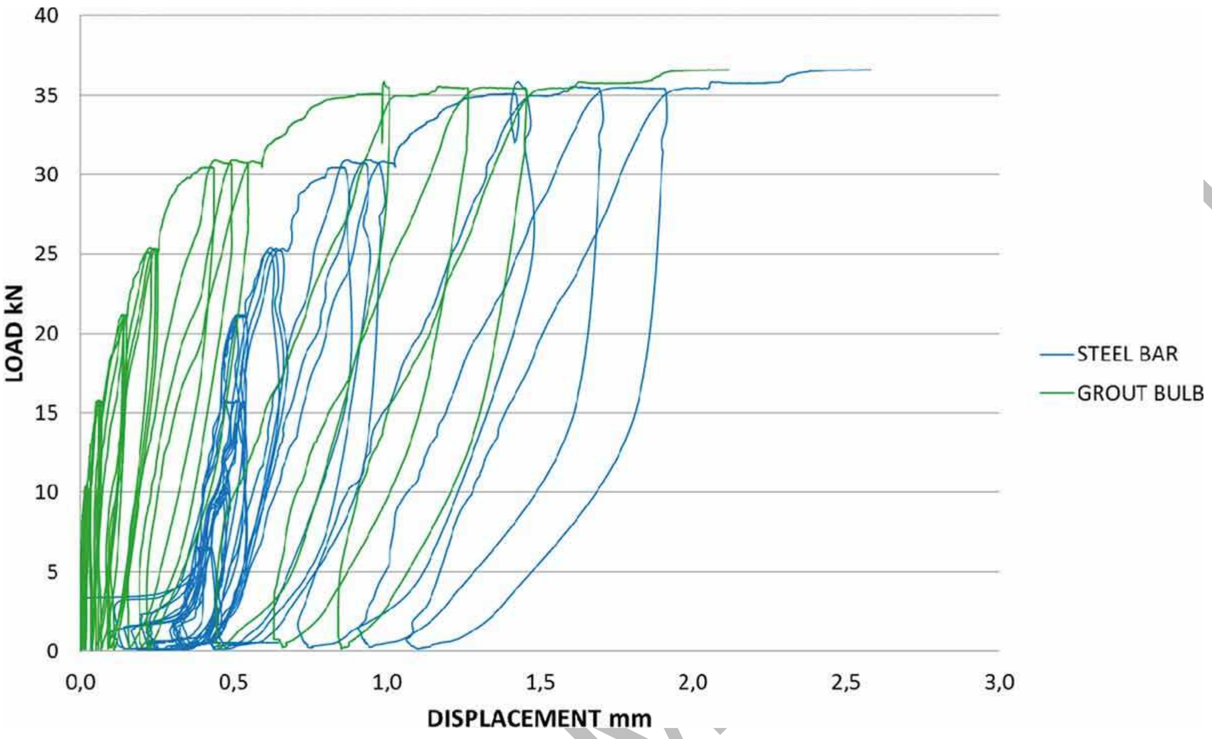


Fig. 12: Anchor A1 graphs during cyclic tests a) Deformation along the anchor for each step of each cycle up to the max load at failure; b) Average tangential stresses along the sections between the strain gauges up to the max load

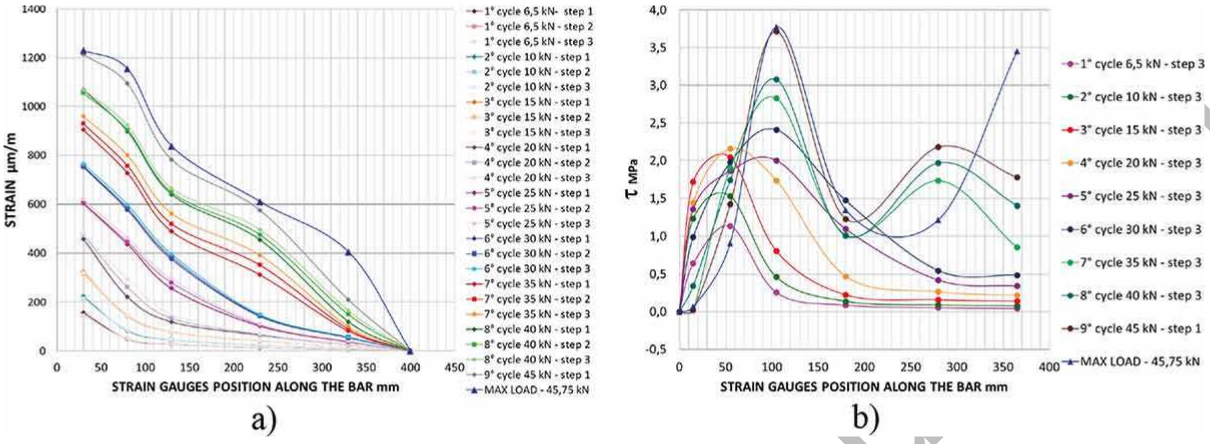
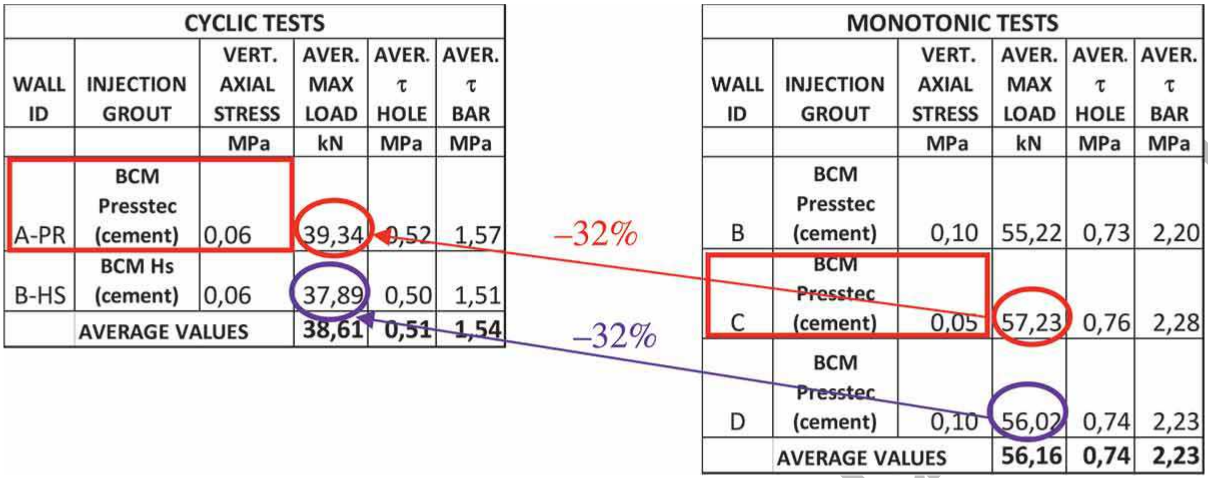


Fig. 13: Comparison between monotonic and cyclic tests results in anchor injected with cement based mortar



CYCLIC TESTS					
WALL ID	INJECTION GROUT	VERT. AXIAL STRESS	AVER. MAX LOAD	AVER. τ HOLE	AVER. τ BAR
		MPa	kN	MPa	MPa
A-PR	BCM Presstec (cement)	0,06	39,34	0,52	1,57
B-HS	BCM Hs (cement)	0,06	37,89	0,50	1,51
	AVERAGE VALUES		**38,61**	**0,51**	**1,54**

MONOTONIC TESTS					
WALL ID	INJECTION GROUT	VERT. AXIAL STRESS	AVER. MAX LOAD	AVER. τ HOLE	AVER. τ BAR
		MPa	kN	MPa	MPa
B	BCM Presstec (cement)	0,10	55,22	0,73	2,20
C	BCM Presstec (cement)	0,05	57,23	0,76	2,28
D	BCM Presstec (cement)	0,10	56,02	0,74	2,23
	AVERAGE VALUES		**56,16**	**0,74**	**2,23**

Fig. 14: Loading history for cyclic tests on "long" anchors

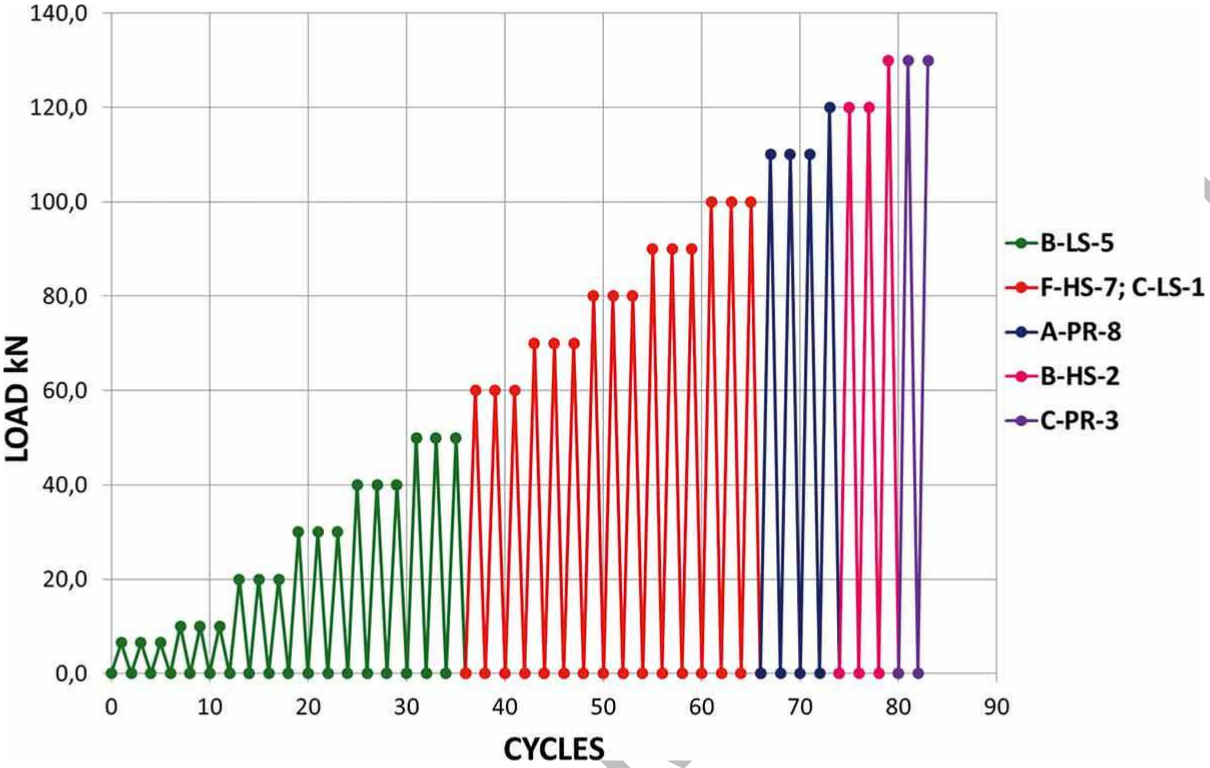
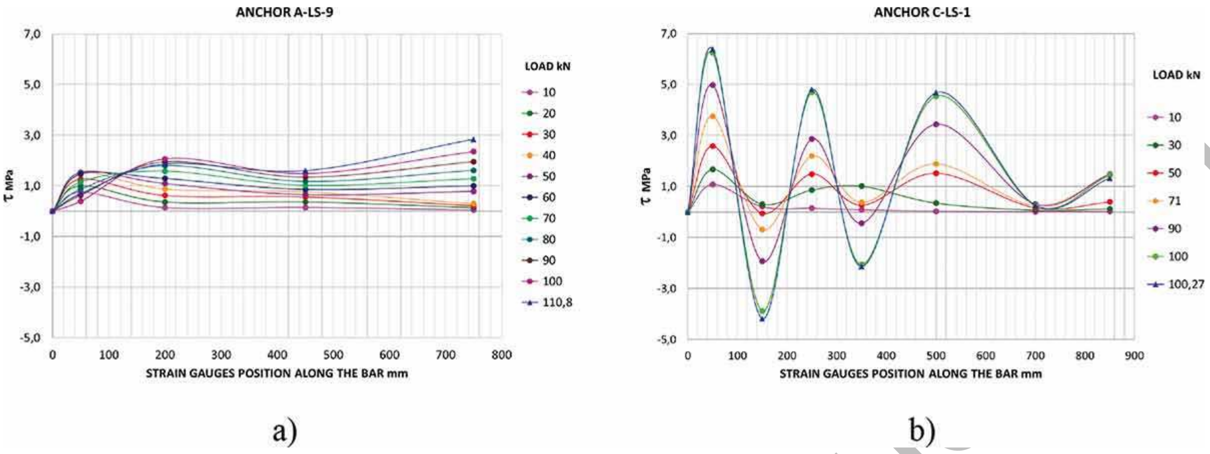


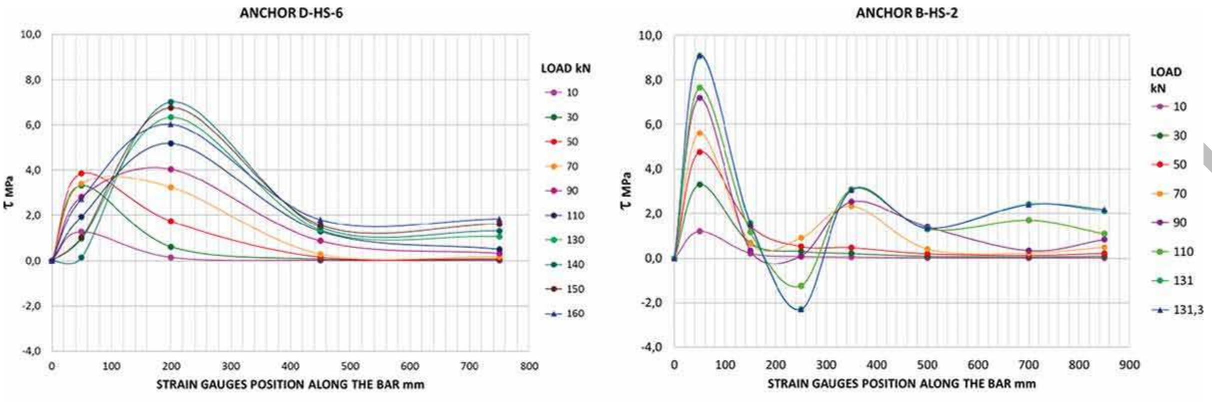
Fig. 15: Average bond stresses along the bar in anchors injected with lime mortar: a) Monotonic test; b) Cyclic test



a)

b)

Fig.16: Average bond stresses along the bar in anchors injected with cement mortar: a) Monotonic test; b) Cyclic test



a)

b)

Fig. 17: Failure mechanisms observed in wall I and H after the tests

Table 1: Full testing programme

TEST SERIES	MASONRY WALLETS				ANCHORS								
	ID	MORTAR	VERT. JOINT	VERT. LOAD [MPa]	ID	BAR DIA [mm]	HOLE DIA [mm]	LENGHT [mm]	INJECTION DIRECTION	POSITION IN THE WALLET	GROUT TYPE	NUMBER OF STRAIN GAUGES	PULL-OUT TEST TYPOLOGY
1. MONOTONIC PULL-OUT TESTS	A	Poor	YES	0,2	b.6	20	60	400 (Short)	Orthogonal	Lateral	BCM PRESSTEC (cement	3	Monotonic
					b.1	20	60	400 (Short)		Central		5	Monotonic

WITH DIFFERENT VERTICAL AXIAL LOADS					b.7	20	60	400 (Short)		Lateral	based)	3	Monotonic
	B	Poor	YES	0,1	b.8	20	60	400 (Short)	Orthogonal	Lateral	BCM PRESSTEC (cement based)	3	Monotonic
					b.2	20	60	400 (Short)		Central		5	Monotonic
					b.9	20	60	400 (Short)		Lateral		3	Monotonic
	C	Poor	YES	0,05	b.11	20	60	400 (Short)	Orthogonal	Lateral	BCM PRESSTEC (cement	3	Monotonic
					b.3	20	60	400		Central		5	Monotonic

							(Short)			based)		
				b.10	20	60	400 (Short)		Lateral		3	Monotonic
D	Poor	YES	0,1	b.12	20	60	400 (Short)	Orthogonal	Lateral	BCM PRESSTEC (cement based)	3	Monotonic
				b.4	20	60	400 (Short)		Central		5	Monotonic
				b.13	20	60	400 (Short)		Lateral		3	Monotonic
E	Poor	NO	0,2	b.16	20	60	400 (Short)	Orthogonal	Lateral	BCM PRESST	3	Monotonic

					b.5	20	60	400 (Short)	Orthogonal	Central	EC (cement based)	5	Monotonic
					b.15	20	60	400 (Short)		Lateral		3	Monotonic
	F	Poor	NO	0,2	b.14	24	72	400 (Short)		Lateral	BCM PRESSTEC (cement based)	3	Monotonic
					b.18	24	72	400 (Short)		Central		5	Monotonic
					b.17	24	72	400 (Short)		Lateral		3	Monotonic
2.	A	Poor	YES	0,06	B1	20	60	400	Orthogona	Lateral	BCM	3	Cyclic

CYCLIC PULL-OUT TESTS ON “SHORT” ANCHORS	-PR							(Short)	l		PRESSTEC (cement based)		
					A1	20	60	400 (Short)		Central		5	Cyclic
					B2	20	60	400 (Short)		Lateral		3	Cyclic
	B-HS	Poor	YES	0,06	B3	20	60	400 (Short)	Orthogonal	Lateral	BCM HS (cement based)	3	Cyclic
					A2	20	60	400 (Short)		Central		5	Cyclic
					B4	20	60	400 (Short)		Lateral		3	Cyclic

	C-LS	Poor	YES	0,06	B5	20	60	400 (Short)	Orthogonal	Lateral	BCM LS (Lime based)	3	Cyclic
					A3	20	60	400 (Short)		Central		5	Cyclic
					B6	20	60	400 (Short)		Lateral		3	Cyclic
3. CYCLIC AND MONOTONIC PULL-OUT TESTS ON	E	Poor	NO	0,06	E-PR-4	20	60	900 (Long)	Longitudinal	Central	BCM PRESSTEC (cement based)	3	Monotonic
	A-P	Poor	YES	0,06	A-PR-8	20	60	900 (Long)	Longitudinal	Central		3	Cyclic

“LONG” ANCHORS	R												
	C	Poor	YES	0,06	C-PR-3	20	60	900 (Long)	Longitudinal	Central		6	Cyclic
	D	Poor	YES	0,06	D-PR-3	20	60	900 (Long)	Longitudinal	Central		3	Monotonic
	D	Poor	YES	0,06	D-HS-6	20	60	900 (Long)	Longitudinal	Central	BCM HS (cement based)	3	Monotonic
	F	Poor	NO	0,06	F-HS	20	60	900 (Long)	Longitudinal	Central		3	Cyclic

				-7								
B-HS	Poor	YES	0,06	B-HS-2	20	60	900 (Long)	Longitudinal	Central		6	Cyclic
A	Poor	YES	0,06	A-LS-9	20	60	900 (Long)	Longitudinal	Central	BCM LS (Lime based)	3	Monotonic
B	Poor	YES	0,06	B-LS-5	20	60	900 (Long)	Longitudinal	Central		3	Cyclic
C-L	Poor	YES	0,06	C-LS	20	60	900 (Long)	Longitudinal	Central		6	Cyclic

	S				-1								
4. MONOTONIC PULL-OUT TESTS IN WALLETS BUILT WITH IMPROVED MORTAR	G	Improved	YES	0,2	1	20	60	400 (Short)	Orthogonal	Lateral	BCM PRESSTEC (cement based)	/	Monotonic
					2	20	60	400 (Short)		Central		/	Monotonic
					3	20	60	400 (Short)		Lateral		/	Monotonic
	H	Improved	YES	0,05	4	20	60	400 (Short)	Orthogonal	Lateral	BCM PRESSTEC (cement	/	Monotonic
					5	20	60	400 (Short)		Central		/	Monotonic

					6	20	60	400 (Short)		Lateral	based)	/	Monotonic
	I	Improved	YES	0,1	7	20	60	400 (Short)	Orthogonal	Lateral	BCM PRESSTEC (cement based)	/	Monotonic
					8	20	60	400 (Short)		Central		/	Monotonic
					9	20	60	400 (Short)		Lateral		/	Monotonic

Table 2: Mix design and Mechanical characteristics of wallets' mortar

MIX DESIGN		
Materials	Quantity	
	[kg]	[%]
NHL 3,5 TCS lime	2	8
slaked lime	1	5
Water	3	15
3 mm Siliceous aggregates	7,5	36
1.5 mm Siliceous aggregates	7,5	36

MECHANICAL CHARACTERISTICS (28 days of curing)	
Average compressive strength	0,42 MPa (CV 0,231)
Average tensile flexural strength	0,20 MPa (CV 0,103)
Young’s Modulus	131 MPa

Table 3: Geometrical and Mechanical characteristics of steel bars (Supplier technical data sheet)

Material	Bar Diameter	Area	Ultimate tensile stress (minimum value)	0,2% yield stress (minimum value)	Minimum tensile failure load	Min. yield point load
AISI	D_{bar} [mm]	S [mm^2]	$f_{t\ nom}$ [MPa]	$f_{y\ nom}$ [MPa]	$N_{t,s}$ [KN]	$N_{y,s}$ [KN]
304	**20**	261	750	650	**196**	**170**
304	**24**	378	750	650	**283**	**246**

Table 4: Mix design and Mechanical characteristics of injection grout used during laboratory tests

MIX DESIGN		
Injection mortar typology	**Materials**	**Quantity**
BCM Presstec (cement based)	Portland Cement	>20% - <= 100%
	Quarz	
BCM Hs (cement based)	Clinker	>20% - <= 100%
	Quarz	
BCM Ls (lime based)	Natural Hydraulic Lime	>10% - <= 50%
	Clinker of white cement	>1% - <= 5%

	Quarz	

MECHANICAL CHARACTERISTICS											
Injection mortar typology	**Average compressive strength MPa**					**Average tensile flexural strength MPa**					**Young's Modulus MPa**
	3 d	**7 d**	**28 d**	**60 d**	**120 d**	**3 d**	**7 d**	**28 d**	**60 d**	**120 d**	**28 d**
BCM Presstec (cement based)	40,90	45,30	49,20	/	/	4,60	6,30	7,60	/	/	24.796
CV	0,029	0,055	0,064			0,277	0,120	0,121			0,025

BCM Hs (cement based)	39,30	48,00	59,10	61,30	69,00	5,00	10,60	10,80	11,60	10,60	27.851
CV	0,056	0,034	0,051	0,203	0,132	0,100	0,096	0,039	0,117	0,055	0,050
BCM Ls (lime based)	0,80	2,00	9,30	9,80	10,60	0,40	0,90	3,10	2,80	3,30	9.484
CV	0,046	0,088	0,039	0,086	0,183	0,014	0,167	0,028	0,059	0,140	0,212

Table 5: Monotonic 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)

WALL ID	BAR DIAM.	VERT. AXIAL STRESS	Anch. ID	Max load	Failure mechanism	Anch. ID	Max load	Failure mechanism	Anch. ID	Max load	Failure mechanism	MAX AVER. LOAD	AVER. τ HOLE	AVER. τ BAR	VAR. COEF.
	mm	MPa		kN			kN			kN		kN	MPa	MPa	(CV)
A	20	0,20	*b.6*	54,84		*b.1*	90,01		*b.7*	77,00		73,95	0,98	2,94	0,240
B	20	0,10	*b.8*	37,5		*b.2*	85,1		*b.9*	42,9		55,22	0,73	2,20	0,472

				8			5			3					
C	20	0,05	*b.11*	40,78		*b.3*	77,04		*b.10*	53,88		57,23	0,76	2,28	0,321
D	20	0,10	*b.12*	55,08		*b.4*	62,30		*b.13*	50,69		56,02	0,74	2,23	0,105
E	20	0,20	*b.16*	58,48		*b.5*	65,96		*b.15*	57,82		60,75	0,81	2,42	0,074
F	24	0,20	*b.14*	30,05		*b.18*	43,29		*b.17*	38,73		37,36	0,47	1,24	0,180

Table 6: Monotonic 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.

WALL ID	**BAR DIAM.**	**VERT. AXIAL STRESS**	**Anch. ID**	**Max load**	**Bar disp.**	**Bulb disp.**	**τ hole**	**τ bar**	**Anch. ID**	**Max load**	**Bar disp.**	**Bulb disp.**	**τ hole**	**τ bar**	**Anch. ID**	**Max load**	**Bar disp.**	**Bulb disp.**	**τ hole**	**τ bar**
	mm	**MPa**		**kN**	**mm**	**mm**	**MPa**	**MPa**		**kN**	**mm**	**mm**	**MPa**	**MPa**		**kN**	**mm**	**mm**	**MPa**	**MPa**
A	**20**	**0,20**	***b.6***	**54,84**	**1,21**	**1,14**	**0,73**	**2,18**	***b.1***	**90,01**	**1,87**	**1,88**	**1,19**	**3,58**	***b.7***	**77,00**	**1,14**	**0,95**	**1,02**	**3,06**

B	**20**	**0,10**	***b.8***	**37,58**	**2,43**	**2,24**	**0,50**	**1,50**	***b.2***	**85,15**	**3,94**	**2,50**	**1,13**	**3,39**	***b.9***	**42,93**	**0,79**	**NP**	**0,57**	**1,71**
C	**20**	**0,05**	***b.11***	**40,78**	**1,46**	**0,81**	**0,54**	**1,62**	***b.3***	**77,04**	**1,79**	**1,81**	**1,02**	**3,07**	***b.10***	**53,88**	**0,96**	**0,93**	**0,71**	**2,14**
D	**20**	**0,10**	***b.12***	**55,08**	**1,39**	**0,67**	**0,73**	**2,19**	***b.4***	**62,30**	**NP**	**5,91**	**0,83**	**2,48**	***b.13***	**50,69**	**1,29**	**0,88**	**0,67**	**2,02**
E	**20**	**0,20**	***b.16***	**58,48**	**1,87**	**0,66**	**0,78**	**2,33**	***b.5***	**65,96**	**8,24**	**8,06**	**0,87**	**2,62**	***b.15***	**57,82**	**1,39**	**1,35**	**0,77**	**2,30**
F	**24**	**0,20**	***b.14***	**30,05**	**11,13**	**10,46**	**0,40**	**1,00**	***b.18***	**43,29**	**8,13**	**7,72**	**0,57**	**1,44**	***b.17***	**38,73**	**4,77**	**3,15**	**0,51**	**1,28**

Table 7: 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)

WALL ID	**INJECTION GROUT**	**Anch. ID**	**Max load**	**Failure mechanism**	**Anch. ID**	**Max load**	**Failure mechanism**	**Anch. ID**	**Max load**	**Failure mechanism**	**MAX AVER. LOAD**	**AVER. τ HOLE**	**AVER. τ BAR**	**Variat. coeff. (CV)**
			kN			**kN**			**kN**		**KN**	**MPa**	**MPa**	
A-PR	**BCM Presstec (cement)**	***B1***	**35,01**		***A1***	**45,75**		***B2***	**37,27**		**39,34**	**0,52**	**1,57**	**0,144**
B-	**BCM Hs**	***B3***	**32,**		***A2***	**44,**		**B4**	**36,**		**37,8**	**0,50**	**1,51**	**0,16**

HS	**(cement)**		**52**			**55**			**60**		**9**			**1**
C-LS	**BCM Ls (lime)**	***B5***	**27,22**		***A3***	**45,90**		***B6***	**29,36**		**34,16**	**0,45**	**1,36**	**0,299**

Table 8: Cyclic 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

WALL ID	**INJECTION GROUT**	**Anch. ID**	**Max load**	**Bar disp.**	**Bulb disp.**	**τ hole**	**τ bar**	**Anch. ID**	**Max load**	**Bar disp.**	**Bulb disp.**	**τ hole**	**τ bar**	**Anch. ID**	**Max load**	**Bar disp.**	**Bulb disp.**	**τ hole**	**τ bar**
			kN	**mm**	**mm**	**MPa**	**MPa**		**kN**	**mm**	**mm**	**MPa**	**MPa**		**kN**	**mm**	**mm**	**MPa**	**MPa**
A-PR	**BCM Presstec (cement)**	***B1***	**35,01**	**2,47**	**0,33**	**0,46**	**1,39**	***A1***	**45,75**	**1,86**	**1,14**	**0,61**	**1,82**	***B2***	**37,27**	**4,05**	**3,28**	**0,49**	**1,48**
B-HS	**BCM Hs (cement)**	***B3***	**32,52**	**1,44**	**0,30**	**0,43**	**1,29**	***A2***	**44,55**	**2,45**	**1,64**	**0,59**	**1,77**	***B4***	**36,60**	**2,51**	**2,05**	**0,49**	**1,46**
C-LS	**BCM Ls (lime)**	***B5***	**27,22**	**4,01**	**3,54**	**0,36**	**1,08**	***A3***	**45,90**	**1,06**	**0,47**	**0,61**	**1,83**	***B6***	**29,36**	**1,48**	**1,05**	**0,39**	**1,17**

Table 9: Cyclic tests results for long anchors: maximum load at collapse, bar and bulb displacement, bond stresses at bar and hole interfaces, failure mode

ANCH. ID	**WALL TYPOLOGY**	**INJECTION GROUT**	**TEST TYPOLOGY**	**FAILURE MODE**	**MAX LOAD [kN]**	**Bar disp. [mm]**	**Bulb disp. [mm]**	**τ hole [MPa]**	**τ bar [MPa]**
E-PR-4	UNRECTIFIED BRICKS - **NO** VERTICAL JOINTS	BCM Presstec (cement)	Monotonic		126,27	2,84	2,21	0,74	2,23
A-PR-8	VERTICAL JOINTS		Cyclic		118,19	2,51	1,69	0,70	2,09

C-PR-3	VERTICAL JOINTS		Cyclic		138,13	6,84	6,25	0,81	2,44
D-PR-3	VERTICAL JOINTS		Monotonic		159,39	3,60	2,84	0,94	2,82
D-HS-6	VERTICAL JOINTS	BCM Hs (cement)	Monotonic		183,78	5,47	2,69	1,08	3,25
F-HS-7	UNRECTIFIED BRICKS - **<u>NO</u>** VERTICAL JOINTS		Cyclic		98,13	6,21	4,44	0,58	1,74
B-HS-2	VERTICAL JOINTS		Cyclic		131,29	4,54	3,70	0,77	2,32

A-LS-9	VERTICAL JOINTS	BCM Ls (lime)	Monotonic		110,82	5,69	4,73	0,65	1,96
B-LS-5	VERTICAL JOINTS		Cyclic		57,96	0,91	0,34	0,34	1,02
C-LS-1	VERTICAL JOINTS		Cyclic		100,29	15,99	10,97	0,59	1,77

Table 10: Mix design and Mechanical characteristics of the new test bench mortar

MIX DESIGN	
Materials	Volumetric ratio
Lime: NHL 3,5 TCS	1,00
Water	0,75
Siliceous aggregates (1,50-2,50 mm)	2,00
MECHANICAL CHARACTERISTICS (28days of curing)	

Avg compressive strength	1,08 MPa (CV 0,1)
Avg tensile flexural strength	0,48 MPa (CV 0,1)
Modulus of Elasticity	3500 MPa (CV0,2)

Table 11: Monotonic tests results for each of the 3 anchors in each new wall (maximum load, failure mode) and average results for each wallet (maximum load and bond stresses on bar and bulb surfaces)

WALL ID	**VERT. AXIAL STRESS**	**Anch. ID**	**Max load**	**Failure mechanism**	**Anch. ID**	**Max load**	**Failure mechanism**	**Anch. ID**	**Max load**	**Failure mechanism**	**MAX AVER. LOAD**	**AVER. τ HOLE**	**AVER. τ BAR**	**VAR. COEFF. (CV)**
	MPa		**kN**			**kN**			**kN**		**kN**	**MPa**	**MPa**	
G	**0,20**	***bn.3***	**146,06**		***bn.2***	**123,89**		***bn.1***	**114,00**		**127,98**	**1,70**	**5,09**	**0,128**
I	**0,10**	***bn.7***	**118,84**		***bn.8***	**142,03**		***bn.9***	**104,03**		**121,63**	**1,61**	**4,84**	**0,157**
H	**0,05**	***bn.4***	**65,07**		***bn.5***	**92,11**		***bn.6***	**61,47**		**72,88**	**0,97**	**2,90**	**0,230**

Table 12: Monotonic tests results for each of the 3 anchors in each new wall: maximum load at collapse, bar and bulb displacement, bond stresses at bar and hole interfaces.

WALL ID	**VERT. AXIAL STRESS**	**Anch. ID**	**Max load**	**Bar disp.**	**Bulb disp.**	**τ hole**	**τ bar**	**Anch. ID**	**Max load**	**Bar disp.**	**Bulb disp.**	**τ hole**	**τ bar**	**Anch. ID**	**Max load**	**Bar disp.**	**Bulb disp.**	**τ hole**	**τ bar**
	MPa		**kN**	**mm**	**mm**	**MPa**	**MPa**		**kN**	**mm**	**mm**	**MPa**	**MPa**		**kN**	**mm**	**mm**	**MPa**	**MPa**
G	**0,20**	***bn.3***	**146,06**	**2,74**	**2,32**	**1,94**	**5,81**	***bn.2***	**123,89**	**2,35**	**NP**	**1,64**	**4,93**	***bn.1***	**114,00**	**12,29**	**12,56**	**1,51**	**4,54**

I	**0,10**	***bn.7***	**118,84**	**1,76**	**0,09**	**1,58**	**4,73**	***bn.8***	**142,03**	**1,71**	**1,30**	**1,88**	**5,65**	***bn.9***	**104,03**	**2,07**	**1,30**	**1,38**	**4,14**
H	**0,05**	***bn.4***	**65,07**	**1,52**	**0,24**	**0,86**	**2,59**	***bn.5***	**92,11**	**NP**	**0,90**	**1,22**	**3,66**	***bn.6***	**61,47**	**1,21**	**0,89**	**0,82**	**2,45**

Table 13: Comparison between results obtained in walls built with first poor mortar and walls built with new improved mortar

First poor mortar					**New improved mortar**					**Ultimate strenght increase with new mortar**
WALL ID	**VERT. AXIAL STRESS**	**AVER. MAX LOAD**	**AVER. τ HOLE**	**AVER. τ BAR**	**WALL ID**	**VERT. AXIAL STRESS**	**AVER. MAX LOAD**	**AVER. τ HOLE**	**AVER. τ BAR**	
	MPa	**KN**	**MPa**	**MPa**		**MPa**	**KN**	**MPa**	**MPa**	
A	**0,20**	**73,95**	**0,98**	**2,94**	**G**	**0,20**	**127,98**	**1,70**	**5,09**	**73%**
D	**0,10**	**56,02**	**0,74**	**2,20**	**I**	**0,10**	**121,63**	**1,61**	**4,84**	**117%**
C	**0,05**	**57,23**	**0,74**	**2,28**	**H**	**0,05**	**72,88**	**0,97**	**2,90**	**27%**