# Out-of-plane flexural behaviour of masonry walls reinforced with UHPPl

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**ABSTRACT:** Ultra-High Performance Plaster (UHPPl) is an innovative seismic strengthening solution for load bearing masonry wall structures. This solution consists of a lime based plastering mortar, reinforced with a carbon fibre mesh, applied on one (internal or external) or both wall faces. The reinforcing mesh is tied by an evenly spaced grid of connectors, going through the wall thickness, acting also as confinement devices.

UHPPl was devised as a compromise between mechanical performance improvements (both for in-plane and out-of-plane actions) and the three pillars of a correct rehabilitation of constructions with some heritage significance: authenticity, reversibility and reduced intrusiveness.

The existence of a well tied reinforcing mesh should greatly improve the flexural strength and deformation capacity of the walls, critical when these are subjected to out-of-plane forces and displacements. These improvements were assessed through an extensive out-of-plane testing campaign on strengthened full scale wall specimens, with different arrangements of the confinement connectors and different vertical load levels. The global performance indices for these specimens (e.g. strength, deformation capacity and energy dissipation) are presented, together with those of un-reinforced specimens, tested as references.

*Keywords:* Seismic strengthening, masonry wall structures, out-of-plane, UHPPl

## NOTATION

| | |
|---|---|
| *UHPPL* | *Ultra-High Performance Plaster* |

## 1 INTRODUCTION

Masonry, made of stone or brick, is very common in the structural walls of ancient buildings of the historical centres of major European cities. In earthquake events, its unreliable behaviour results in shortcomings as a building material (e.g., lack of tensile strength). Hence seismic strengthening procedures need be developed to limit the risk, both in terms of property and human losses.

The R&D Project “Rehab Toolbox” is aimed at the development of several strengthening technologies to improve the structural behaviour of ancient buildings or structures when subjected to

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earthquakes. Each of these technologies was specifically developed to tackle one of the main flaws of by loadbearing masonry wall buildings, commonly identified in every earthquake occurrence.

As part of the “Rehab Toolbox” set, UHPPI was conceived to improve the structural performance of one of the weakest structural elements of load bearing masonry buildings, the masonry walls. This strengthening technique, originally developed to improve out-of-plane behaviour, should also present significant improvements in terms of the in-plane behaviour.

Recent interventions to improve the seismic safety of old buildings tend to be intrusive and could harm their intrinsic cultural value. With this concern in mind, specific hydraulic lime based mortars are starting to be very commonly used in conservation works of ancient masonry, due to their compatibility with the original components, and the similar nature of the two materials. The technique presented here respects the principles of originality and low intrusiveness with which the interventions should comply.

However, lime-based mortars do not have the mechanical characteristics to reinforce the masonry material so it can resist seismic action (low tensile resistance). Therefore, the development of a composite material, composed of an hydraulic lime based mortar and a carbon fibre (CFRP) mesh, was used to cope with such limitations.

Improved out-of plane behaviour implies that the reinforcement technique can achieve significant resistance combined with compatible displacements for the reinforced masonry wall. By allying it with significant ductility (meaning that the ultimate strength is associated to a large ultimate displacement), the overall seismic behaviour of the masonry should be enhanced. To be effective, the adhesion of the reinforcement to the masonry will is a critical issue, as the failure or success of the technique will be strongly dependent on this feature.

The experimental work outlined for the evaluation of such particular aspects of the reinforcement technique includes an extensive range of tests:

- Seven direct tensile tests to UHPPI strips;
- Nine lashing(anchoring) pull-out tests to UHPPI strips;
- Two out-of-plane flexural tests to pseudo-masonry walls (non-reinforced walls);
- Eight out-of-plane flexural tests on masonry walls (reinforced walls).

Other material characterization tests were also conducted.

## 2 LASHING PULL-OUT TESTS

### 2.1. Experimental tests

Cyclic pull-out tests were performed to assess the reinforcement behaviour and mechanical properties, before the testing the large scale masonry wall specimens:

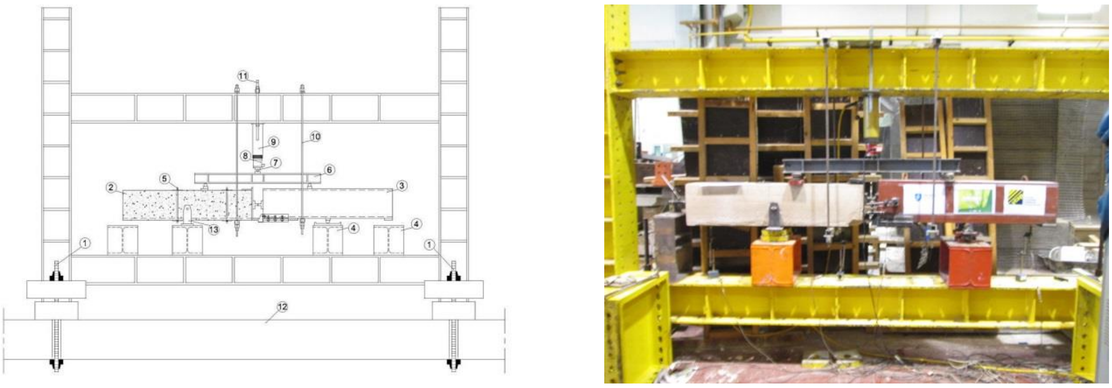


**Figure 1.** Cyclic Pull-out test scheme

For each test, an UHPPI strip was applied to a pseudo-masonry (in fact a very poor concrete) beam, with specific surface preparation to simulate different bonding substrates. This part of the test was termed the active element. Connected to this, a steel (fully rigid) beam behaves as the passive reaction in the test. The hinged connection between both blocks allows the determination of the force in the strip by simple static equilibrium (Figure 1).

The main objective with this test scheme was to analyse the binding of UHPPl strips to the masonry substrate, as well as at their connection to the passive block.

The tests were divided into 3 specific phases, each one with different conditions regarding the variables to be studied. 1. The mortar application technique was examined. 2). The adhesion solution. 3).. The type of CFRP mesh applied. Each phase was repeated three times (Table 1).

**Table 1.** Cyclic adhesion pull-off test variables

| Test Phase | Mortar application | Lashing solution | CRFP mesh |
|---|---|---|---|
| Phase 1 (P07.1 to P07.3) | Lime based mortar manually applied | Mechanical | 80 g of carbon per square meter |
| Phase 2 (P07.4 to P07.6) | Lime based mortar applied by projection | Organic | 80 g of carbon per square meter |
| Phase 3 (P07.7 to P07.9) | Lime based mortar applied by projection | Organic | 200 g of carbon per square meter |

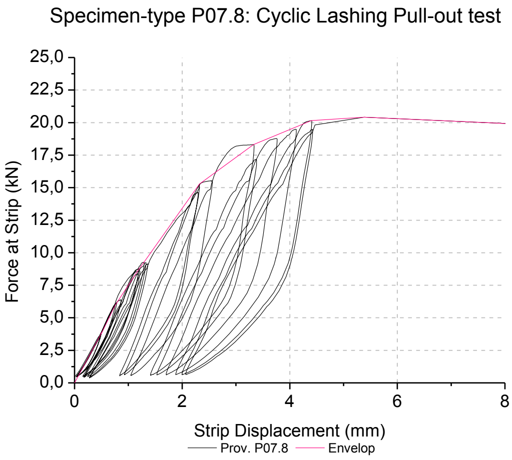
## 2.2. Experimental Results

For the final stage of the pull-out tests (Phase 3) a mesh with 200 g of carbon per square meter of reinforcement strip was used, the strongest of the two commercial solutions available. Application of the reinforcement mortar was made raising it proud of the surface to enhance the adhesion between the pseudo-masonry beam and the UHPPl strip (Figure 2). Further, to ensure better adhesion between pseudo-masonry and reinforcement strip a set of 2 steel anchors were used. Such connectors were tensioned before the test, with a controlled gripping force of 40 N.m (Figure 3):

**Figure 2.** Reinforcement application

**Figure 3.** Steel connectors

Figure 4 and Figure 5 present the results for the Phase 3 tests (specimen's P07.7 to P07.9):



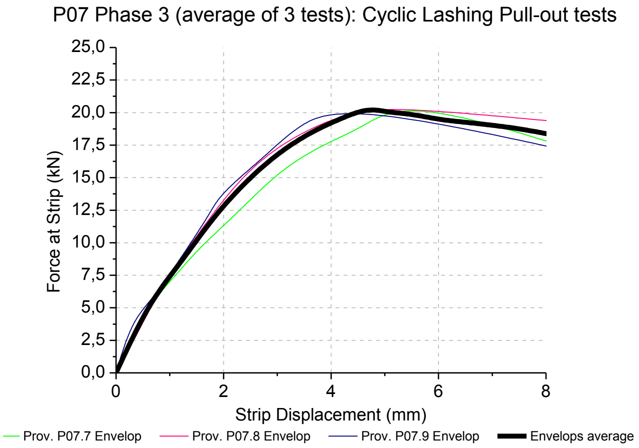


**Figure 4.** P07.8 cyclic test

**Figure 5.** Cyclic test envelops and their average

The failure mode of the Phase 3 stage was tensile collapse of the CFRP mesh (for all specimens). Visible damage were observed at the end of the interface between the UHPPI strip and the pseudo-masonry beam, showing that the mortar part of the reinforcement strip is also involved (Figure 6 and 7). Between the steel connectors and up to the other end of the active block no damage was observed to the UHPPI strip:

**Figure 6.** Failure mode

**Figure 7.** Mortar damage

## 3 OUT-OF-PLANE FLEXURAL TESTS

### 3.1. Experimental testing

Out-of plane cyclic flexural tests (Figure 8) are one of the main experimental methods to characterize the retrofitting technique's structural characteristics:

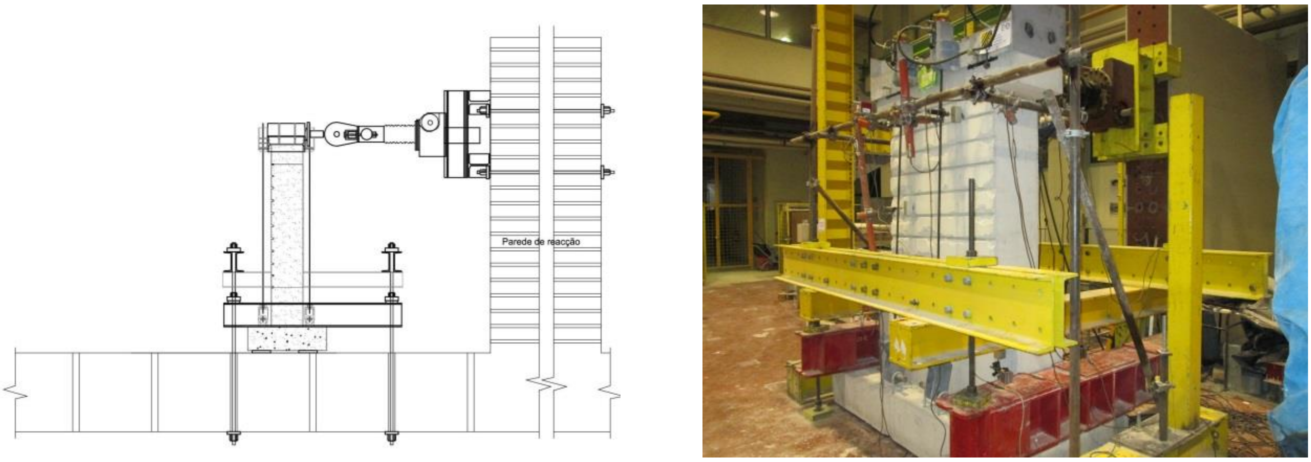


**Figure 8.** Out-of plane flexural test scheme

Regarding the “pseudo-masonry” concrete used to build the specimens, its composition was established to represent the mechanical behaviour of stone masonry. Its characteristics were determined from standard laboratory tests on this kind of material (compression strength and Young Modulus). It is noteworthy that this material does not include the use of cement in its composition, only hydraulic lime as a binder. The application of reinforcement was itself a demanding challenge, since the mortar projections were made inside the laboratory facilities. Further, the simple transportation within the laboratory of such weak and heavy walls was also challenging.

The UHPPl mesh was applied in all cases to only at one of the wall faces. In some repairs a rehabilitation intervention may only be possible on one side, so it is valid to study walls with that limitation. Consequently, the results will not be symmetrical regarding to the out-of-plane flexural resistance.

From the variables that could be studied in these tests (Table 2), the axial stress level and the use (or not) of steel connectors – Figure 11 – proved to be the most suitable to consider. For each reinforcement combination, 2 identical tests were performed.

**Table 2.** Out-of-plane flexural test variables

| Test | Axial Load | Reinforcement Connection | Observation |
|---|---|---|---|
| P08.1 | 100 kN | Not applicable | Reference tests |
| P08.2 | 200 kN | | |
| P09.1 and P09.2 | 100 kN | With confinement connectors | Low axial load behaviour |
| P09.3 and P09.4 | | Without confinement connectors | |
| P10.1 and P10.2 | 200 kN | With confinement connectors | Medium axial load behaviour |
| P10.3 and P10.4 | | Without confinement connectors | |

Horizontal load/displacement was applied at the top of the specimen, by a mechanical actuator attached to a steel casing bearing on the top of the wall. Vertical axial load was kept stable during all the horizontal force application, which represents the state of axial load of a structural wall during a seismic event. Hence the vertical load system was made independent of the support at the base of the specimens, and applied directly to the wall (at its top and base). A horizontal steel frame was introduced at the lower part of the wall to prevent “rocking” or “sliding” rigid body movements, as no specific measures to constrain the wall at its base were considered. Horizontal Load cycles (Figure 9) were established according the main principles of the 2005.ASTM E.2126-05 standard:

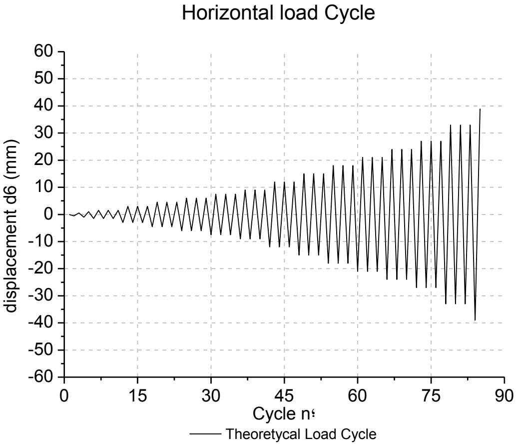


**Figure 9.** Load Cycle

Special attention was given to the reinforcement adhesion to the pseudo-masonry wall, as one of the variables studied was the importance of the use of steel connectors to enhance the mortar binding to the masonry support. Nevertheless, all wall specimens had small frontal slots to ensure a better connection between reinforcement and wall, simulating the effect of a masonry joint either prior to final pointing or during the scraping out process during repointing and prior to the final application of mortar

Another critical issue to an effective contribution of the reinforcement was its connection to the wall base. The results from cyclic pull-off tests indicated that the preferable solution to assure a proper anchorage of the UHHPI material to the specimen base was to use an organic (epoxy resin) solution, similar to the one used in the pull-off tests. Once it wasn´t determined that bonding conditions at the wall ending did not affect the experimental results, this solution proved to be extremely reliable. It was also decided to only proceed with the bonding of the UHPPI after the axial load level desired was applied to simulate the fact that reinforcement is applied to the wall under normal serviceability conditions of the building (Figure 10).

**Figure 10.** Reinforcement application

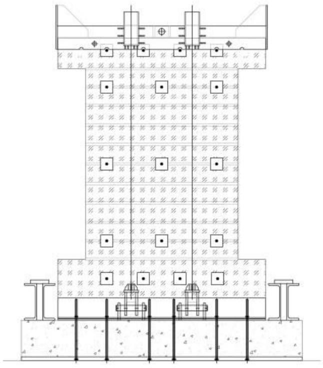


**Figure 11.** Connectors distribution

## 3.2. Experimental Results - Reference Tests

Near constant vertical axial load was applied (Figure 12), and the energy dissipated by each wall during the test is presented in Figure 13:

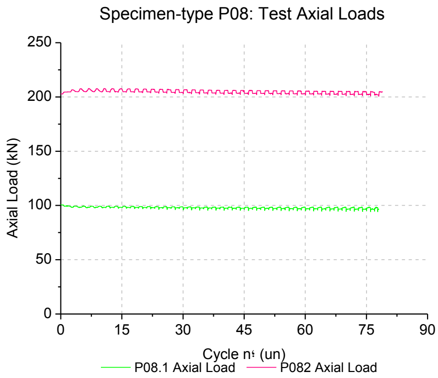


**Figure 12.** Reference Test Axial Loads

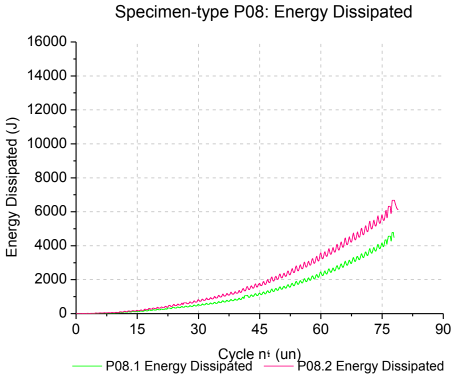


**Figure 13.** Reference Test Dissipated Energy

The Horizontal Force vs. Displacement diagrams (figures 14 and 15) are very similar, a greater load capacity being observed on the wall with higher axial load.

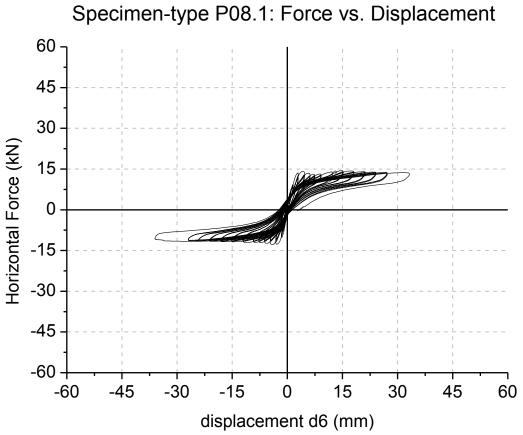


**Figure 14.** P08.1 Test

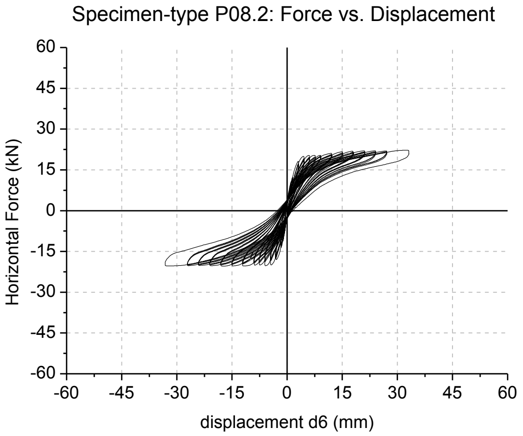


**Figure 15.** P08.2 Test

Crack damage was observed at the sides of the tested walls, with horizontal fissures at the base of the pseudo-masonry pier (reduced cross section) (figures 16 and 17).

**Figure 16.** P08.1 frontal damage

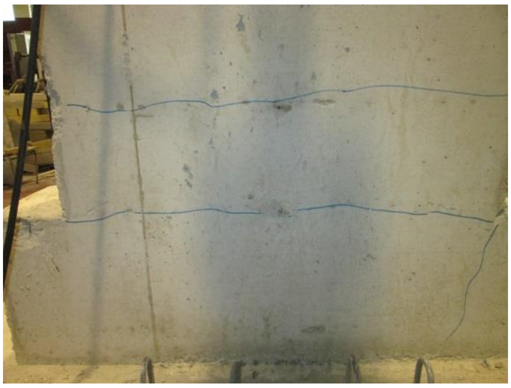


**Figure 17.** P08.2 rear damage

## 3.3. Experimental Results – Low Axial Load behaviour

The study of behaviour under low axial loads involved 4 experimental tests, all with similar axial loading. Two of the tests considered the use of steel connectors (P09.1 and P09.2), but in the other two, there were no connectors (P09.3 and P0.4). Nearly constant axial vertical load was applied as shown in Figure 18. The Energy Dissipated by each wall during the test is presented in Figure 19.

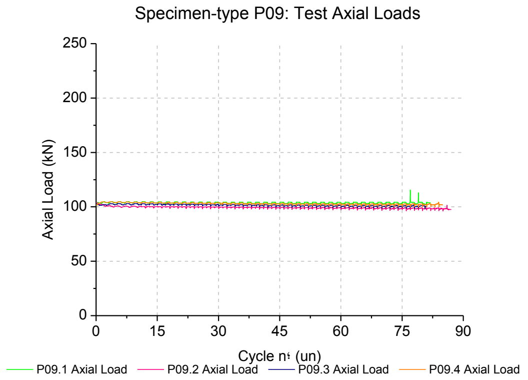


**Figure 18.** P09.1 to P09.4 Axial Loads

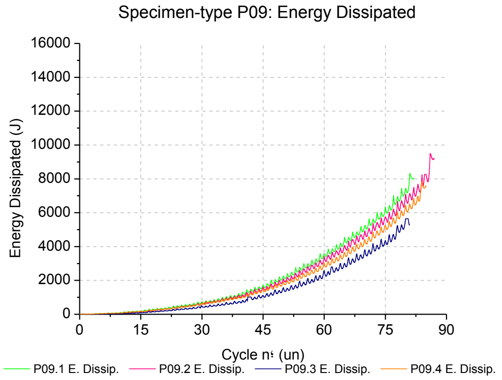


**Figure 19.** P09.1 to P09.4 Dissipated Energy

For the experimental tests of walls with installed steel connectors (P09.1 and P09.2) (Figure 22), the horizontal force vs. displacement diagrams are shown in Figures 20 and 21. The diagrams are asymmetric (regarding the displacement axis), as a consequence of applying the reinforcement only to one face of the walls. The wall's resistance to out-of-plane movements was greatly enhanced, when the reinforcement was subjected to tensile stresses. When load was applied form the other side resistance was only marginally increased when compared with the Reference Test with the same axial load.

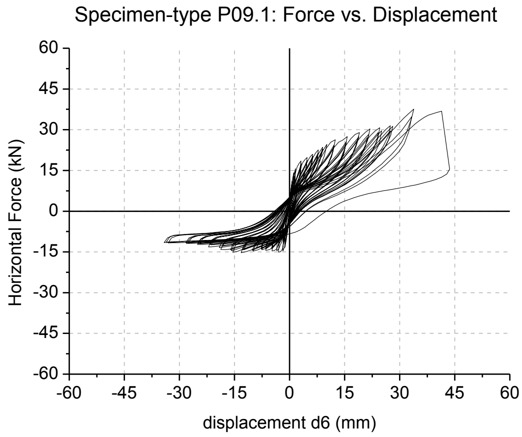


**Figure 20.** P09.1 Test

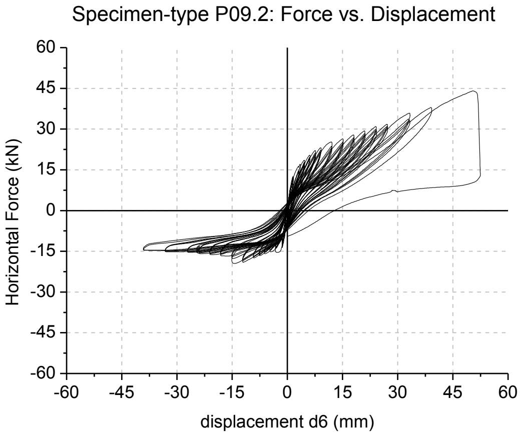


**Figure 21.** P09.2 Test

The behaviour of the wall, when the reinforcement was subjected to tension, was also significantly modified, emphasizing the fact that much larger ultimate displacements were reached, thus representing a significant increase in ductility.

On the face where UHPPI reinforcement was not applied, damage to the wall occurred at the pier junction (reduced cross section), with the appearance of horizontal cracks, similar to those of the reference test (Figure 23). On the other face, flexural cracks appeared up to half height of the pier. The mortar supporting the UHPPI reinforcement suffered horizontal cracks, and for the larger displacements, the CFRP mesh started to fracture:

**Figure 22.** P09.1 test (beginning stage)

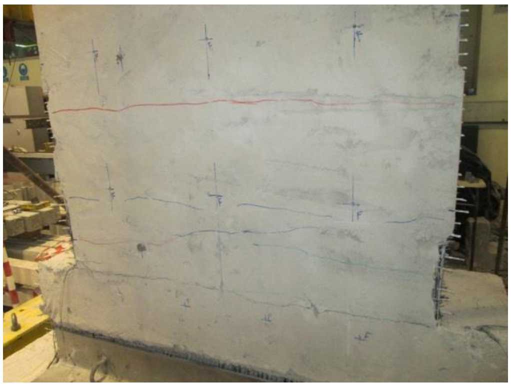


**Figure 23.** P09.2 damage

For the experimental tests of walls without installed steel connectors (P09.3 and P09.4) (Figure 26), the horizontal force vs. displacement diagrams are shown in Figure 24 and 25. The diagrams are similar to the ones concerning P09.1 and P09.2, although the wall's resistance was slightly decreased, when the reinforcement was subjected to tensile stresses.

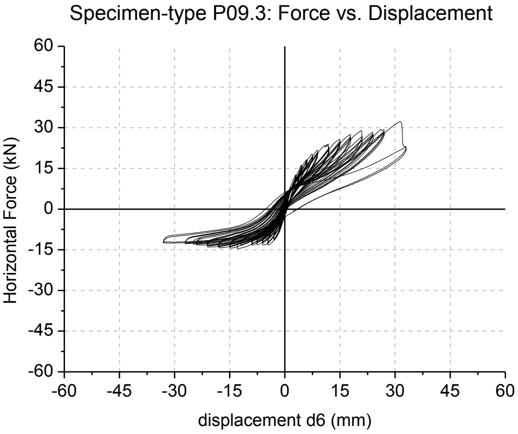


**Figure 24.** P09.3 Test

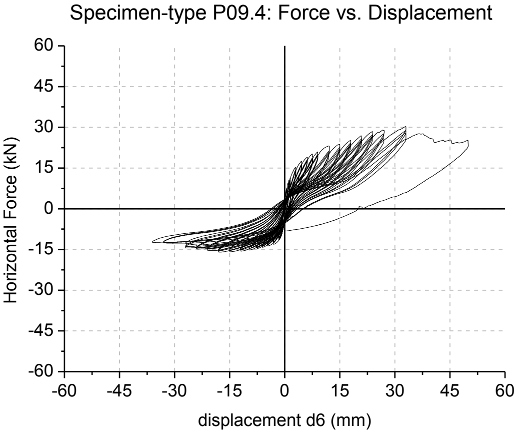


**Figure 25.** P09.4 Test

The damage, cracks and fissures were very similar to those observed in walls P09.1 and P09.2. With respect to its reinforcement, although the CFRP mesh had not fractures, it was observed to be detached where it had been mortared in (Figure 27).

**Figure 26.** P09.3 test (beginning)

**Figure 27.** P09.4 damage

### 3.4. Experimental Results – Medium Axial Load behaviour

The study of the intermediate axial load behaviour again included 4 experimental tests, all with similar axial loading. Two of the tests included the use of steel connectors (P10.1 and P10.2), but with the other two, no steel connectors were applied (P10.3 and P10.4).

The axial vertical load was applied as nearly constant (Figure 28). Wall P10.2 test had a slight superior axial loadbut this has not affected the experimental results. The Energy Dissipated by each wall during the test is presented at Figure 29:

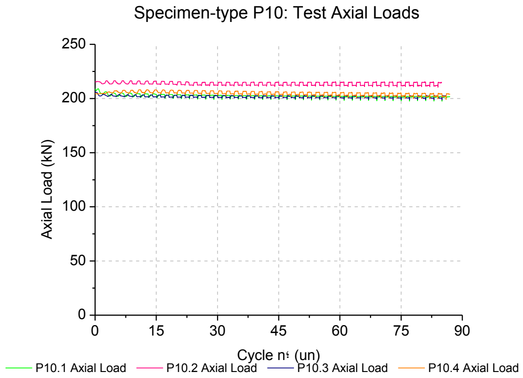


**Figure 28.** P10.1 to P10.4 Axial Loads

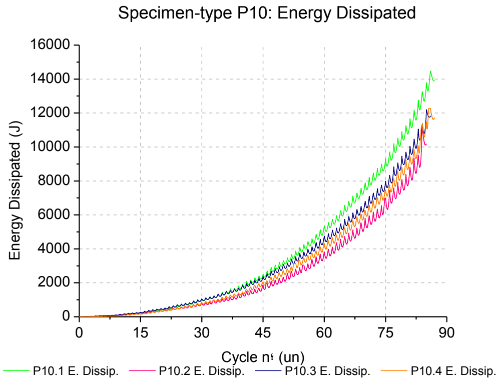


**Figure 29.** P10.1 to P10.4 Dissipated Energy

For the walls with connectors (P10.1 and P10.2) (Figure 32), the horizontal force vs. displacement diagrams are shown in Figures 30 and 31. Once again, the wal'ls resistance to out-of-plane movements was greatly enhanced, when the reinforcement was subjected to tensile stresses. When load was applied on the same side as the reinforcement the resistance was only slightly increased when compared to the Reference Test with the same axial load.

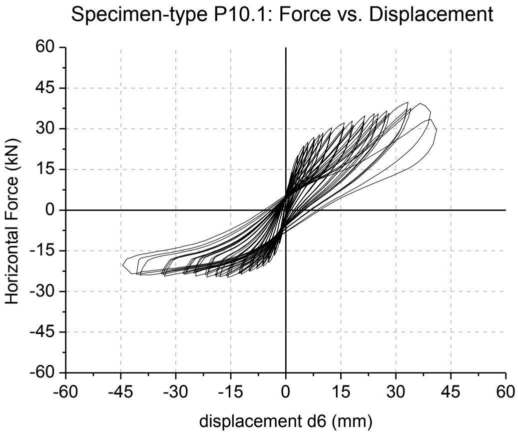


**Figure 30.** P10.1 Test

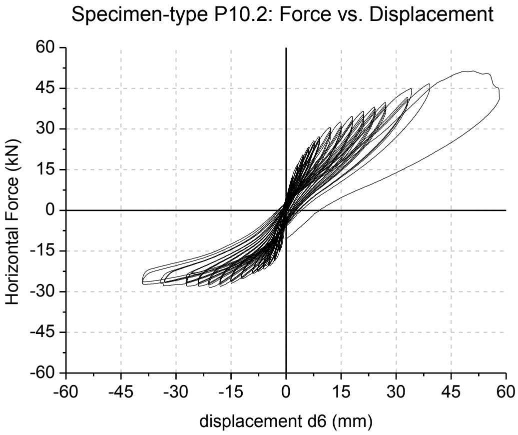


**Figure 31.** P10.2 Test

The behaviour of the wall, when the reinforcement was subjected to tension, was also significantly modified, achieving much larger ultimate displacements thus representing a significant increase in ductility.

On the face where the UHPPI reinforcement was not applied, damage to the wall occurred at the beginning of the pier, with the appearance of horizontal cracks, similar to those of the Reference Test. On the other face, flexural cracks appeared up to half the height of the pier wall. Where bonded the UHPPI reinforcement caused horizontal fissures in the mortar, and with the larger displacements, the CFRP mesh started to fracture (Figure 33).

**Figure 32.** P10.1 test (beginning stage)

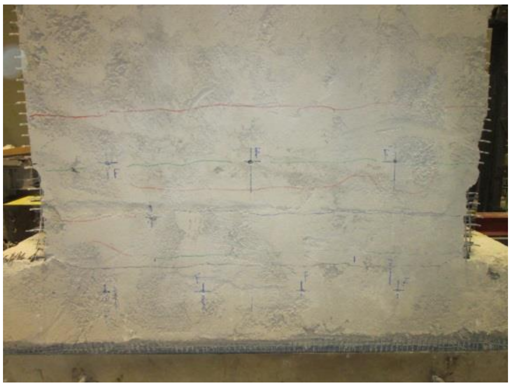


**Figure 33.** P10.2 damage

For the experimental tests of walls without installed steel connectors (P10.3 and P10.4) (Figure 36), the horizontal force vs. displacement diagrams are shown in Figure 34 and 35. The diagrams are similar to the ones for walls P10.1 and P10.2, with the wall's resistance also similar, when the reinforcement was subjected to tensile stresses.

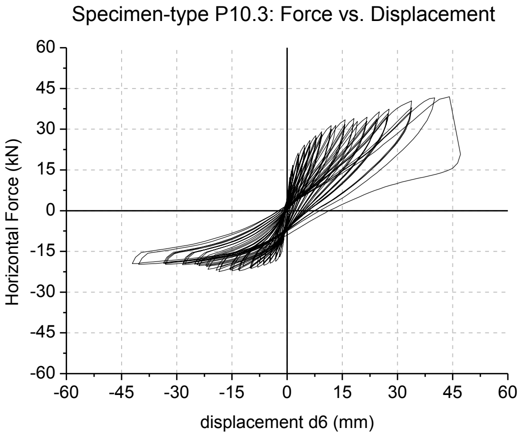

Specimen-type P10.3: Force vs. Displacement

**Figure 34.** P10.3 Test

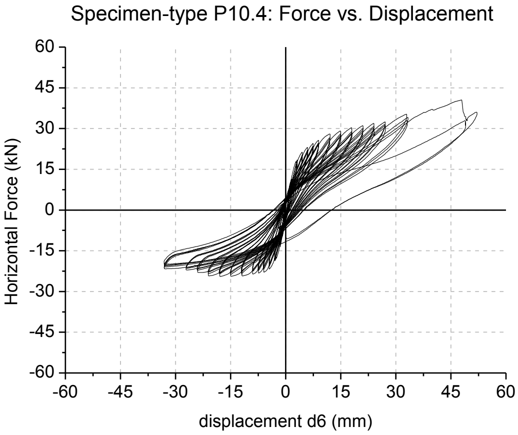

Specimen-type P10.4: Force vs. Displacement

**Figure 35.** P10.4 Test

Damage, cracks and fissures were again very similar to the ones observed in walls P10.1 and P10.2. The CFRP mesh had fractured, and there was some detachment of UHPPl mortar, but not as significantly as for the tests with low axial force without steel connectors (Figure 37).

**Figure 36.** P10.3 test (beginning stage)

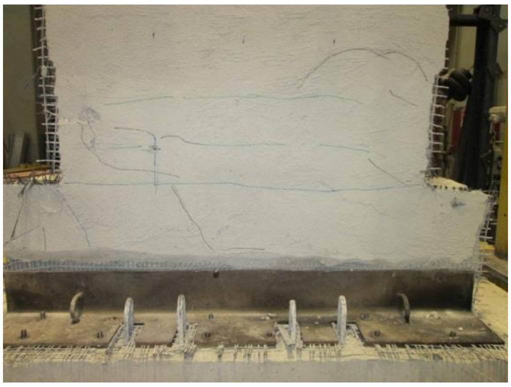


**Figure 37.** P10.4 damage

## 4 OVERALL REMARKS

The results to characterize the reinforcement technique to enhance out-of-plane flexural behaviour of masonry walls are encouraging, achieving the aims set at the outset of this programme. Carried out simultaneously with the out-of-plane experimental tests, the testing describing the in-plane behavior of masonry walls is in its final phase, and also with satisfactory results.

It is now possible to meaningfully enhance the out-of-plane behaviour of masonry walls, retaining at the same time their original characteristics. Seismic response will be improved, both in terms of strength and ductility (and/or deformation capability).

Notwithstanding the fact that the material properties of the reinforcement are of great importance, the application procedure is also significant. Appling the plaster manually was less promising.

To ensure this technique is effective the applicatin procedure neds to be carefully manged and skilled operatives are required.

A mathematical evaluation of the work will be undertaken in the future which will include a parametric study that will establish the limits of the reinforcement technique. Its development wil then be concluded and relevant design guidance produced.

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