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ULTRA-HIGH PERFORMANCE PLASTER (UHPPl) FOR SEISMIC REINFORCEMENT OF MASONRY WALLS

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ABSTRACT

This work presents the preliminary results for a retrofitting technique to use on the seismic reinforcement of ancient structures (buildings and others). The technique involves the replacement of masonry walls exterior or interior plasters or renders, with a retrofitting material that will significantly enhance the out-of-plane and in-plane mechanical behaviour of such walls, with major significance for the seismic response of the intervened structure. The reinforcement material (UHPPl) must respect the physical features and traits of the substratum in which it will be applied, as also its mechanical characteristics have the specific need to be consistent with the same substratum.

Keywords: seismic, reinforcement, CFRP (carbon-fibre reinforced polymer), plaster, masonry

INTRODUCTION

Masonry is very commonly found at ancient building structural walls of the historical centres of major European cities. Being of stone or brick masonry, it is recognized its unreliable behaviour in case of earthquake activity, being also granted the need of seismic reinforcement to assure a reliable behavior to the safety of the structure and surroundings users. Recent interventions to improve the seismic safety of old buildings tend to be very intrusive and could harm its cultural value. Because of it, specific hydraulic lime based mortars are starting to be very commonly used in conservation works of ancient masonry, due to its compatibility with the part intervened, given the similarity of the two materials nature. The presented technique followed the same requirement, respecting the principles of originality and low intrusiveness that the intervention must comply.

Such mortars don't have however the mechanical capacities to reinforce the masonry to seismic action (low tensile resistance). Therefore, the definition of a composite material, composed by a hydraulic lime based mortar involving a carbon fibre (CFRP) mesh, was used to cope with such limitations, being the first results (the ones to present) very promising to the goals in hand. A cement based material was also tested at an early stage, with randomly dispersed short fibres and without any mesh.

Seven (total of 7 tests to essay) direct tensile tests and nine (total of 9 tests to essay) lashing pull out tests to UHPPl strips were already carried out. Two (total of 15 tests to essay) in-plane flexural tests to masonry walls were also held (on non-reinforced walls), whereas the experimental campaign comprises also 13 out-of-plane flexural tests on masonry walls (none yet conducted). Other material characterization tests are also predicted (some of them already performed).

DIRECT TENSILE TESTS

Direct Tensile Tests to UHPPl strips were performed to assess the main mechanical characteristics of the materials essayed, as well as to define the best lashing solution to use at the pull-out tests to follow:

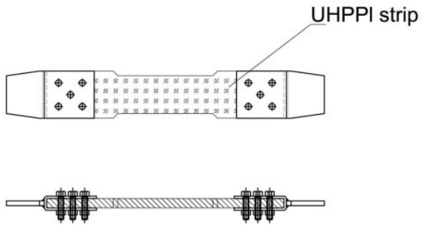

Fig. 1 – Direct tensile test specimen

As the specimen dimensions were the same for all the tests conducted, the only variables for these experiments were the specimen material and the lashing solution used:

	Specimen Material	Lashing Solution
Ref. 02.1	Cement based mortar without reinforcement mesh	Mechanical 1 (5 bolts for anchor)
Ref. 02.2	Cement based mortar without reinforcement mesh	Mechanical 2 (4 bolts for anchor)
Ref. 02.3	Cement based mortar without reinforcement mesh	Mechanical 3 (3 bolts for anchor)
Ref. 02.4	Cement based mortar without reinforcement	Organic (epoxy resin at specimen body)
Ref. 02.5	Lime based mortar with CFRP mesh strips	Mechanical (5 bolts for anchor)
Ref. 02.6	Lime based mortar with CFRP mesh strips	Organic 1 (epoxy resin at specimen body)
Ref. 02.7	Lime based mortar with CFRP mesh strips	Organic 2 (epoxy resin at mesh strips)

Table 1 – Direct tensile test variables

The results from the direct tensile tests are shown in Fig. 2 and Fig. 5.

At the four tests presented in Fig.2 (specimen's ref.02.1 to ref.02.4) the strips were produced with the referred cement based mortar with randomly dispersed short fibres reinforcement but without reinforcement mesh:

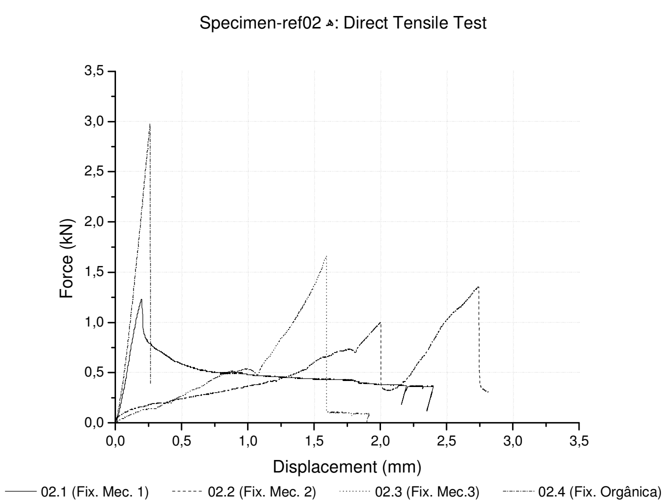

Fig. 2 – Direct Tensile Test results for cement based mortar with reinforcement fibers

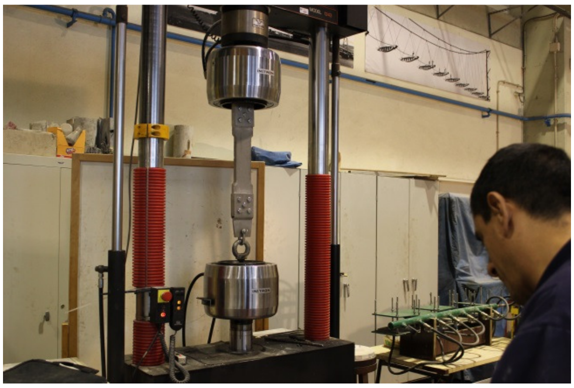

Fig. 3 – Ref. 02.1 Test
Mechanical lashing (test scheme)

Fig. 4 – Ref. 02.4 Test
Organic lashing (failure mode)

Fig. 5 presents the results for the lime mortar based specimens reinforced with a CFRP mesh (specimen's ref.02.5 to ref.02.7):

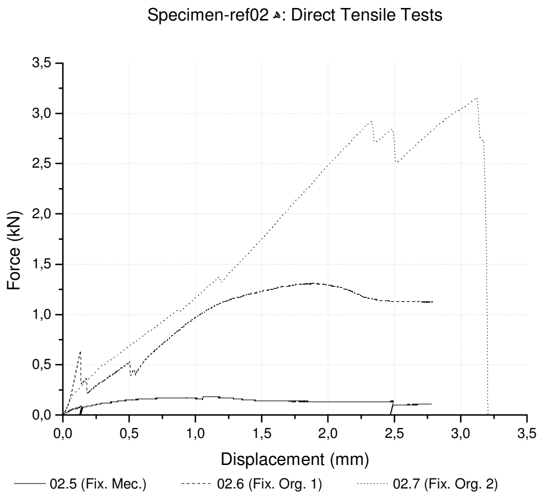

Fig. 5 – Direct Tensile Test results for lime based mortar with reinforcement CFRP mesh

Fig. 6 – Ref. 02.6 Test
Organic lashing at mortar (failure mode)

Fig. 7 – Ref. 02.7 Test
Organic lashing at mesh strips (failure mode)

CYCLIC LASHING PULL-OUT TESTS

Cyclic lashing pull-out tests were performed to better assess the reinforcement behavior and mechanical properties, before the application and test at the large scale dimension masonry walls specimens.

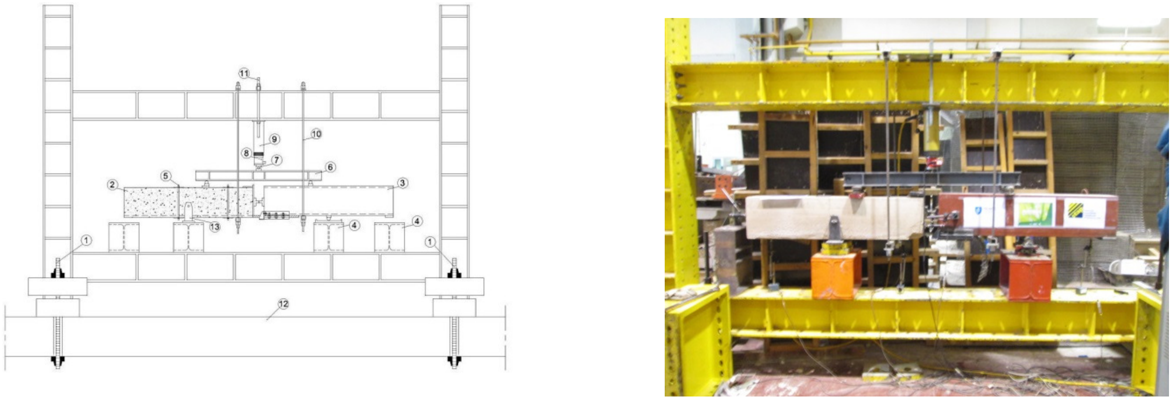

Fig. 8 – Cyclic pull-out test scheme

The UHPPl reinforcement strips were applied to pseudo-masonry (in fact a very poor concrete) beams and then connected to a metallic beam (Fig. 8 left shows the test scheme while Fig. 8 right shows a test photo). To ensure a better adhesion between pseudo-masonry beam and reinforcement strip a set of 2 metallic anchors were applied, as shown at Fig. 9:

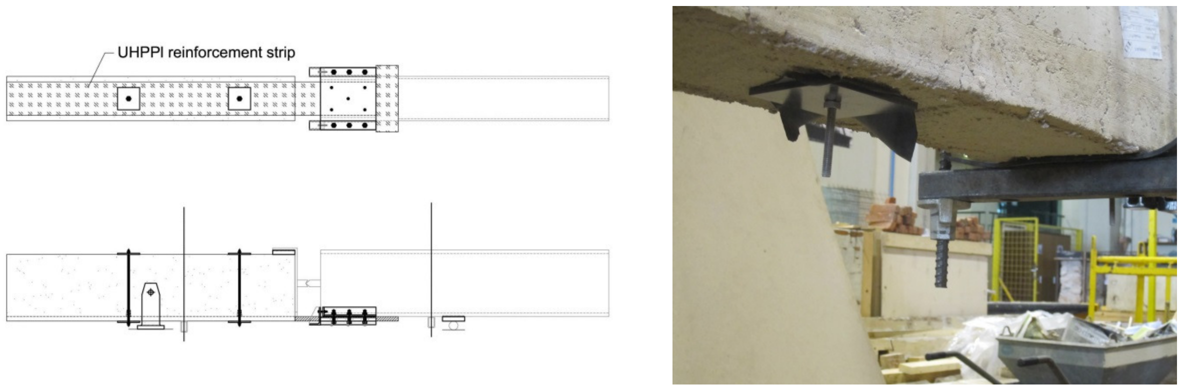

Fig. 9 – Cyclic Pull-out Test Specimen

The tests were divided in 3 specific parts, each one with different conditions regarding the variables in study, namely the mortar application technique, the lashing solution, and the CFRP mesh applied. Each phase had 3 identical tests, for statistical purposes:

	Mortar application	**Lashing Solution**	**CFRP 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

(*)- The P07.1 had a different test scheme (and premature failure of the specimen)

Table 2 – Cyclic lashing pull-out test variables

Phase 1

For the 1st phase tests a mechanical anchorage solution was considered working mainly by friction between the reinforcement strip and the metallic piece to fix it to the metallic beam.

A mesh with 80 g of carbon per square meter of reinforcement strip was used, the weakest one from the two commercial solutions available. The application of the reinforcement mortar was made manually:

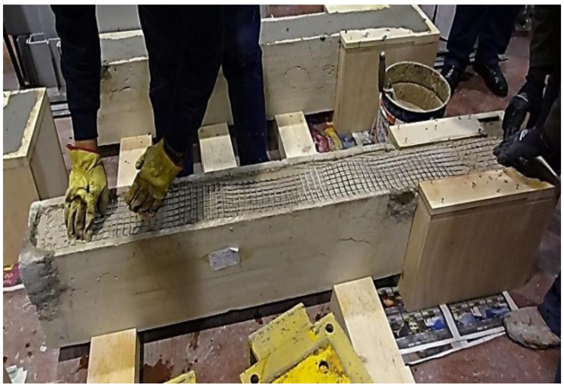

Fig. 10 – Reinforcement application (manual)

Fig. 11 – Phase 1 test (failure mode)

The failure mode, for the 2 (of 3) valid tests, was associated to the slipping of the carbon mesh in the hydraulic lime mortar matrix, associated with the detachment of the reinforcement strip between the beam end and the first fixing anchor.

Fig. 12 (one of the cyclic tests) and 13 (cyclic test envelops and their average) present the results for Phase 1 tests (specimen's P07.1 to P07.3):

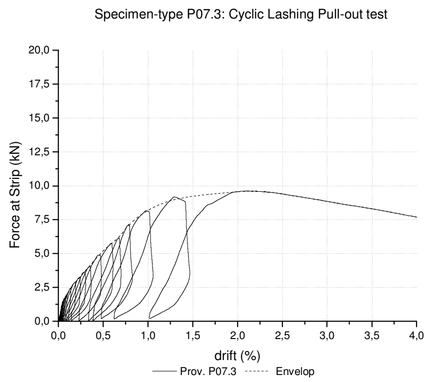

Fig. 12 - Cyclic lashing pull-out test result (P07.3)

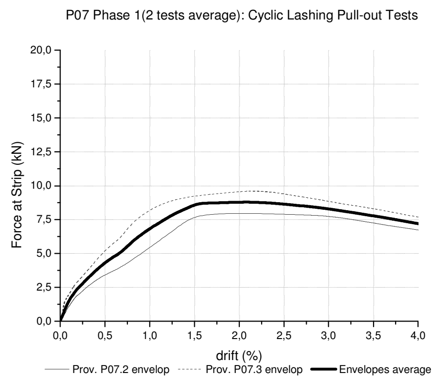

Fig. 13 – Phase 1 results (envelops and average)

From the testing conditions and results of these tests, the first improvement to consider at the following stages was to define a better way to anchor the reinforcement strip endings, allow the collapse to occur at the anchorage associated with the ultimate tensile strength at the reinforcement material (the preferable failure mechanism for the pull-out test).

A solution that would allow an efficient adhesion between UHPPl strip and the pseudo-masonry material would also be very appealing, as the pull-out collapse will happen soon after the detachment between these two materials.

Phase 2

As a conclusion of the direct tensile tests to UHPPl strips, the preferable solution to anchor them at their endings is by using an organic based (epoxy resin) lashing, applied directly to the CFRP mesh. Considering this, at the Phase 2 tests the anchorage solution at the metallic beam was switched to an organic bonding between the strips and two metallic plates then fixed to the metallic beam.

The mesh used at this stage was the same as the precedent one (80 g of carbon per square meter of reinforcement strip). The application of the reinforcement mortar was made by projection (Fig. 14), to enhance the adhesion between pseudo-masonry beam and the UHPPl strip (failure mode shown in Fig. 15):

Fig. 14 – Reinforcement application (by projection)

Fig. 15 – Phase 2 test (failure mode)

Fig. 16 (one of the cyclic tests) and 17 (cyclic test envelops and their average) present the results for the Phase 2 tests (specimen's P07.4 to P07.6):

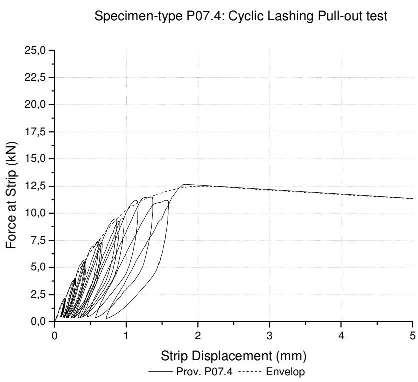

Fig. 16 - Cyclic lashing pull-out result (P07.4)

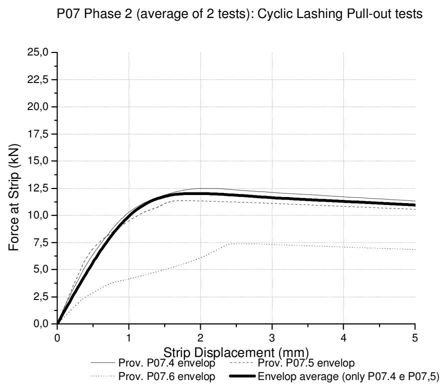

Fig. 17 - Phase 2 results (envelops and average)

P07.6 test had a premature collapse due to an inefficient bonding at the anchorage to the metallic beam (Fig. 18). Thereby, at the presented results (Fig. 17), the P07.6 wasn't considered to the envelop average. Comparing the Phase 1 and 2 results, the improvement to the reinforcement ability was about 36%.

Fig. 18 – P07.6 test (inefficient bonding)

Phase 3

The failure mode for the Phase 2 tests was the tensile collapse of the UHPPl strip CFRP mesh, near the connection to the metallic beam. For all specimens insignificant damage occurred to the remaining part of the strips, as if the reinforcement could be largely requested if the CFRP mesh was stronger.

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 one between the two commercial solutions available. Application of the reinforcement mortar was kept the same as Phase 2 (projection – Fig. 19):

Fig. 19 – Reinforcement application (by projection)

Fig. 20 – Phase 3 test (failure mode)

Fig. 21 (one of the cyclic tests) and 22 (cyclic test envelops and their average) present the results for the Phase 3 tests (specimen's P07.7 to P07.9):

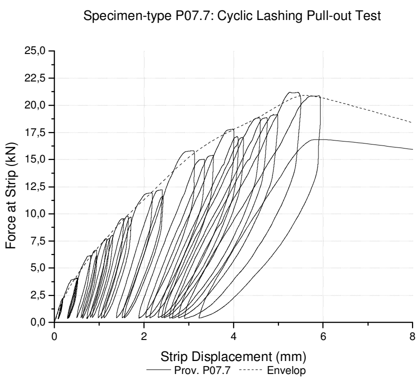

Fig. 21 - Cyclic lashing pull-out test result (P07.7)

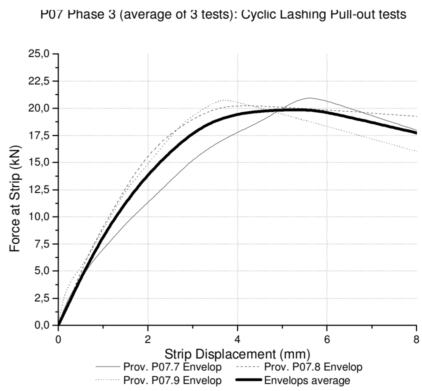

Fig. 22 – Phase 3 results (envelops and average)

Similarly to the Phase 2 tests, the failure mode at this stage was the tensile collapse of the CFRP mesh (for all specimens). Visible damages were observed at the end of the interface between UHPPl strip and pseudo-masonry beam, expressing some solicitation to the mortar part of the reinforcement strip (Fig. 23).

Fig. 23 – Reinforcement strip damage (mortar)

Significant values of applied force at strips were achieved, enhancing the tensile capacity of the reinforcement to 127% when compared to Phase 1, and 67% when compared to Phase 2.

MAIN CONCLUSIONS

The experiments presented are included in an extensive campaign to evaluate the capacity of a reinforcement technique to the seismic retrofit of part of ancient buildings – the masonry walls. The tests executed so far, with results largely satisfactory, allow establishing the technical parameters for the reinforcement with UHPPl of the large scale dimension masonry test walls, to execute at following stages.

The lime based mortar solution with carbon fiber mesh presented a slightly higher strength when compared with the solution studied with the cement based mortar with randomly dispersed short fibers (for the best anchorage solution studied). The compatibility advantages of the lime based material made possible to phase out the cement based mortar for the development of UHPPl.

Different lashing solutions at the reinforcement ends were used (mechanical and organic). The best way to fix the material endings was to use an organic (epoxy resin) anchorage solution.

Two solutions for the CFRP mesh of the UHPPl with lime based mortar were studied. For those, the cyclic pull-out tests allowed to obtain the preferable failure mechanism, associated to the ultimate tensile strength of the UHPPl that may be considered the same as the CFRP mesh, due the small tensile resistance of a lime based mortar.

For the strongest CFRP mesh, the detachment between the UHPPl material and the substratum where it was applied started to occur. That means that possible solutions with stronger CFRP mesh are limited to a maximum close to the one obtained (at least for the lime based mortar used at the cyclic pull-out tests). Stronger lime based mortars may be analyzed in further studies, if stronger CFRP meshes are needed.

Independently on the lime based mortar to use (the large scale dimension masonry walls will have reinforcements with two different lime based mortars, one equal to the one used, and another with stronger mechanical properties), the application procedure by projection brings greater improvement to the adhesion between the UHPPl and the substratum (i.e. masonry wall). Manual application can also be used, but with mechanical limitations (when compared with solution with application by projection).

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