IN SITU TESTING OF THE OUT-OF-PLANE CAPACITY OF TRADITIONAL STONE MASONRY WALLS

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SUMMARY

This paper reports on an *in-situ* experimental programme under development by the Laboratory for Earthquake and Structural Engineering (LESE, FEUP, Porto) on existing traditional masonry constructions hit and damaged during the 1998 Azores earthquake. The work seeks for a better understanding of traditional stone masonry wall behaviour under out-of-plane cyclic loading, by providing experimental evidence and realistic data of particular relevance for numerical modelling calibration of these elements in their original conditions. Following the same strategy adopted for another experimental activity performed in laboratory on a similar masonry wallet, this *in-situ* programme involved a second stage for structural strengthening according to schemes similar to some of those adopted during the reconstructions process in Faial Island. Further tests were then performed in order to assess the seismic capacity improvement of the strengthened structures. Very interesting and promising results were obtained concerning both strength and energy dissipation enhancement, thus fully confirming the basic objective achievement subjacent to the adopted seismic strengthening strategy.

1. INTRODUCTION

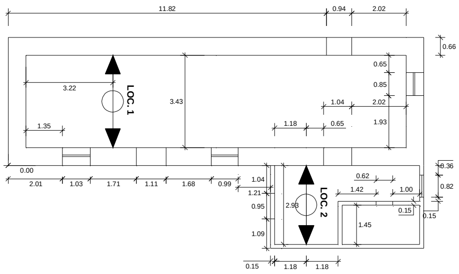
It is well known that traditional stone masonry constructions exhibit a poor behaviour under seismic loading (Griffith *et al.*, 2007). In Azores this is periodically and dramatically confirmed during earthquake occurrence, as evidenced after the most severe seismic crises of 1980 in Terceira and of 1998 in Faial, Pico and S. Jorge islands. Besides other important effects arising in the typically cohesionless material of such masonry structures, the poor out-of-plane response of walls is for sure one of the most critical issues during earthquake action since it is very likely to entail severe wall damage as well as extensive or complete failure of floors and roofs supported by the walls. This effect is particularly relevant for these structural configurations essentially based on stone masonry walls (single or double leaf) and wooden floors/roofs, usually without adequate connections between vertical and horizontal elements. Moreover, this type of horizontal systems are often not very effective concerning in-plane diaphragm stiffness that is essential to ensure a global mobilization of the whole structure by transferring horizontal forces (as desirable) to the walls in their own vertical plane.

In this context, the present work provides some experimental evidence on the response of masonry walls of existing Faial constructions damaged by the 1998 earthquake. After first testing, the structures were strengthened by providing walls with steel reinforced cover and introducing parts of wood floors and roofs duly connected to the walls using appropriate steel elements. The first experimental campaign (Arêde *et al.*, 2007) developed in May 2007 on walls with their original (though seismically damaged) conditions while the second testing stage was performed one year later, in May and July 2008. All the experimental activity was carried out by the Laboratory for Earthquake and Structural Engineering (LESE) of the Faculty of Engineering of University of Porto, with the collaboration of local institutions of Faial on the houses´ preparation before testing and on the essential *in-situ* logistics (Costa *et al.*, 2007).

2. EXPERIMENTAL PROGRAMME AND SET-UP

The basic idea of the adopted experimental system relies on simultaneous testing two opposite walls of a given house, by applying horizontal forces one against the other and resorting to a pair of hydraulic actuators operating under displacement control. Loading has been applied at the top of walls in the form of quasi-static increasing forces during repeated and alternate cycles, in order to simulate the horizontal action of roofs on masonry walls. Figure 1-a) provides an overall view of the experimental set-up in one tested house, where two experiments were performed on the locations indicated in the plan layout shown in Figure 1-b).

a)



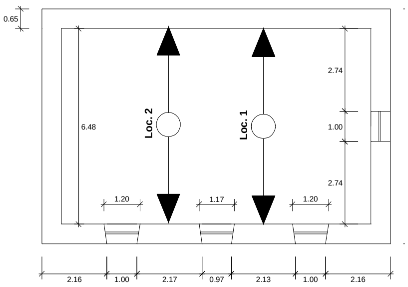
b)

Figure 1. Basics of the testing system in house 1: a) general inside view; b) plan layout and test locations

Three houses were available for testing throughout this campaign, namely two single storey houses in the Salão parish (Horta district) and a two-storey house in Cedros location. The one-storey house 1 is illustrated in Figure 1, while house 2 refers to that shown in Figure 2-a) corresponding to the horizontal layout depicted in Figure 2-b). An outside view of house 3 (similar to house 1) is included in Figure 2-c), for which only one test was made in the same location as for the first test on house 1.

Houses 1 and 3 have two-leaf walls made of basalt stone masonry, quite irregular and of poor quality. House 1 has also a more recent annex made of unconfined hollow brick masonry panels. In turn, house 2 exhibits a much better and regular masonry construction of two-leaf walls without any signs of mortar in the joints.

a)



b)

c)

Figure 2. House 2: a) general outside view and b) plan layout with test locations. c) Outer view of house 3

The first testing campaign (on 2007) was carried out on houses 1 and 2 in their original conditions by imposing forces at the top level of the walls. In the former, two tests were made, one in a stone masonry panel of the main construction (location 1) and another in the annex (location 2 - involving both one stone panel and one hollow brick panel), whereas in house 2 only one test was made in location 1. After these tests, strengthening interventions were made on these two houses according to the schemes briefly described in the next section.

On May 2008, a first testing round was performed on the same locations of house 1 and 2, in order to compare the results and to assess the strengthening efficiency. An additional test was carried out on location 2 of house 2 where a different reinforcement configuration was included; a first test was also made on one panel of house 3. Finally, the second round of this second testing campaign, foreseen to July 2008 during the seminar in which this paper is to be presented, aims at assessing other strengthening strategies meanwhile implemented. Results herein reported refer to the 2007 testing campaign and to the first round of 2008 tests.

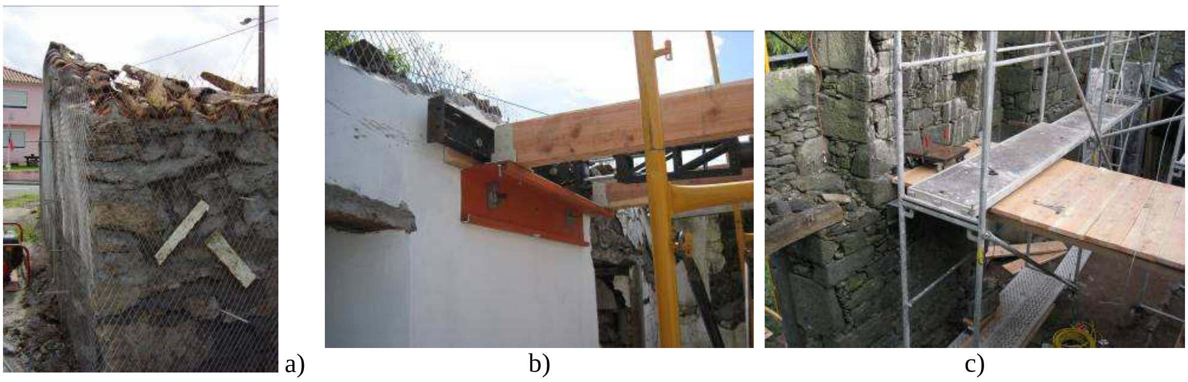
For all the tests, the applied force was measured resorting to a load cell and the out-of-plane displacements were read at several points of the wall using draw-wire position transducers. All measurements were handled and recorded by a data acquisition and control system from National Instruments, supported by a portable computer.

3. STRENGTHENING SCHEMES

Seismic strengthening for this type of structures was based on proposals implemented after the 1998 earthquake (Costa and Arêde, 2006) and defined according to the following main guidelines: *i)* to improve the strength of masonry walls aiming at preventing their disaggregation during seismic events; *ii)* to enforce a global behaviour of the construction as a whole by improving connections between different structural elements, namely walls, floors and roof.

In order to pursue these main objectives, masonry walls were strengthened with steel reinforced mortar cover, about 3-4cm thick as shown in Figure 3-a), placed in the outer and inner wall faces (Costa, 2002). Transversal steel rods were included to ensure a more monolithic behaviour of the wall cross section by improving the shear connection between the new mortar covers and the existing wall core. This technique leads to a sort of “poor” reinforced concrete wall section, while preserving the original material inside that is quite suitable for hygrothermic and acoustic purposes.

Aiming at simulating the presence of wooden floor/roof structures effectively connected to the walls, two or three criptomeria wood beams (9x20cm^2, cross section) were placed between opposite walls, supported and bolted to right angle steel shapes fixed to each wall by steel rods crossing its total section (Figure 3-b). This procedure was adopted at the roof level of houses 1 (loc. 1) and 2 (loc. 1 and 2). Where floor presence should be simulated, wood boards were also nailed to the beams as adopted in house 2 (loc. 1) and shown in Figure 3-c).

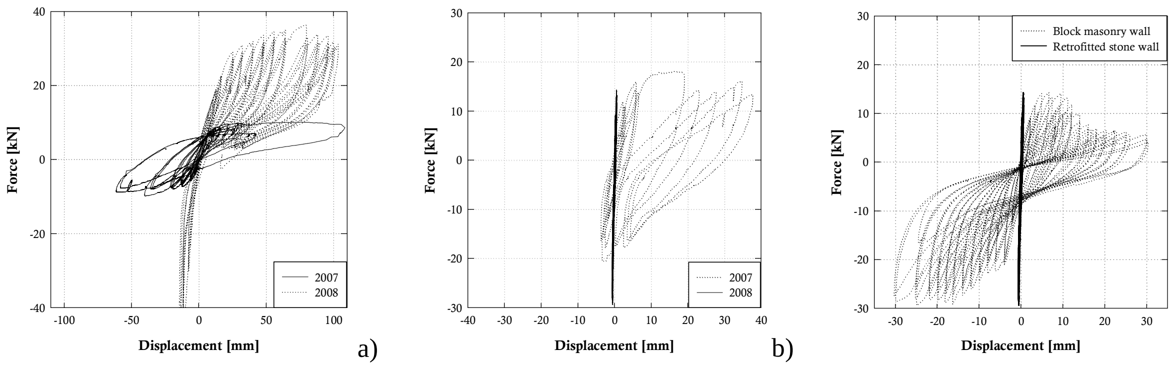


a) b) c)

Figure 3. Strengthening schemes: a) steel reinforced mortar cover in masonry walls; b) wood beams supported and fixed to opposite walls; c) wood boards nailed to floor beams to include pavement contribution

4. TEST RESULTS

Although not yet fully processed, some of the main tests results are briefly referred here in terms of force-displacement diagrams, where the displacement always refer to the top section of the walls. Plots shown in Figure 4 refer to tests on house 1, including comparisons between results from original (2007) and strengthened conditions (2008).



a) b) c)

Figure 4. Test results for house 1. a) Location 1: original v.s. retrofitted, b) location 2: original v.s. retrofitted and c) brick *v.s.* retroffited stone masonry panels

Figure 4-a) clearly shows the benefits of the strengthening strategy where the strength increased more than three times the original value for the wall in location 1; the strange response in the negative sense (walls approaching) is due to wood beams that become mobilized in compression. Results for the wall in location 2 are depicted in Figure 4-b), showing that in 2007 the stone masonry panel was seriously damaged during a test where appropriate reaction could be mobilized thanks to the return walls orthogonal to the panel. After strengthening, this panel became so stiff that it almost did not move in 2008 tests, which in turn allowed exploring the opposite hollow brick masonry panel as shown in Figure 4-c).
Figures 5-a) and 5-b) illustrate test results for house 2, where again the comparison between original (2007) and strengthened (2008) puts into evidence a clear gain of strength for both senses of wall displacement (positive outwards) on location 1; note that wall deflection in 2008 was not pushed so far as in 2007 for safety reasons related to eminent wall instability. The response of both front and rear walls in location 2, connected by roof beams and tested in 2008 for the first time, shows a quite stable behaviour with appreciable energy dissipation throughout a loading history that reached about 1.2% drift (equivalent to *t/10*, where *t* is the wall thickness). Finally, Figure 5-c) shows the response of tested walls of house 3 where a clear degrading mechanism is evidenced after reaching 1% drift, although with significant capacity for energy dissipation.

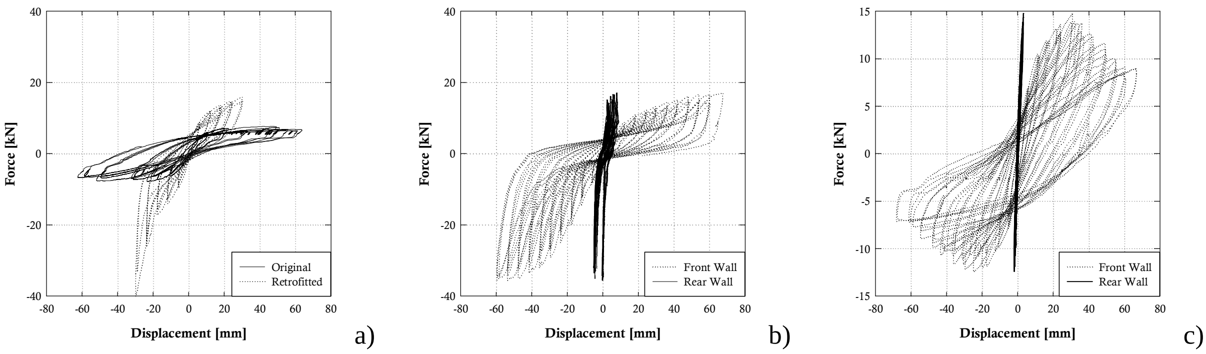


Figure 5. Test results: house 2, a) Location 1: original *v.s.* retrofitted, b) location 2: front and rear walls and c) house 3, front and rear walls

5. CONCLUSIONS

Although in a very succinct way, the above described allows concluding the great potential of the *in-situ* tests as performed in the last two years on typical masonry constructions of Faial Island, Azores. The outcome of such tests is of utmost importance for understanding the behaviour of traditional masonry walls as they exist, particularly concerning the out-of-plane response as addressed in this study. A significant contribution is also achieved for appropriate numerical modelling calibration. In addition, concerning the assessment of actually implemented strengthening interventions, the brief insight herein provided allows concluding the clear improvement of structural behaviour under cyclic loading. This fact is even more important since these strengthening schemes were effectively used in the reconstruction process after the 1998 earthquake.

6. REFERENCES

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