Out-of-Plane Cyclic Experimental Testing of Traditional Stone Masonry Walls with Distributed Loads

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SUMMARY:

Stone unreinforced masonry walls frequently suffer out-of-plane collapses when undergoing seismic motions. This inherent seismic vulnerability of the URM walls has been dramatically confirmed by the recent earthquakes worldwide. In this context, this paper aims at assessing the out-of-plane behavior of existing stone masonry buildings by an in situ experimental testing campaign. For the testing purposes, an experimental test setup based on a self-equilibrated scheme was developed and optimized to be applied in situ in two specimens on original and strengthened conditions. Uniform loading was applied on both sides of the walls using a system of airbags. The obtained results are presented and carefully discussed namely from the reinforcement solutions' efficiency point-of-view, as well as compared to previous experimental data obtained for the same type of masonry walls.

Keywords: in situ test, cyclic tests, airbag testing, URM walls, out-of-plane, strengthening

1. INTRODUCTION

In Azores islands, where traditional stone masonry construction is still a must, recent earthquakes led to the abandonment of deteriorated buildings by local people and owners, putting in risk the preservation of traditional construction heritage. However, an increasing research effort is being developed by the scientific community, fostering studies to search solutions which allow building and/or rehabilitating existing constructions in order to ensure increased safety against seismic actions.

In this framework, this paper focuses on tests carried out aiming at characterizing traditional stone masonry walls when exposed to dynamic actions, namely earthquakes. In the project herein presented, a test technique was developed, first in laboratory and later in-situ, distinct from other techniques already described in the literature (Costa *et al.* 2011; Costa *et al.* 2012), since it basically consists in applying distributed loads on masonry walls' surfaces, trying to simulate masonry inertia forces developed under seismic action.

Costa *et al.* (2011) held a series of in-situ tests, considering that the application of an horizontal load in the top of the wall, actually distributed height wise, could be assumed as a good representation of the seismic action; this assumption was further supported by the weak connection between traditional masonry and horizontal elements, meaning that individual wall panels are likely to behave as vertical cantilevers.

In Griffith *et al.* (2007), Mosallam (2007), Derakhshan *et al.* (2008) and more recently, in Dizhur *et al.* (2009), Dizhur *et al.* (2010) and Dizhur *et al.* (2010)) applied an innovative testing technique, which consisted on applying distributed loads in the surface of the wall, using airbags and a load cells' system to evaluate the force applied in the wall surface during cyclic and bidirectional tests (outwards and inwards).

2. LABORATORY DEVELOPMENTS

For the present work, before applying the technique *in-situ*, a series of studies and laboratory tests was carried out to better understand and properly implement the technique. The procedures adopted for the test setup development are briefly described in the next subsections.

2.1. Airbags calibration

The laboratory development was based in a master thesis work (Garcia 2010), which concluded that issues such as the contact area estimation, the reaction structure, the test control optimization/automatization, as well as the force and displacement measurements should be further developed. In the same work (Garcia 2010), it was concluded that the used airbags (Gorilla type) did not fulfil the needs, since they evidenced a number of shortcomings, not only geometric, but also regarding the input/output air flow and the insufflations capacity (which was found to limit the horizontal displacements).

In order to solve the referred problems, the "Gorilla" type airbags (Figure 1-a)) were replaced by Nylon airbags (Figure 1-b)). The main differences between the two airbags types refer to the material strength (the Nylon airbag is more robust), to the airbag rectangular shape (with lateral edges) that provides a more regular rectangular geometry of the contact surface and to the larger number of input/output air holes which allow better accuracy in the air pressure control.



a)



Figure 1. Adopted airbags: a) Gorilla airbags; b) Nylon airbags

A series of laboratory tests were carried out to calibrate the contact area, being found that the area is not constant during the test, since it is directly related to the wall displacement relative to the reaction structure. Figure 2-a shows the correlation of the force correction factor with the displacement of the wall relative to the deflected configuration presented in Figure-b.



Figure 2. Contact area correction: a) correction factor; b) displaced wall.

2.2. Development of testing and control system

For the tests it was used a program developed in LabVIEWTM (NI 2010), which allows controlling the test variables, namely the input/output air pressure, the target displacement and the load application rate, as well as recording all the structure displacements at the same time.

In order to check the control and acquisition system, a series of laboratory tests were carried out (Figure 3), in which the in-situ conditions were simulated as real as possible. The acquisition system is composed by an acquisition device (National Instruments hardware), where displacements and pressure sensors are connected to.



Figure 3. Test setup for software validation: a) test setup; b) electric valves; c) pressure transducer.

The tests carried out allowed to conclude that the data acquisition is satisfactory, pointing that in the initial phase, in which the airbag pressure increases, there is a slight gap between the defined loading law and what is in fact happening; this gap is due to the fact that, in the beginning, the airbag is completely empty, so it needs some time to fill its volume before the pressure monitoring starts.

The adopted test methodology, resorting to distributed load application, allows a closer approximation to the real distribution of the seismic loads which are mass proportional, when compared to the techniques that apply a concentrated load in one point (or line) of the structure.

Nevertheless, this technique also has shortcomings, namely the impossibility of visual evaluation of the damage evolution in real time during the test, because the wall surface is covered with the airbags.

3. IN SITU TESTS

3.1. General comments

The tests presented in this paper proceed from a previously carried out experimental campaign described in Costa *et al.* (2011), and mainly aim at using an innovative test technique, by applying the same principles that other authors used (Griffith *et al.* 2007). The tests were performed in Azores typical houses, specifically in two-leaf stone masonry wall panels which consist of external leafs of shaped stones, with rubble infill made of weaker materials. This kind of masonry exhibits a high seismic vulnerability, as noticed during the 1998 earthquake.

3.2. Tests' description

The defined reaction structure consists of steel elements specially designed for versatile and easy insitu installation. Despite a reasonable global weight of the structure, a group of individual elements was defined weighing less than 30kg each, thus allowing its manual transportation and assemblage without requiring heavy machines. The final solution was a frame structure, approximately symmetric, composed by a significant number of elements of similar type in order to simplify its assemblage. The structure was supported by a set of steel tubes (\emptyset =60mm), connected to the house back wall (parallel to the tested wall). For supporting the airbags, the structure included also timber elements and plywood plates (Figure 4-c)).

Besides the steel and timber structure, the test system included three airbags in each side of the wall, an air compressor, hose (to connect all the necessary devices to apply the pressure), valves to control the input/output air pressure, a pressure reducer, several wire transducers and pressure monitoring duly connected to the data acquisition card, which sends the information to a computer.

As previously mentioned in section 2, the method of application of the distributed loads used in these tests was already used by other authors. However, the conception of the test system, regarding for example the structure, the automatic control system and the possibility of reaching large wall displacements represents a step forward in this research activity.



Figure 4. Main test setup: a) general view; b) external view; c) internal view

3.3. Tested houses and elements

As previously referred, most of the structures in the rural areas of Faial Island are 1, 2 or 3 storeys a made of double-leaf basaltic stone walls, with poor infill material between the two leafs. The external side of the wall is usually more shaped or regular than the internal leaf. Most of the times, the walls are covered with plaster in both internal and external sides.

In order to evaluate the out-of-plane behavior of masonry walls, tests were made in two houses namely the "Casa Nove" (CN – Figure 5) and the "Casa do Salão" (S – Figure 6), both with only one floor.



Figure 5. House CN: a) main façade and tested panel; b) plan view and location of the tested panel.



Figure 6. House S: a) main façade; b) plan view and location of the tested panel.

These structures were damaged during the 1998 Azores earthquake, with partial roofs' collapse and some local damages which did not affect the integrity of the tested elements. In the first house (CN), the walls were tested in the original conditions, while in the second one (S) the

tested elements were retrofitted using the technique described in the next section.





Figure 7. Tested panels and monitoring layout. Main façade and wall section for: a) house CN and b) house S

3.4. Strengthening solution

The strengthening technique used in the wall panel of house S essentially consists in reinforced connected plaster as recommended in Eurocode 8 Part 3 – Annex C.5.1.7. According to Costa (2002),

it was widely used during the reconstruction of Faial Island for the rehabilitation of Azores traditional constructions after the 1998 earthquake. Shortly, this technique involves the application of steel mesh layers in both wall sides, linked by steel connectors installed across the wall (in the transverse section), as shown in Figure 8 a). Subsequently, a cement based mortar is applied in both wall sides to cover the steel mesh, thus providing an enhanced monolithic behaviour of the wall. This strategy corresponds to the simple use of reinforced connected plaster.

However, the structural response to cyclic lateral loading can be further improved by providing appropriate anchorage of the steel mesh at the foundation level, resorting to lintel beams adjacent to each wall side as illustrated in Figure 8 b). This strategy was adopted for the tested panel of house S as herein presented.

Increased strength can be further achieved by attaching both lintel beams to the wall resorting to transverse steel rods; this option was not considered in the house S wall panel, but its efficiency was assessed in previous campaign tests as reported in Costa *et al.* (2011).

Figure 8 c) shows the widespread use of reinforced connected plaster in the main façade of house S, evidencing that, by contrast with the CN house panel, the spandrel beams are likely to influence the response of each wall panel in between openings.



Figure 8. Strengthening solutions and application: a) reinforced connected plaster; b) reinforced concrete beams; c) main façade

4. RESULTS

As previously referred, a number of experimental campaigns were carried out in the same houses (CN and S), in similar wall panels, regarding material, geometry and boundary conditions. The only difference from the previous tests, relative to the present ones is that the applied load was distributed in the wall surface rather than being concentrated in the top of the wall (Costa *et al.* 2011). Therefore, the comparison between the results obtained in these tests and in the previous campaign (Costa *et al.* 2011) will then be influenced by the fact that the walls were tested using different load distribution.

4.1. Discussion of the results

Figure 9-a) shows the Force vs. Displacement and Stress vs. Drift hysteretic plots of the CN house wall tests (herein denoted as CN03_1) where large displacements were imposed (positive values refer to outwards motion), up to about 180mm, when the test had to be stopped because the setup did not allow larger displacements.

The maximum surface stress reached approximately 6.2 kPa, for about 1% drift, after which progressive strength degradation started taking place up to approximately 4 to 5%. However, from then on, an unexpected strength recovery started developing, that was found to be caused by the wall contact with the reaction structure. Therefore, such results are meaningless for the wall response which is evidenced in the plot by the dashed line, in contrast with the solid line that refers to the valid results (i.e. representing the real behaviour of the wall).

The non-symmetric response exhibited in Figure 9 is caused by different free height of the wall which is larger outside than inside the house due to the internal pavement located about 30cm upper than the external one. Thus, for outwards motion, the panel is more flexible and allows accommodating larger deformations without significant strength loss, resulting in increased ductility for this motion sense. This effect is further justified also by the presence of a good cement mortar cover on the external surface (thicker and stronger than the internal one) and by the larger wall width of that surface.

All these effects summed-up lead to low ductility for inwards motion, but also to quite reasonable ductility values of at least about 3 to 4 for outwards displacements (which are those of most concern for this type of construction, because the internal sense the motion is restricted by roofs and floors).

However, in order to clarify the "final" outwards response, after stopping the CN03_1 test, a second one was made (CN03_2) by pushing the wall only into the outer direction (positive sense), though starting from the previous residual displacement. Plotting the response curves of both tests (Figure 9-b)) it can be seen that the outwards strength degradation is not as intense as for the inwards direction and the overall behaviour shows more ductility than pointed out before.



Figure 9. Results of the tests on house CN. a) Test CN03_1: outwards/inwards motion. b) Test CN03_2: inwards motion only (Dashed line refers to meaningless results for the real behaviour).

The displacements' profiles along the wall height (Figure 10-a)) allow observing a linear displacement pattern up to 1.75m high. This evolution turns into non-linear from that level up to the top (2.41m high), which can be related with the fact that the upper part of the wall was more deteriorated due to the demolition of the connection between the wall and the window lintel. Figure 10-b) evidences a linear increase of dissipated energy, thus at an approximately constant rate in agreement with the progressive damage observed during the test. The linear trend of both the displacement profiles and the evolution of dissipated energy are consistent with the essentially rocking type response exhibited by the wall panel.



Figure 10. Performance evolution: a) displacement profile; b) energy dissipated

Concerning the house S, due to in-situ constraints (Figure 11), the test S01R2 was carried out only in outwards direction, on a stone masonry wall panel strengthened with the technique described in 3.4. The free space in the exterior part of the house was reduced and did not allow the installation of one part of the reaction structure, thus preventing the bidirectional test to be accomplished. The obtained results are shown in Figure 12 and Figure 13.



Figure 11. House S, test panel S01R2: a) test setup; b) outside view of the strengthened wall



Figure 12. Force-displacement and stress-drift results for panel S01R2 test

Figure 12 evidences the initial phase with linear elastic behaviour, until approximately 4mm top displacement. The second phase shows elasto-plastic response (with increasing plastic displacement) coupled with rocking behaviour until 210mm top displacement. The latter was found to be due to rotation at the foundation level, without significant damage in the wall as a result of the adopted

strengthening technique of wall which behaved as a rigid block. The foundation rotation prevented the test to proceed beyond 210mm because the lintel beams started interacting with the reaction structure, thus affecting the correct test development.



Figure 13. Panel S01R2 behaviour evolution: a) vertical displacement profile; b) energy dissipated

However, it is clear that this strengthening technique provides a very high stiffness when compared to the initial wall stiffness, the same holding true for strength as well. Although some influence might exist due to differences in spandrel beams, both CN and S01R2 wall panels are similar regarding its geometry and material, thus allowing comparing the obtained results, namely in terms of strength for which the S01R2 panel exhibited 3.7 times larger value than the non-strengthened wall (CN). The height wise horizontal displacement profiles for the S01R2 panel test (Figure 13-a)) show slightly curved shapes for the initial stage, turning into more linear like for larger displacements, thus in

curved shapes for the initial stage, turning into more linear like for larger displacements, thus in agreement with the rocking response. However, the energy dissipation (Figure 13-b)) developed exponentially, evidencing that almost 1/3 of the total energy was dissipated in the first half of the test, whilst the remaining 2/3 of energy was dissipated afterwards.

4.2. Comparison with previous tests results

In order compare the present results with those obtained in previous experimental campaigns, the values of initial stiffness, maximum force and correspondent displacement are summarized in Table 1 for the different tests.

Table 1. Previous and present experimental results			
House	Kinicial	F_{max}	d_{max}
	(kN/m)	(kN)	(mm)
CN	1826	21	179,7
CN*	1844	14,5	66,6
S01R2 _{strengthened}	5138	76,5	209
S01R2*strengthened	6955	50,1	213,9

*Previous experimental campaigns (Costa et al. 2011)

By comparing the CN and CN* tests is possible to conclude that, with airbag testing, the peak force is increased about 6.5 kN (less than 50%) while peak displacements are much larger. However, since the resultant force in the two tests was applied at different levels of the wall, i.e. in CN the force was applied at 1.2m from the base while in CN* it was applied on the top (2.41 m from the base), the bending moments at the base can be computed leading to values of 25 kN.m and 35kN.m, respectively for CN and for CN* cases. Nevertheless, the two tests exhibit very close initial stiffness values.

Concerning the house S, the results of S01R2 strengthened and S01R2*strengthened tests show that both walls reached large displacements (with a minor difference of 4mm) but the applied forces differ approximately 26.4 kN (again larger for the airbag testing). However, using the same load application heights as for CN panel, the corresponding bending moments at the base take the values of 92 kN.m and 121kN.m, respectively for S01R2 strengthened and for S01R2* strengthened cases. The initial stiffness follows a similar trend, as for the peak force, evidencing lower values when distributed forces were applied, when compared with the force applied on the top.

These values show how the load application method (on the top or distributed in the surface) can lead to different strength values.

5. CONCLUSIONS

After the tests described herein, it is possible to conclude that the adopted test technique is adequate and functional, allowing to run both bidirectional and unidirectional cyclic tests. The campaign allowed validating the developed test setup, meaning that future tests may use this setup type, and provided additional data for the characterization of traditional stone masonry of Azores buildings.

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