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RECENT ADVANCES ON IN-SITU EXPERIMENTAL ASSESSMENT OF MASONRY ELEMENTS UNDER OUT-OF-PLANE ACTIONS

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ABSTRACT

Experimental testing of existing structures possesses great advantages but also severe inconveniences, especially when dealing with masonry structures. Indeed, the simulation of existing masonry materials under laboratorial environments is one of the major drawbacks when dealing with experimental characterization of masonry elements, also with the representativeness of the local boundary conditions.

On the other hand, a controlled environment under lab tests turns out possible the use of large reaction structures and extensive instrumentation, characterizing more clearly the desired behaviour and taking into account any other possible disturbances to the test protocol.

In order to assess the out-of-plane behaviour of existing masonry structures, several advances have been made in the last decade, aiming at characterizing masonry specimens in their original conditions.

In this article, the main experimental tests developed for experimental in-situ assessment of the out-of-plane behaviour of masonry elements will be addressed on a constructive perspective. The main contributions of different experimental apparatus will be presented, both for single leaf and multiple leaves masonry walls, where similar test setups may lead at significant different approaches and results.

As the main objective of this experiments is to reproduce the effects of the seismic excitations on the masonry elements, the differences of experimental setups devoted for single and multiple leafs masonry walls will also be addressed.

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INTRODUCTION

The use of experimental activities on structural engineering is widely used for the correct characterization of different properties of structures, especially for the important outcome of assessment and design objectives. Several different test types can be performed on elements/structures, such as material characterization, fatigue, cyclic behaviour or even seismic performance assessment of complete structures. Each test should be selected taking into account the final objectives and this choice is also dependent of technical and economical issues. Therefore it is possible, through ingenious solutions, to obtain equivalent experimental results with test setups alternative to the preferable ones.

These experiments are a key issue on the prediction of seismic response of masonry panels even for quasi-static loads because, as reported by Tomazevic (1999), a cyclic response of a test represents the minimum possible envelope of the dynamic behaviour.

The main purpose of an experiment should be the reproduction of the conditions that the specimen may be subjected to in real conditions. Concerning earthquake resistance evaluation of elements (e.g. piers, walls, etc.), the materials, axial load and boundary conditions are those parameters that should be more correctly controlled and conveyed in order to validate the experiment.

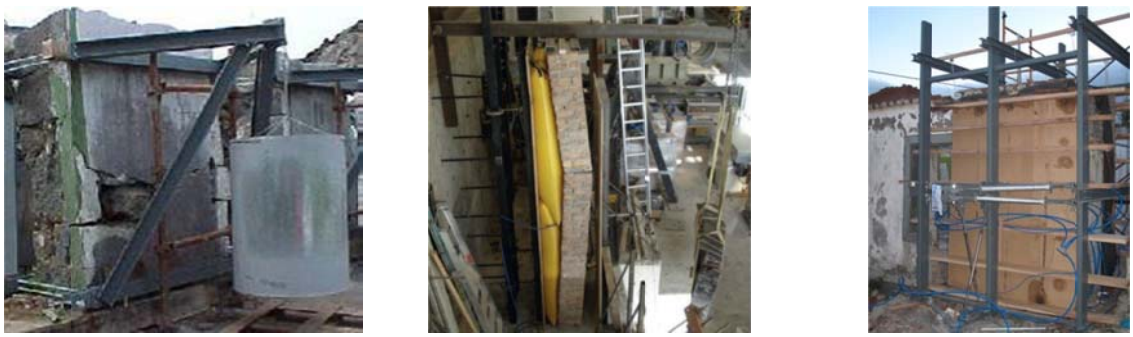
A brief description of different types of experiments will be presented in the next sections for point loads and distributed loads tests taking into account the complexity of the test setup and its applicability to laboratory or in-situ (field) conditions.

The out-of-plane behaviour of masonry walls during earthquake motions addresses several difficulties and it is described by Paulay and Priestley (1992) as "one of the most complex and ill-understood areas of seismic analysis".

In order to investigate the problems of masonry walls' behaviour during earthquakes, several experimental tests were already performed making use of different testing techniques. Generally the experiments related to this topic are essentially based on point or line loads materialized by more or less ingenious systems (e.g. two steel buckets Costa (2002)) and distributed loads, resorting to airbags (e.g. Griffith et al. (2004)) or waterbags (e.g. Mosallam (2007)), Figure 1. The main objective of the experiments concerning regular masonry should be an adequate simulation of the panels' distributed load due to the seismic excitation.

However the seismic action on traditional constructions excites the structure in a different manner when compared with the case of new masonry performing as load bearing (or just infill panels) along with lightweight reinforced concrete slabs. In traditional constructions, the mass of the building is essentially due to the wall (and not to the floors) leading to an excitation of the walls based on the deformed shapes of the global vibration modes. In this line, a concentrated mass at the top may approximately reproduce, through the displacement profile, the potential deformed shape of a complete wall including the influence of the roof. It is thus clear that old and new masonry behave differently during earthquakes especially due to different masses and boundary conditions.

In this context, different experimental test setups were already carried out searching for innovative solutions which turns out possible to characterize (with adequate conditions) the behaviour of traditional masonry walls.



(a) (b) (c)

Figure 1. Some in-situ experimental tests on masonry elements in last decade: a) Costa (2002); b) Derakhshan et al. (2013); c) Costa et al. (2013).

DESCRIPTION OF IN-SITU TESTS WITH POINT OR LINE LOAD

The first test presented in this section refers to an experimental campaign carried out after the Azores 1998 earthquake and it was the first of this type performed in-situ, Costa (2002). The test setup used to perform the experiment is represented in Figure 2 and consisted in two steel buckets, one on each side of the specimen, suspended by a steel cable to an auxiliary steel structure attached to the masonry wall. The steel buckets could be filled with sand introducing vertical load on the wall and, by imposing free vibrations, horizontal out-of-plane loads were also applied to the wall. In addition, cyclic loads could be introduced by means of forced oscillation of the buckets placed on each side of the wall varying each phase angle.

(a) (b)

Figure 2. In-situ test setup, Costa (2002): a) test apparatus; b) monitoring devices

In order to overtake these disadvantages, it was also adopted a test setup which permitted performing experimental tests on existing constructions based on the action-reaction principle. This is the basis of the testing schemes that will be presented afterwards where the absence of a physic and external reaction structure is overcome. The core of the methodologies is a self-reaction structure because the load which will be applied on the tested specimen gains reaction on the same structure. In other words, the out-of-plane movement of the wall will be introduced by a reaction of the testing system in other part of the structure, as a wall in the perpendicular direction to the tested specimen or a stiffer wall. The two walls are connected with the acting system with a load cell between them. In this manner the applied load is known and the acting system is controlled by displacement transducers mounted on external reference structure.

Indeed a simple, inexpensive, lightweight and portable testing scheme was already developed to perform cyclic tests on existing structures on a displacement control basis. This system consisted on two Dywidag rebars connected to a steel hollow tube with significant torsion and buckling resistance. The purpose of this hollow tube was to diminish the weight of the test setup and to reduce 2nd order effects which could introduce spurious damage to the acting system especially in the connections. The other ends of the Dywidag rebars were attached in one side to the testing wall through a screwed connection and, in the other side, to the "reaction wall" by recourse to a hinged connection provided with a load cell. In this way, through a variation on the position of the screw (making use of a specially made manual long key), the Dywidag reacted against the reaction wall imposing a controlled displacement on the tested wall which produced a reaction force monitored with a load cell. Since the Dywidag rebar was provided with another screw at the exterior part of the wall, this allowed performing cyclic loads on a displacement control basis.

Figure 3 shows the test apparatus and the output obtained in such test, highlighting the achievement of a post peak descending branch up to collapse of the specimen in a displacement controlled process. Moreover, with this test setup, it was possible to reach a displacement range of almost ± 100 mm that could be even higher, if necessary, through the introduction of longer Dywidag rebars.

(a) (b)

Figure 3. Overview of a simple displacement-based testing scheme Costa et al. (2009): detail of the connection to the wall and aluminium tube.

The usage of hydraulic actuators turns out possible to improve this type of testing system though with the drawback of increasing the system weight. In this line, an experimental test setup was developed based on the same principle as described in the previous example with the main difference relying on the use of lightweight aluminium hydraulic jacks. This type of jacks provided a significant advantage when compared with regular steel hydraulic jacks concerning the total weight of the testing system.

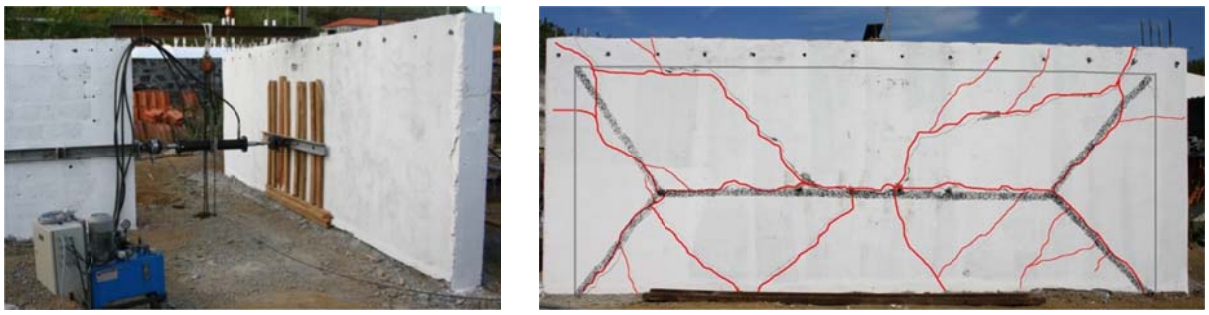
This test setup was developed to assess the behaviour of masonry walls in field testing and was already used on old stone masonry walls as well as on regular brick/block masonry panels Arêde et al. (2008).

Based on the action-reaction principle, it turned out possible to test the in-plane and out-of-plane capacity of masonry elements with a significant load capacity (up to 100 kN tensile/compression force) and displacement range (± 250 mm). The following example aims at illustrating the capability and efficiency of the developed test setup, showing the applicability of the testing system on the field assessment of the out-of-plane behaviour of masonry panels.

Indeed it relates to an experiment carried out on a confined block masonry panel as representative of new constructions of Faial Island after the 1998 earthquake. This is a construction technique where hollow concrete blocks with significant hole ratio (35%) usually used for infill panels and not designed for load bearing elements. Therefore, the shape and dimensions of the blocks are not specifically optimized for vertical or horizontal loads. However, the post-earthquake observations of the building stock after the main event leaded to a global opinion of the population that stone masonry buildings should not be reconstructed, thus leading to the preference by recent r.c. frames with confined masonry panels. In this context, it was found important to perform tests for out-of-plane movements of this structural system aiming at characterizing their expected seismic behaviour.

Therefore, a confined masonry panel built by local workers and masons was tested on the field with the mentioned developed test setup. Despite not being an existing building, the specimen was constructed on the field next to existing constructions and not at the lab.

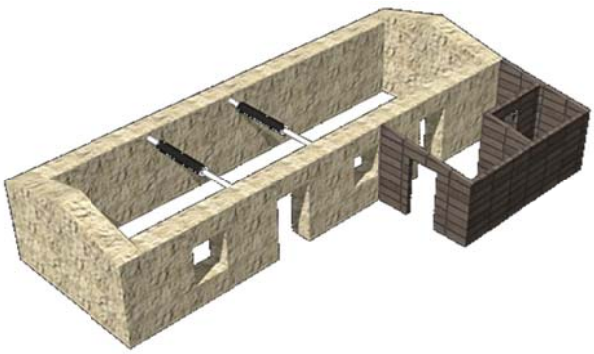
Figure 4 represents the test setup apparatus used to perform the experiment, with relevance to the load application system which aimed at distributing the load on the masonry panel.



(a) (b)

Figure 4. Test on confined masonry Costa et al. (2009): a) test setup apparatus; b) final cracking pattern superimposed with preferential failure mechanism.

Another application of this experimental setup was made on an experimental campaign carried out on typical stone masonry walls at Azores, constituted by double leaf basalt stone masonry with poor infill, including some strengthening techniques used on damaged constructions after the 1998 Azores earthquake.
An advantage of this method is the absence of a specific external reaction structure because the system is self-equilibrated within the tested construction using the existing structural elements to provide the required reaction. Figure 5 shows the proposed test setup to assess the out-of-plane performance of masonry walls to clarify the implementation of the developed method. Hydraulic devices are placed at the top of the walls and connected to them through hinged links ensuring well-known acting loads and restraint conditions.



(a)

(b)

Figure 5: Experimental test setup proposal Costa et al. (2011): a) schematic representation; b) in-situ implementation (interior view).

Obviously, the method can be also applied to new constructions but the destructive nature of the test is very likely to diminish its interest for such type of cases; however, it can be applied under rehabilitation interventions on the existing constructions if partial demolitions of the structure are prescribed.

DESCRIPTION OF TESTS WITH DISTRIBUTED LOADS

In other types of masonry, others have dedicated themselves to the development of an innovative technique of applying test using distributed loads across the surface of the wall, assuming distributed loads are a good representation of the action seismic.
In 2007, Griffith MC. et al. applied a new technique of tests, which consisted of applying distributed loads by the wall surface using airbags. The bidirectional test containing a system of load cells to evaluate the force applied to the wall surface.
Also in 2007, Mosallam conducted tests to characterize the masonry infill wall out of the plane with FRP reinforcement. Although, using distributed load applied with airbags inflated with water, with the particularity that the wall was parallel to the floor, it was because otherwise it would be impossible to sustain the water bags due to their weight and to ensure a uniform distribution actuating load.
In the work of H. Derakhshan and Ingham (2008) a similar test technique used by Griffith MC. et al. in 2007, with the peculiarity that the test was developed only in one direction. This work was carried out an unidirectional test due to poor leakage of airbag placed opposite to the force application, so creating an unaccounted reaction force.
More recently, in 2009 and 2010, Dizhur D. et al. conducted a test campaign in different buildings to characterize the behaviour of masonry infill wall when subjected to dynamic loads. Out of plane tests with distributed load over the surface of the wall using airbags were carried out.
Indeed, the study performed by Garcia (2010) on airbags' behaviour concluded that factors such as the estimated contact area, the reaction structure, optimizing the automation of the control of the test

process and the evaluation of strength parameters and displacement are content to develop. Garcia also studied the influence of shape, aspect ratio and airbag's material in the final response and loaded area. For these reasons, other airbags were studied in order to optimize the final results (Gorilla, Figure 6 – a; Nylon, Figure 6 – b). The main differences between these airbags are: the material; (being the most resistant Nylon); rectangular geometry (in the side edges); number of orifices for input, output and control air pressure.

a) Airbag Gorilla b) Airbag Nylon

Figure 6: Type of Airbags.

One of the cons identified in previous tests is related to the number of outputs that the air bag contains. The fact that the air bag has only one in the Gorilla's type compromised the reliability of the output pressure reading because the pressure sensor is connected to the hose where the air circulates, influencing the pressure by the air speed/flow (entry and/or exit) in the bag. This difficulty is overcome by the use of new air bags Nylon, where the number of inputs and outputs varies according the required conditions.

Another issue important to correctly obtained the contact force is related to the contact area and its nonlinear variation with the airbags pressure and distance to the wall. As during the tests the wall deforms out-of-plane, the variation of the contact area modifies and this parameter should be corrected during the test or post-processing the results.

This phenomenon occurs because the bag, when inflated, does not provide perfect parallelepiped geometry, but is left with all its slightly convex faces, so that only the most central part is in intimate contact with the wall (Figure 7).

Initial displacement. Final displacement.

Figure 7: Contact area of the airbag depending on the distance between the wall and the reaction structure.

For calibration of the contact area, a test campaign was carried out to estimate a correction factor, by simulating the displacement of the wall face to the reaction structure. This information can be consulted in Gomes et al. (2013).

This calibration was performed to two distinct situations: (i) using a single row of air bags; (ii) using two rows of air pockets. From this test campaign was then possible to obtain two different correction factors (CF), translated through equations (1) and (2) and their calibration curves shown in Figure 8 and Figure 9.

$$CF = -0.00031 \times |d|^2 - 0.00108 \times |d| + 1.08599 \quad (1)$$

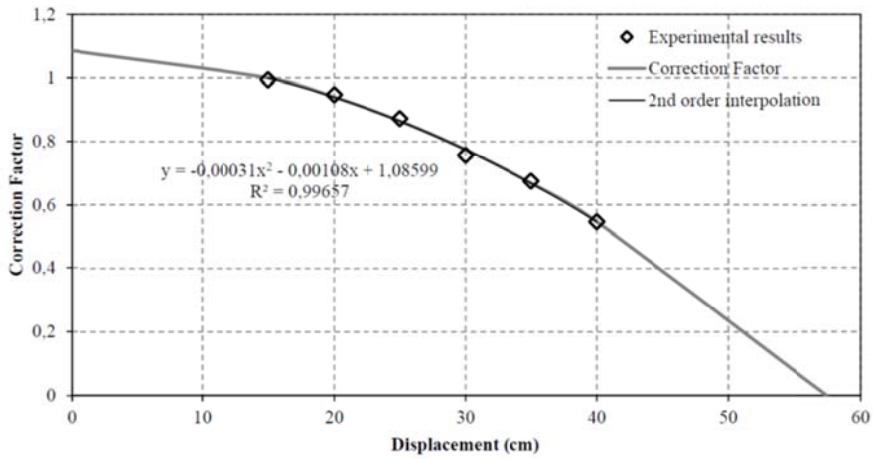


Figure 8: Study of Correction Factor, CF, for tests with only one row of airbags Gomes et al. (2013)

$$CF = -0.00007 \times |d|^2 - 0.00025 \times |d| + 1.07571 \quad (2)$$

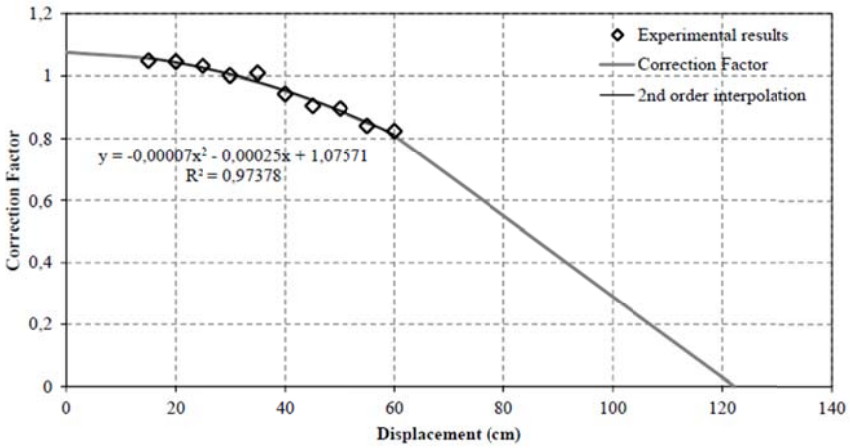


Figure 9: Study of Correction Factor, CF, for tests with two rows of airbags Gomes et al. (2013)

An experimental campaign performed in-situ at Faial island (Azores), following a research line of investigation initiated after the 1998 earthquake, was performed with the testing technique presented above but being used in-situ resorting to out-of-plane distributed loads applied on masonry walls. Figure 10 presents the case study used in this experimental campaign (*Casa Nova*).

a) View from main road b) Main entrance

Figure 10: Exterior view of the Casa Nova.

The reaction structure required to perform the tests was developed to take into account the following assumptions: implementation of bidirectional tests; low weight for simple transportation; simple assembly with small size elements.
The final solution consisted of a steel frame structure with hollow sections and symmetric sections. In addition, plywood planks were used to provide a rectangular and smooth area of contact to the airbags (see Figure 11).

Figure 11: Experimental test setup

Three airbags were used on each side of the wall, including an air compressor, pipes (that connects all necessary devices for pressure application), control valves for airflow control (in and out), pressure and displacement transducers connected to a data acquisition system and portable computer.
As the airbags had 40 cm amplitude and were placed between the wall and reaction structure at 15cm of distance, the test setup had a displacement capacity of 25 cm in both directions. Some results obtained with this test setup will be presented in the following subsection.

DESCRIPTION OF TESTS IN SUBSTRUCTURES

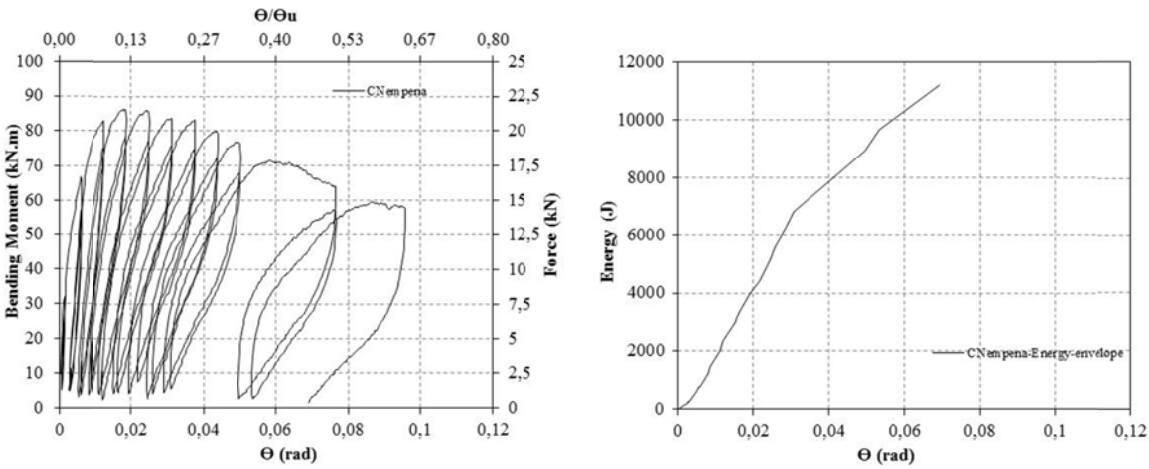
In July 2013, a further step in this field was made with the application the previously presented setup on a masonry façade (at *Casa Nova*), making use of the same steel frame (versatile structure).
For this case, a new airbag was made specifically with the shape of the masonry façade in order to have the most correct contact between the airbag, reaction structure and tested wall.

Figure 12 presents the assembly of the reaction structure at the interior and the outside view of the monitoring external structure, where draw wire displacement transducers were placed

Figure 12: Assembly of the reaction structure and transducers.

Figure 13: Mechanism and final collapse

Figure 14 presents some results obtained in this experimental test, where it is possible to observe well defined load-load displacement controlled cycles as well as post peak behaviour. Moreover, the information is plotted in the form of θ-M, where θ_u signifies the theoretical instability of the complete façade.



(a) (b)

Figure 14: Façade experimental results: (a) hysteretic curve; (b) envelope of energy dissipation

Making use of displacement transducers positioned along the height of the wall, the displacement profile (Figure 15) shows mainly flexure behaviour and mostly concentrated above the opening. This behaviour may be explained by the presence of the window and due to vulnerability of the gable, as commonly observed in post-earthquake surveys. Moreover, the collapse figure is very similar to those observed in earthquake affected constructions, validating and highlighting the reliability of the experimental setup performed as well as the results obtained.

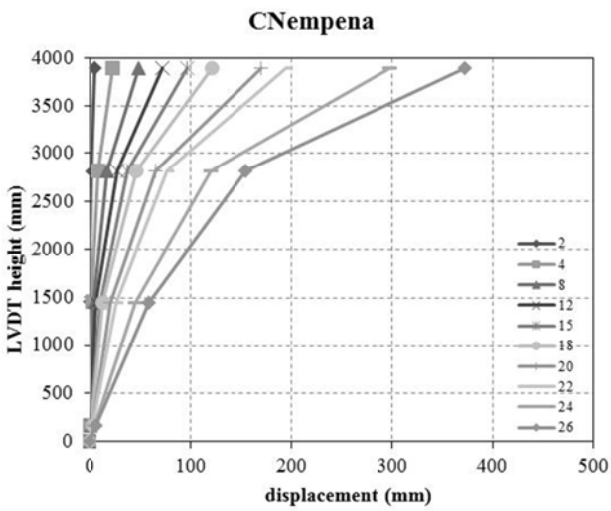


Figure 15: Displacement profile.

Table 1 presented the main results obtained in the experimental performed on the façade.

Table 1. Results of the façade

Surface Pressure (kPa)		displacement (mm)		Bending moment (kN.m)		Rotation (rad)		Energy (J)	Average hysteretic damping (%)
max	ultimate	F_{max}	ultimate	max	last	M_{max}	last		
5,931	3,818	72,216	373,200	86,195	55,487	0,019	0,096	11191	2,7

CONCLUSIONS

This paper addressed a general overview of out-of-plane in-situ experiments performed on masonry constructions in the last decade, presenting some advances and novel techniques developed. As it was possible to observe, the developments are significant but several parameters should be always taken into account, as the problematic of providing a reaction structure to the acting system as well as the calibration of no well-known parameters (e.g. correction factors for airbag testing).
Moreover, and considering the amount of recent earthquakes with significant magnitude and damage observed (e.g. L'Aquila 2009, Christchurch 2011 or Emilia-Romagna 2012), increase the interest on performing experiments on real structures, as well as test new testing techniques not only on masonry elements but also substructures.
At the end of the article, an in-situ experimental test on a full scale masonry façade was presented, highlighting the application of simple but well controlled setups in larger structures. In the authors opinion, in-situ experiments should be the main objective of future researches in order to overcome the most common but problematic issues of existing masonry constructions (e.g. material reproducibility in lab conditions), understanding their behaviour. In this manner, it will be possible to develop tools that simulates the real conditions of our masonry constructions, which will enable us to protect built heritage for future seismic events.

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