Old masonry structures in L'Aquila historical centre: Retrofitting strategies and full scale tests The assessments

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SUMMARY:
After the 6th April 2009 L'Aquila' Earthquake, the historical centre of this city was strongly damaged by it. In order to research and obtain an effective and sustainable strategy of intervention, strictly connected to this masonry typology, a destructive in-situ test campaign for full-scale structural elements was planned. According to the Municipality Authorities, a corner palace permanent damaged was chosen. It is placed along the left side of Saint Peter' Square, beside to the homonym church. The masonry features: no ordinary setting, small size of the stones, regular flatten made in bricks, no transversal section links, made hard the consolidation approach detection. Seven panels were selected, strengthened with different methods, and tested with the final aim to evaluate in-plane and out-of-plane masonry response. This paper will point up panels' out-of-plane answer, data reading and final remarks (in-plane mechanical characterization is illustrate in Candela et al. (2012).

Keywords: Absence of headers, stonework settled with no regular shape, no stones linking, full-scale tests.

1. INTRODUCTION

The building analyzed and tested, it is placed in Saint Peter'Square, in the heart of L'Aquila historical center, Abruzzo region, Central-Italy (see Fig. 1.1).

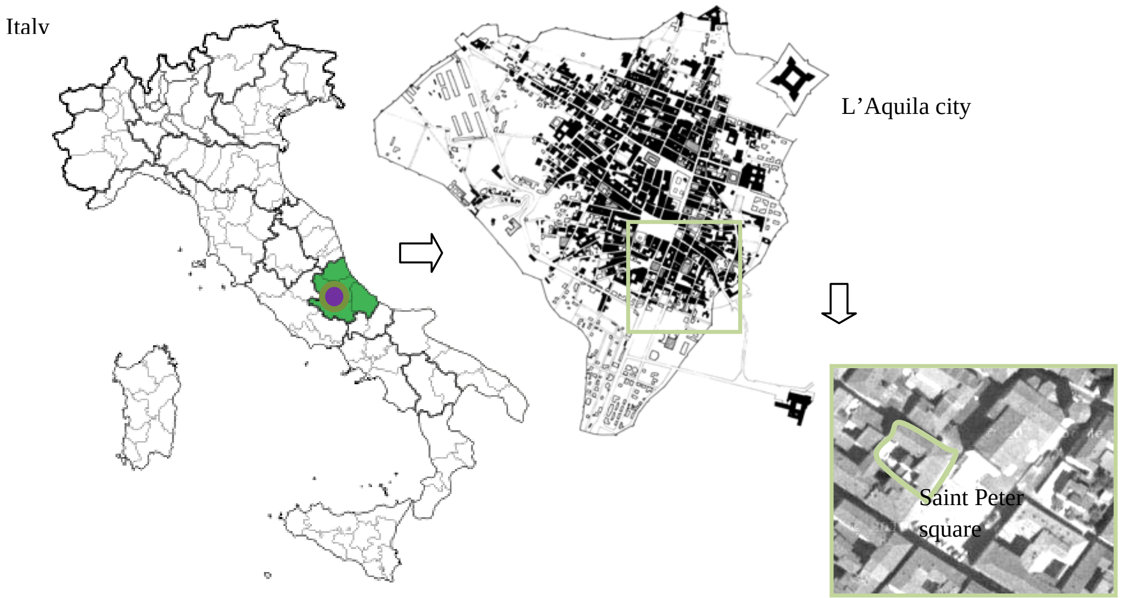

Figure 1.1. Building pinpoint – Italian Peninsula, Abruzzo region (in green), L'Aquila city (historical centre map) and Saint Peter square plane (before Earthquake).

It was seriously damaged by the seismic event; it mainly shows the failure of the façade, in particular for the corner part.(see Fig. 1.2) This is one of the most common local mechanisms that can be noticed in old masonry structures under seismic action. The last concept it's strictly connected to the first collapse mode, that is largely considered the primary cause for building break-down, during earthquake. In fact, this paper is focused on the out-of-plane L'Aquila masonry response identification.

Figure 2.2. Building 'photo after the 6th April 2009 Earthquake.

1.1. The place condition

The panels tested are seven, placed at the first floor in both the façades (see Fig. 1.3. and 1.4.); two of them (n.6 and n.7) were posted useful for masonry mechanical characterization; the others five were strengthened with different approaches.

Figure 3.3. Pretatti street façade – Panels selection

Figure 4.4. Saint Peter square façade – Panels selection

The panels are physically separated by a regular progression of windows, therefore, each masonry part closed to the openings was easily identified like rigid block (dimensions: wide 60cm, high 400cm, large - variable near 210cm), see Fig. 1.3. and 1.4.
L'Aquila built background show several masonry typologies but it follows that two of them are the most representatives. The first type caught on in L'Aquila city and no in the neighborhood, it is overall considered quite good. However, its constructive scheme takes into account no ordinary stones setting, with no regular shape of the elements and small size of them. As a direct consequence of it, total absence of headers is noticed and lacks among the stones or thickness mortar joints can be pointed out; moreover, this stone irregularity sometimes is filled up by wedges elements. Regular flatten made in bricks and stretcher elements are present. See Fig. 1.5.

Figure 5.5. Masonry sampling (1m x 1m) typology one, L'Aquila historical centre. Local mechanism: out-of-plain - rigid block behaviour.

Instead, the second typology is typical of the surrounding area and it show a masonry setting deficient in many mechanical features: stone size smallest, no transversal section links, no stretcher elements, no bricks layers, no sufficient wedges elements (see Fig. 1.6.). All that makes hard the strengthening approach detection!

Figure 6.6. Masonry sampling – 1m x 1m – typology two, L'Aquila surrounding area. Local mechanism: out-of-plain – buckling occurrence.

The Palace examined match to the first masonry specimen (see Fig. 1.5); therefore, the followings strategies were centre around this specific masonry category: each reinforcement was tweaked for mechanical scheme failures' adjustment. Two principal defects noticed: *absence of headers* and *no contact among stones*.

2. THE STRENGTHENINGS

2.1. The building site

According to the demolish program planned by the Municipality of L'Aquila, the old Palace was decomposed in all its parts excepted for the ground floor structures. This condition determined the opportunity to involve the first floor panels in a destructive test campaign devoted to identify in-plain and out-of-plain response and mechanical characterization also. In this context great was the To.Di.Ma. srl (building firm winner of the contract work) contributes in building site safety, in particular for the required demolish work. See Fig. 2.1.

Figure 2.1. The building site after the controller demolish work. Edifice area perimeter, the plan.

Following that, the test campaign began and the five methodologies of intervention were filled.

2.2. The reinforcements' overview

The five strengthening strategies start from the common injections until the more advanced methods like "the reticolatus", without overlook the tradition techniques. Each approach will improve in different way the out-of-plane panel response. In this perspective, we report the panels sequence according to the fault adjusted.

2.2.1. Panel n.4
Fault corrected: none
Strengthening method: Injection (See Fig. 2.2.)
Executive phases: 1) Panel drilling (n.17) 2) Anchors setting in the holes, pitch 60cm, 3) Masonry cleaning 4) The injection. The grouting (lightweight mortar) was injected with light pressure near 2 bar.

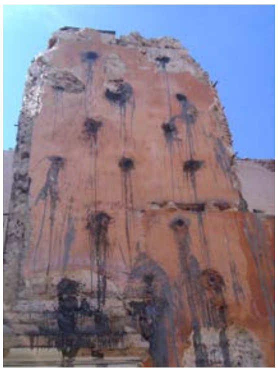

Figure 2.2. Panel n. 4 – Masonry reinforcing with anchors

2.2.2. Panel n.1

<u>Fault corrected</u>: no transversal section links

<u>Strengthening method</u>: “Reticolatus”

<u>Strategy of intervention description</u>:

The reinforcement approach applies two different solutions for both internal and external surfaces. This last one is strengthened by the “reticolatus” technique; instead, the other face by GFRP reinforced plaster. See Fig. 2.3.

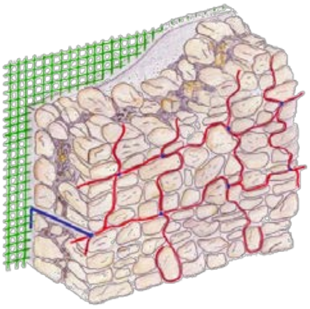

Figure 2.3. Panel n. 1 – reinforcement approach: Reticolatus(external surface) and GFRP reinforced plaster (internal surface).

The strengthening idea born from the gabion (box filled with rocks), this engineering application work through Morsch resistant mechanism. The engineering solution was studied strictly in connection to L’Aquila old masonry type. (See Fig. 2.4.)

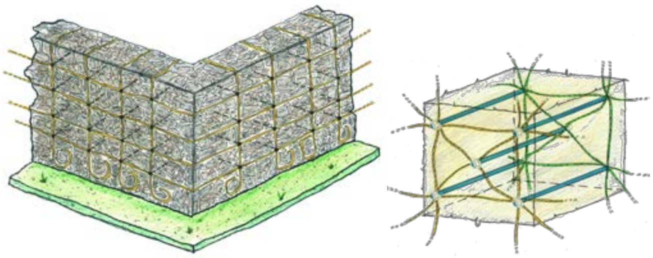

Figure 2.4. Panel n. 1 – Strengthening idea:

The transversal connections between the two differ solutions applied was realized by some little bars (See Fig 2.3. elements in blue). A particular cable (Dyneema rope) was rolled around these tie elements; the rope setting follow the stones one like a mesh. Therefore, bars connect the two meshes, one in GFRP and another in rope. (See Fig. 2.5).

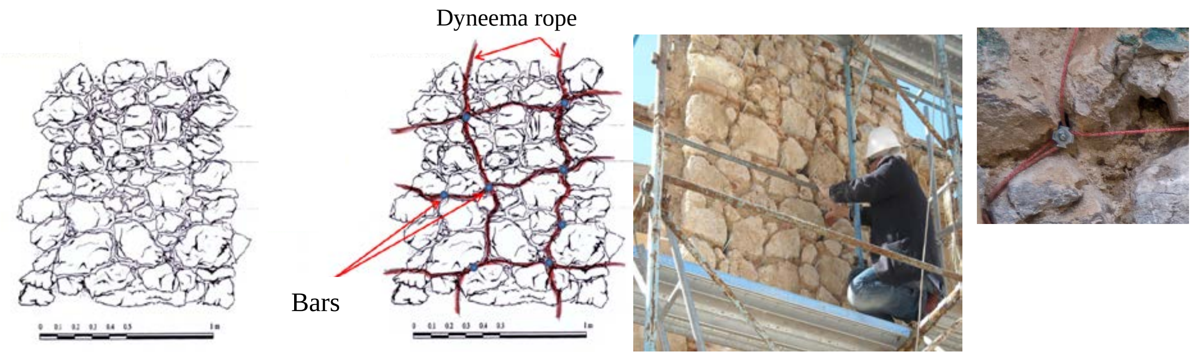

Figure 2.5. Panel n. 1 – Strengthening: the “Reticolus” technique and bar detail.

2.2.3. Panel n.2

Fault corrected: no transversal section links

Strengthening method: Traditional technique with innovative “headers”

Strategy of intervention description:

The strengthening idea starts from the traditional reinforcement technique of “headers” to reach a new typology of it, in order to guarantee good transversal connection and re-establish regular stress condition. The headers are some big stones, placed in strategic positions; they generally tie the panel from one side to the other side. (See Fig. 2.6).

The innovative “header” is made of lighten concrete with a T shape modeled in order to be able to fill some metallic elements like abductor wedge in preformed empty area. (See Fig. 2.6).

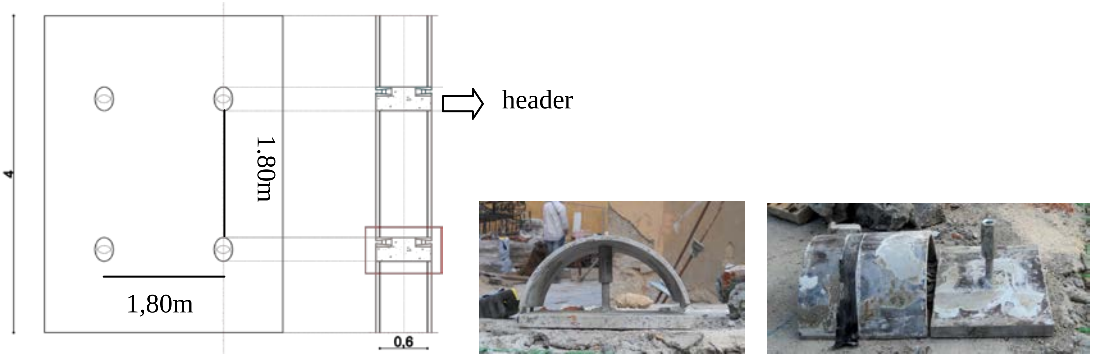

Figure 2.6. Panel n. 2 – Strengthening method: headers setting and abductor wedge provided.

Executive phases:

1) Panel drilling; The horizontal boreholes were placed full in wideness, four in numbers 2) The header’s build up, elements dimensions 30cm x 20cm made about lighten concrete in order to obtain robust and light stone-like material; 3) Setting of the T headers 4) Setting of the abductors wedge. (See Fig. 2.6). Four headers were placed; the result is show in Fig. 2.7.

Figure 2.7. Panel n. 2 – Strengthening final result

2.2.4. Panel n.3

Fault corrected: no transversal section links

Strengthening method: Innovative “header” with Bossong system technology

Strategy of intervention description:

The strengthening idea begins from the improvement of drilling techniques, which allow the embedding of reinforcement steel anchors inside masonry walls with a minimum impact. This system patented by the Bossong Spa it’s called “injection anchors with sock”; it provides a special sock made of fabric sleeve that wraps the metal bar and guarantees the total control of injection and the adherence with the substrate throughout all its length. The strengthening approach is a flexible combination of different kinds of steel bars enclosed in a mesh fabric sleeve into which a specially developed grout is injected under low-pressure:

• the injection anchor with sock is embedded inside a hole drilled in the masonry to be strengthened;

• one injects the grouting material, at low pressure, coaxially with the steel reinforcement bar, through an appropriate system of injection pipes;

• the special sock, placed around the bar, is gradually filled during the injection, until its complete saturation, adapting itself to the substrate shape and so assuring an effective bonding to the masonry.

Therefore, the injection anchors were considered suitable for arrange artificial headers perfectly bonded to masonry inner surfaces (See Fig. 2.8.). In this way will be possible obtain both transversal section link and mechanical interlock.

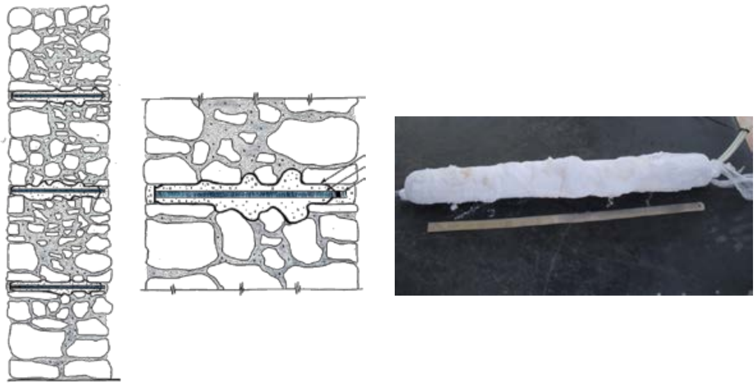

Figure 2.8. Panel n. 3 – Injection anchors with sock-like headers – schematic plan for irregular stonework (transversal section) and header photo after panel test.

<u>Executive phases</u>:

1) Panel drilling. The horizontal boreholes were placed full in wideness with variable length from 560 to 800 mm and diameter 60 mm (See Fig. 2.9);

2) Bars setting. Threaded bars, type GBOS, diameter 60 mm and 500 mm long were placed. This bars are covered by a special fabric sleeve, able to expand and to adapt itself to the hole diameter and the substrate shape. The mesh of the sock, which is a porous membrane, is designed to contain the aggregates constituting the mixture, and to allow the cement enriched water to pass through the sock a chemical bond with the substrate. The sock diameter is designed according to the diameter and length of the drilled borehole.

3) Very smallest nylon tube were used in order to give the injection. The injection devices are designed according to anchors size and features, in this case a diameter of 8mm was provided.

4) The injection. The special grout is a concrete (Presstec), specially designed to be injected into the fabric sock. The injection material is a pre-packed product that contains graded aggregates and other constituents which, when mixed with water, produces a pumbable grout that exhibits good strength. The grout has to be enough fluid to be injected in the special feed pipes. (See Fig. 2.8).

At the end, thirteen headers were settled inside the panel with a pitch of 65cm in the horizontal direction and 70cm in vertical one. (See Fig. 2.9).

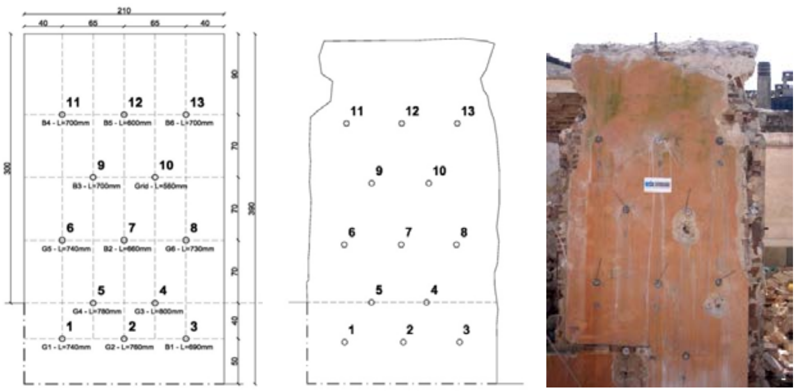

Figure 2.9. Panel n. 3 –schematic plan for irregular stonework and the real one: comparison.

2.2.5. Panel n.5
Fault corrected: no transversal section links and *no contact among stones*
Strengthening method: Traditional technique - headers setting and mortar joints replacement with wedge elements.
Strategy of intervention description:
The strengthening idea born from Abruzzo' local engineering for old masonry constructions; in Abruzzo built wooden elements were widespread employed for masonry connections and building safety. Therefore, some wooden headers were placed in order to obtain the mechanical interlocks (in transversal section) of the two panel's surfaces. In fact, the first step for the approach detection was masonry setting' study and the following elements setting comparison to the "rules of art". This step was important since the different of the two panel faces pointed out to the recognition of the special headers setting scheme provided. (See Fig. 2.10)

Figure 2.10. Panel n. 5 –Schematic plan for wooden headers setting and executive phases' photos. Wooden header and wedge-elements settled photo' detail.

Executive phases:
1) Panel drilling. The horizontal boreholes were placed full in wideness with 4 holes diameter 200mm; 2) Replacement of the mortar joints with stone wedge elements; 3) Setting of the wooden headers and the regular stress condition re-establishing by wooden wedge-elements. (See Fig. 2.10)

3. IN-SITU TEST CAMPAIGN

The panels were tested in order to identify the L'Aquila' masonry mechanical parameters and the behaviour in both dynamic and static conditions. The last one was performed to recognize in plane (see Candela et al., 2012) or out-of-plane masonry response. The out-of-plane tests were divided in two different typologies: "displacement-control" test, with the possibility to produce displacements with alternate directions and "force-control" destructive test. Tests' results carried on through static forces applied will be show only.

3.1. The Pretatti street' out-of-plain-tests

The panels show in Fig. 1.3 were tested in "force-control" condition. The masonry elements were pulled out through a cable. The worker safety and the smallest accessibility to the building site made difficult the test set-up. Therefore, the results were recognized to the geometrical barycentre and they were referred to masonry portion 1m large. The panels n.2 and n.6's results will be explain only.

3.1.1. Panel n.2
Panel n.2.The following data are referred to strains applied at the height of 3.20m.(See Table 3.1) Both the maximum displacement and force obtained are respectively: 34cm and 690 daN. (See Fig. 3.1.) Panel geometrical dimension are: 2.6m in width, 4m in high and 0.6 in depth. In the following table,

the results were recognized to the geometrical barycentre and they were referred to masonry portion 1m large. (Data standardization was done for all panels).

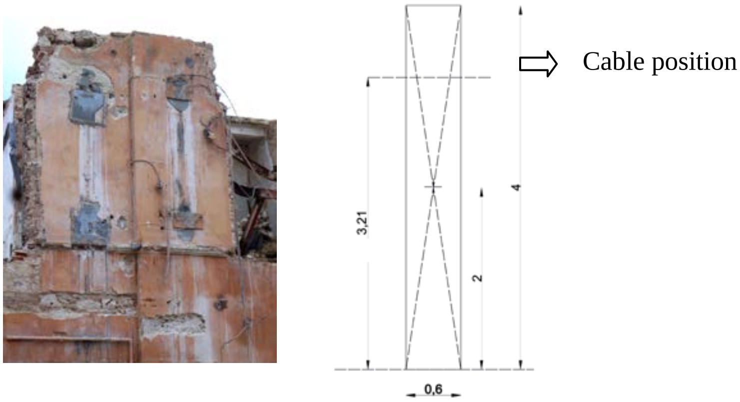

Figure 3.1. Panel n. 2 –Cable position and panel n.2 geometrical dimensions

Table 3.1. Panel n.2 response compared to rigid block behaviour

F max (daN)	F homol. (daN)	Trust (daN)	Mr (daN*m)	Ms=Mr (daN*m)	Efficiency compared to a Rigid block response
690	1107	426	852	1570	**0,54**

Panel n.6.The following data are referred to strains applied at the height of 2.75m.(See Table 3.2) Both the maximum displacement and force obtained are respectively: 22cm and 176 daN. Panel geometrical dimension are: 1.67m in width, 3.5m in high and 0.6 in depth.

Table 3.2. Panel n.6 (no reinforced) response compared to rigid block behaviour

F max (daN)	F homol. (daN)	Trust (daN)	Mr (daN*m)	Ms=Mr (daN*m)	Efficiency compared to a Rigid block response
176	277	166	290	1373	**0,21**

By comparing the no-reinforced panel to the strengthened one, it is possible notice that the improvement of mechanical interlock in transversal section produce two times and one-half more of the starting efficiency.

3.2. The Saint Peter square' out-of-plain-test

The panel n.5 (See Fig. 1.4) was tested in "displacement-control", with the possibility to produce displacements with alternate directions and a final pullout phase. The piston pulled out the panel; the set-up was performed to take advantage of panel position in the building scheme (See Fig. 3.2.).

Figure 3.2. Panel n. 5 –Set-up details

3.1.1. Panel n.5

Panel n.5.The following data are referred to strains applied at the height of 2.25m.(See Table 3.3) Both the maximum displacement and force obtained are respectively: 22cm and 1469 daN. (See Fig. 3.3.) Panel geometrical dimension are: 2.1m in width, 4m in high and 0.6 in depth.

Table 3.3. Panel n.5 response compared to rigid block behaviour

F max (daN)	F homol. (daN)	Trust (daN)	Mr (daN*m)	Ms=Mr (daN*m)	Efficiency compared to a Rigid block response
1469	1653	787	1574	1570	**1**

By comparing the no-reinforced panel to the strengthened, it is possible notice that the improvement in mechanical interlock and the wedge elements influence produce four times more of the starting efficiency. Therefore, the panel performance is comparable to rigid block response.

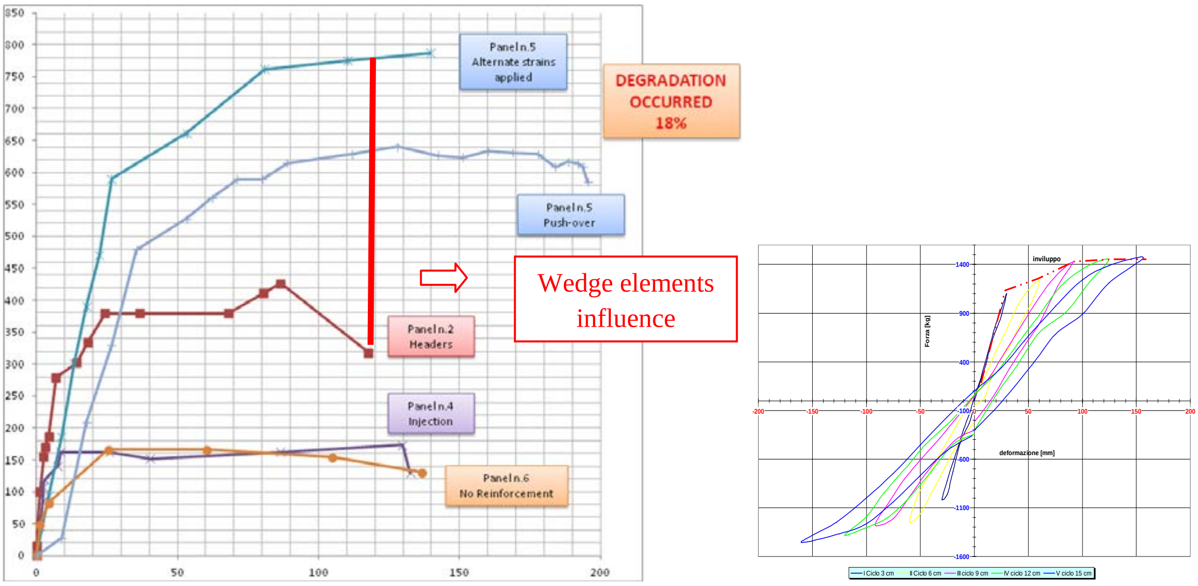

Figure 3.3. Panel n. 5 alternate directions test and panels' pushover final comparison

4. CONCLUSIONS

Data reading provided as important issue wedge elements influence. Therefore, we can recognize that L'Aquila stonework mainly needs reinforcements directed to guarantee both vertical and horizontal mechanical interlock; in fact, according the "rules of art" gaps, the horizontal strains pointed out are different. This means that there is a masonry part of the tested panels that cannot be involved in resisting moment in a corresponding manner to the gaps noticed. Consequently, bending moment is reduced and the experimental activity matches masonry mechanical elements identification.

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