# THE ROLE OF THE MASONRY QUALITY EVALUATION IN HISTORIC CONSTRUCTIONS IN SEISMIC AREA

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## ABSTRACT

The worst structural defect of a masonry wall can be the lack of monolithic behaviour and this can happen in case of poor quality and morphology, for instance when the wall is made by multiple leaves even well ordered but not mutually connected. In case of a seismic event, external forces act in horizontal direction, causing the wall to become more vulnerable with separation of the leaves. Therefore it's important to verify from the beginning the masonry quality in an existing building and to carry out properly this work.

The present Italian seismic code (NTC 14.01.2008 and annexes) requires, for existing buildings, different levels of knowledge; the lowest, named LC1, requires only to classify the masonry among the typologies reported in a table and allows the use of the mechanical parameters in a range of values related to each typology. Serious mistakes can be made in the structural evaluation of a historic stone masonry if the definition of the masonry typology is incorrect. In several cases a masonry texture can appear externally good and regular while the cross section is poor with non-connected multiple leaves, or, on the contrary, the masonry texture appears to be irregular from the prospect with small irregular stones of different dimensions while the cross section shows a well interlocked masonry with long stones used as connection among the leaves.

Several parameters may be thus important to be determined in order to evaluate properly a masonry.

A methodology to define essential parameters and consequently the stone masonry quality, especially in seismic areas, is presented in this paper.

**KEYWORDS**: stone masonry walls, masonry quality, NDT, sonic test, flat jack test

## INTRODUCTION

Historic masonry buildings may present different masonry structures in function of their typology and consequently of their use. Thus, according to the role of the building, a different masonry typology, with a different and suitable constructive technique, can be observed in each historical construction. In addition, historical masonry buildings may have experienced a constructive evolution over time that led to an additional number of masonry typologies.

The term "masonry", a non-homogenous material made of mortar and stones or bricks. describes an extremely differentiated system not only in terms of the different component materials but of the constructive technique according to the historic period of construction, the geographical area location, the economical conditions and the building function [1].

The study of the structural behavior of the stone masonry is different and more complex than the one of the brick masonry. In Italy there is a great variety of types of stone masonry construction and this makes their study even more complicated.
The contemporary relevance of a study on stone masonry is linked to the possibility of re-appropriation of knowledge, once widely spread and of the heritage "practice" for everyone, but now forgotten in the construction practice and still not yet studied in theoretical framework.
One of the first steps for this study is the correct analysis and classification of the load-bearing masonry quality, with the help of both an accurate visual inspection and diagnostic investigation.
From a structural point of view, the worst structural defect of a masonry wall can be the lack of monolithic behaviour and this can happen in case of poor quality and morphology, for instance when the wall is made by multiple leaves even well-ordered but not mutually connected. In case of a seismic event, the external forces act in horizontal direction, causing the wall to become more vulnerable with the separation of the leaves
The latest Italian standard on constructions (NTC 14.01.2008 and annexes [2]) has recently acknowledged this necessity, supplying guidelines for masonry investigation with different levels of knowledge (LC1, -2 and -3) and tables with some general mechanical parameters to be used for the seismic evaluation in case of a poor level of knowledge, varying from the reported masonry typology classes. It is so extremely important to define properly the quality of the load-bearing masonry.
Serious mistakes can be made in the structural evaluation of a historic stone masonry if the definition of the masonry typology is incorrect. In several cases a masonry texture can appear externally good and regular while the cross section is poor with non-connected leaves, or, on the contrary, the masonry texture appears irregular from the prospect with small irregular stones of different dimensions while the cross section shows a well interlocked masonry with long stones used as connection among the leaves.
This last example is the case of the XIX cent. ex-hospital of Savona, a three storey masonry building, where diagnostic tests showed a reliable mechanical behaviour despite the appearance of the masonry texture.
On the contrary, a poor irregular stonework may be poor also in its cross-section, as a large number of historic masonry buildings of the Abruzzo region (area hit by a large number of past earthquakes, till the last in 04.06.2009) but, despite the diagnostic test results classified it as a real poor masonry, traditionally this poor masonry typology was used also for important constructions along centuries.
The research developed by the authors within the frame of the RELUIS project [3], has the aim of giving guidelines to characterise the masonry quality at different levels of investigation (single masonry, building, historic centre) with the elaboration of a special proposed template for the on-site survey. The suggested survey procedure in fact requires the masonry qualification at a first level of investigation through visual survey and local geometrical measurements, while at a further level requires on site non-destructive or slightly destructive tests (sonic pulse velocity and flat jack tests), a small masonry disassembling for sampling of stones, bricks and mortars and survey of the masonry section and laboratory tests to characterise the sampled materials.
A methodology is presented in the paper to define essential parameters and thus the stone masonry quality especially in seismic areas.

## STONE MASONRY FEATURES

The study of the effects of earthquakes that struck Umbria, Marche ad Abruzzo regions, showed how several retrofitting, carried out in the '70s and '80's, mainly consisted in upgrading interventions (substitutions of timber floors and roofs with r.c. structures, jacketing of walls, etc.). These retrofitting techniques caused unforeseen and serious damages especially out-of-plane effects (large collapses, local expulsions), due to the "hybrid" behaviour activated from the new and the old structures.

It was also clear that the main cause of inappropriate choice for the intervention techniques was due to: (i) the lack of knowledge on the masonry and on the structural behaviour of the peculiar type of construction used in the past centuries for historic buildings, (ii) the use of structural models far from their real behaviour, (iii) the lack of control on the applicability of the retrofitting techniques.

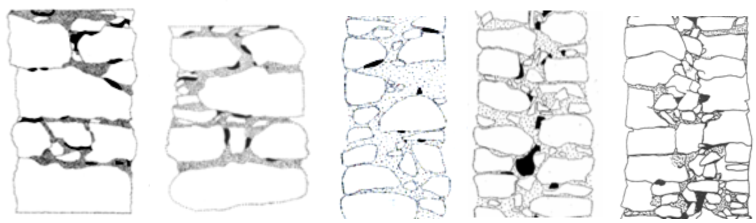
There is a real difficulty in applying some intervention techniques for some type of stone masonry [4]. For example the results obtained from direct inspections showed that some masonry walls were not injectable or injectable with great difficulties if the voids inside the masonry did not exceed a minimum percentage (around 4%) and were not transversally connected (Fig.1) The injections are effective where cracks are present but it is practically impossible to inject the mortar even if it is highly porous and weak.

In the case of stone masonry, the load bearing capacity depends on the deficiency of the constructive details, which may be the cause of a local mechanism. In addition the historical evolution of the building have to be taken into account, so to find the effect of the past interventions on the whole construction. In details accurate evaluations of the morphological characteristics of the masonry texture and its cross section are of a main importance. The observation of only the external masonry texture is not enough to reveal how the masonry is constituted in each parts.


**Figure 1: Examples of cross masonry sections of poor residential buildings that present no or very few voids and so no injectable: a) residential building in a seismic town (Onna,L'Aquila, Abruzzo region; b) fully filled form for masonry cross sections (Campi, Perugia, Umbria region).**

A first classification can include the following descriptions:

- the type of masonry: brickwork, stonework, mix of stone and brick masonry;
- the shape of the stone elements: regular or irregular. The average stones dimension. The type of manufacturing: cut sides and sharp edges, split sides, non manufactured sides, round pebbles, and so on;
- the thickness of the horizontal mortar joint, realized with different types of binder, aggregates and aggregates dimensions;
- the horizontality of the courses (masonry can show horizontal courses, sub-horizontal courses or irregular courses), the stagger of the vertical joints (respected, partially respected or non-respected), the presence of wedges and levelling of other materials. The correct survey of the masonry texture should refer to an area of 1 x 1 m of dimension;
- the type of cross section of the masonry wall [5]: one or multiple leaf, well interlocked or not (Fig. 2).



*a* *b* *c* *d* *e*

**Figure 2: Examples of masonry cross sections: a) one single leaf; b) 2 leaves well interlocked (with one "*diatono*"); c) 2 leaves partially interlocked; d) 2 leaves not interlocked; e) 3 leaves or multiple leaf.**

## MASONRY QUALITY EVALUATION

The data can be collected in a dedicated survey form [6, 7] following, in general, a procedure developed for the definition of the masonry quality that should have its steps in the following order: (a) choice of the most representative areas of the different masonry walls to be investigated and analysed in a building (the stratigraphic method allows subdivision of the building into homogeneous blocks characterised by relative chronological relationships). Any block corresponds to a unique building phase, recognized by the observation of constructive details. This identification will help in choosing the most representative masonry walls), (b) survey of the masonry texture (it could be necessary to remove a portion of the plaster 1x1 m); (c) sonic pulse velocity test by direct transmission on a grid of about 1x1 m with a graphical elaboration of the results represented on the drawn area, through the calculation of the velocity distribution; (d) single flat jack test to define the masonry vertical state of stress, (e) double flat jack test and elaboration of the stress-strain plot indicating also the measured local state of stress; (f) local inspection till ¾ of the masonry cross section thickness with removal of some stones (Fig. 3) or brick (it is suggested to start the disassembling in correspondence of one of the highest sonic pulse velocities in order to verify the presence of transversal connection elements or "*diatoni*"); (g) graphical representation of the excavation survey and recognition of the masonry section (Figs.4 and 5); (h) sampling during disassembling of mortar and stones; (i) restoring of the analysed area, replacing the sampled stones/bricks with compatible mortar, (j) laboratory tests on the sampled masonry materials.

Attention should be paid to verify the correspondence between the visible masonry texture and its cross section before defining the quality of the masonry structure.

As said before in f), when it is impossible to observe directly masonry sections, a small masonry disassembling can be carried out, not larger than 40 x 40/50 cm (depending on the stones dimension) and ¾ of the section deep. This should be realised in the same wall portion after the diagnostic investigations, so to verify the correspondence with the higher or lower values of the sonic pulse velocity tests.

The example here showed (Figs. 3 and 4) is referred to the masonry of the St. Paul Hospital in Savona, where there was no correspondence between the prospect texture and the cross section of the masonry walls [8].

The XIX cent. ex-hospital of Savona (Italy) is a three storey masonry building (plus a mezzanine floor), built in 1860, that has gone out of use since many years, waiting for repair strengthening and functional reconversion in a multifunction building. The history of the building and its complex evolutionary dynamics required exploratory investigation tests in-situ, in order to have a comprehensive and detailed overview of its nature and state of health and, at the same time, to direct the correct conservative intervention, recovery and respectful adaptation to the peculiarities of the building.

The building is characterized by an irregular stone masonry walls; the irregular stonework of the highest floors presents bricks layers and thicker mortar joints

The first attempts to disassemble the masonry of the St. Paul Hospital were not enthusiastic, because, despite the irregularity of the stones, they all were perfectly interlocked, with wedges, avoiding to reach easily the centre of the masonry cross section and showing an efficient stonework. This aspect confirms the good results achieved with the ND tests. In a second time the direct inspections were carried out more deeply in correspondence to the diagonal compression tests.

The prospect of the masonry showed an irregular distribution of roughly cut stones of variable dimension (larger than 30 cm), bricks and wedges, with a grey lime mortar of a good quality. Smaller stones during the disassembling revealed to be larger in the depth and well stuck, showing two layers well interlocked with no voids. In several cases some "Diatoni" were found in half of the sections inspected (Figs.3-4).

The stone masonry resulted, following the table given by the present Italian code, as the one with the poorest quality. On the contrary, this masonry cross section can guarantee a monolithic behaviour under vertical and horizontal loads.

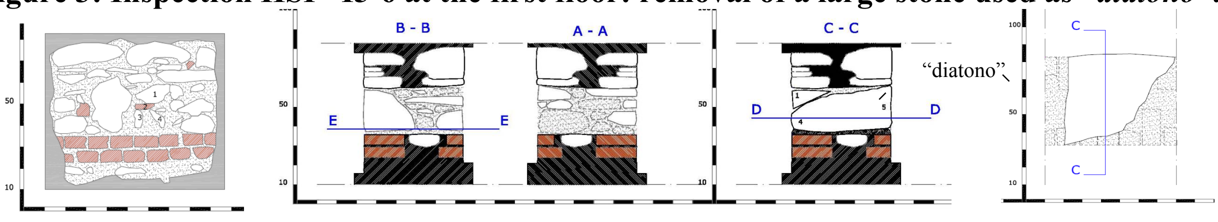
Indeed, the ND- and MD-tests revealed a compact and dense masonry, still within the elastic behaviour, despite the high vertical stresses measured. In general, no cracks were visible before carrying out the tests. The diagonal compression tests, carried out by the University of Padua, also gave good results, with values of shear strength above those given by the national standard [8].

*a)*

*b)*

*c)*

**Figure 3: Inspection HSP- I5-6 at the first floor: removal of a large stone used as “*diatono*”.**




*a* *b* *c* *d* *e*

**Figure 4: Inspection at First floor (HSP-I5-6): a) South facade of the masonry before disassembling; b) right vertical cross section; c) left vertical cross section; d) central vertical cross section considering the removed stones; e) D –D horizontal cross section showing the upper façade of the “*diatono*”.**

The diagnostic investigation carried out on a certain number of historic masonry buildings (both palaces, churches and minor buildings) of some historic centres of the Abruzzo region shows in general a masonry of a rather poor quality, made by round pebble stones and a high quantity of mortar (sometimes of a very good quality as in the church of St. Biagio Amiterno in L’Aquila), rather low values of sonic pulse velocity and high vertical and horizontal deformation.
The visual inspection and the local survey during the disassembling phase show the typology of some masonry cross sections, mainly with three leaves, with a low adhesion among the materials and limited or no interlocking among the stone units (Fig. 5).
According to the experimental results, indicating a low quality of the masonry, it turned out that the structural units in the historical centres of Abruzzo region, if subjected to seismic action, show a better in plane than out of plane response, demonstrating a rather high vulnerability. Furthermore during the double flat jack tests unexpected displacements distribution (and so tension), due to the rotation of stones, was observed in the masonry. Comparing this aspect with the historical one (many heavy seismic events in the same buildings over centuries) teaches us to consider other aspects, such as the presence of an intrinsic ductility of that poor masonry. This parameter maybe should also be considered in the vulnerability analysis, so to understand why this constructive technique was used for centuries in this seismic area.

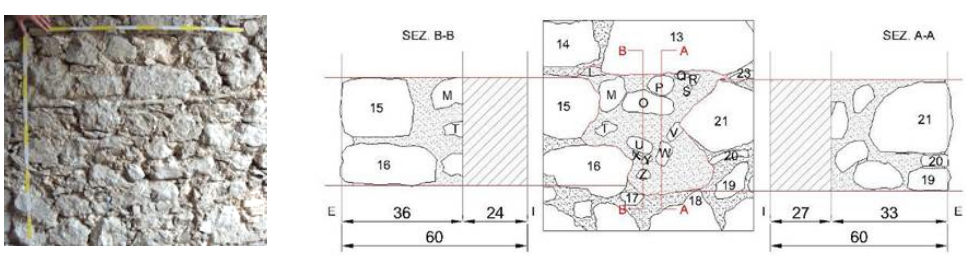



**Figure 5: Three-leaf masonry section on a residential palace of the historic centre of Sulmona (L’Aquila) [9].**

## THE ROLE OF DIAGNOSTIC INVESTIGATION WITH NON- AND MINOR DESTRUCTIVE TESTS

The evaluation of the masonry quality may assume quantitative values if the survey is followed by some in situ diagnostic tests, aimed to define the physical and mechanical masonry properties. The in situ diagnostic investigation allows to reach the level of knowledge L2 required by the Italian National code [2]. But it is important to remark that the here proposed investigation tests to reach the L2 are not able to supply the shear strength but allow to identify more precisely the masonry typology (as table C8B.1 in [2] for the most recurrent typologies) and some important parameters as the Young Modulus, the transversal dilation coefficient, the stress value at the onset of cracking under compression.

The investigation phases were designed in order to give an answer to the questions put by the surveyed damages. In fact NDTs always need to be appropriately used in order to solve known specific problems, taking into account also the high costs and the difficulties in the interpretation of the results. All the information given by the historical investigation and the crack pattern survey were used in the choice of the NDTs.

The suggested tests for the masonry quality evaluation, to be carried out on the same selected area, are: (a) sonic pulse velocity test by direct transmission on a grid of about 1x1 m with a graphical elaboration of the results represented on the drawn area through the calculation of the velocity distribution; (b) single flat jack test to define the masonry local vertical state of stress, (d) double flat jack test and elaboration of the stress-strain plot indicating also the measured local state of stress.

The NDT sonic pulse velocity test is based on the generation of elastic waves in the frequency range of sound (20 Hz-20 kHz), by means of mechanical impulses at a point of the structure. In the case of masonry, due to its heterogeneity, the pulse velocity represents a qualitative characteristic of the masonry. The velocity is influenced by the composition of the masonry as well as by the presence of inhomogeneities, voids and deteriorated areas, as well as the number of intersected mortar joints. A velocity reduction corresponds to an increase of mortar joints or voids or to cracks presence. Higher velocity peaks states higher density of the materials and in stone masonry could represent the presence of a “diaton”. It is better to carry out the test by direct transmission on a grid of measurements points that covers the area analysed later on with the double flat jack test (Fig. 6).

The application of the flat-jack test for the detection of the state of stress in compression and the stress-strain behaviour of historic masonry was introduced in Italy by P.P. Rossi from ISMES, Bergamo in 1981. The test was codified by ASTM in 1991 and recommended by RILEM later. The test as part of the on site and laboratory investigation on existing masonry buildings, is also recommended by the new Italian Seismic Code since 2003.

The authors have carried out more than hundred tests on different types of Italian and European masonry structure usually coupling the flat-jack test with the sonic test and with the observation of the masonry section by sampling. The accumulated experience allows to define not only the limits and advantages of the test, but also to show that the flat jack when coupled with sonic tests is useful to classify different types of masonry (solid, multiple leaf, stone, brick masonry, etc).

In figure 6 the results of the tests with single and double flat jack carried out on some sample buildings of Campi di Norcia (Perugia) are reported, where the masonry materials were always the same, while the texture was different. Results pointed out the differences in behaviour of masonry belonging to important buildings or complex structures (church or the bell tower) in comparison with private buildings. In particular, it is possible to see that both sonic velocity and flat jack results are in agreement, assuming higher values for more important constructions.

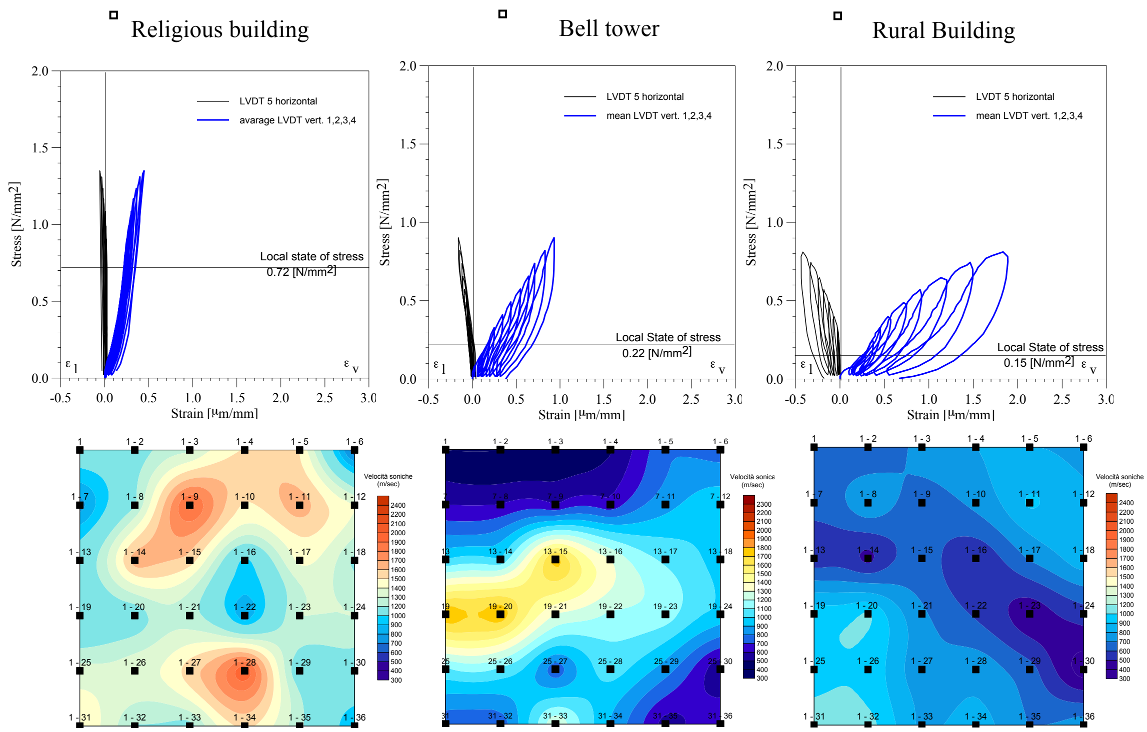



**Figure 6: Results of double flat jack tests and sonic pulse velocity tests carried out an a same stone masonry (same materials) but of different building typologies of Campi Alto di Norcia (Perugia)** [10].

Similar results are here presented for the ex-hospital of St-Paul in Savona. The test points selected for sonic pulse velocity tests in the masonry showed a non-homogeneous distribution of the sonic velocity, as usual in a irregular stone masonry; nevertheless the values are on average high for a stone masonry 0,64 m thick, around 2000 m/s, presenting a good connection among the stone elements. Higher peak values could represent the presence of longer stones like “*diatoni*”. (Fig.7).

Single and double flat-jack tests were carried out in the same area where sonic tests were executed. The single flat jack tests were aimed to define the local state of compressive stress and presented a good behaviour and a low scattering of the results despite the irregular stone masonry. Found values are quite high (from 0,7 to 1,5 N/mm$^2$) but no cracks were visible, showing a good performance of this masonry.

The execution of the double flat jack tests was difficult due to non-homogeneity of the masonry: large stones can show too high stiffness and small stones can reduce the reliability of the results. However the average values obtained in all tests showed a rather compact masonry, well organized and with resources higher than 2,5 times the measured local state of stress (Fig.7).

Figure 7 also allows to notice that the first floor masonry is weaker than the ground floor one.

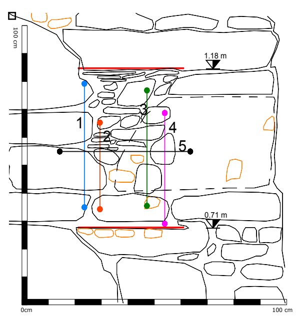
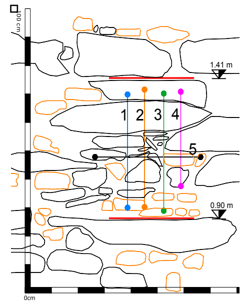
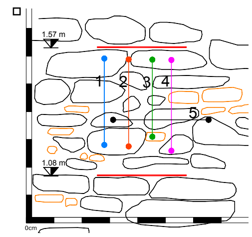
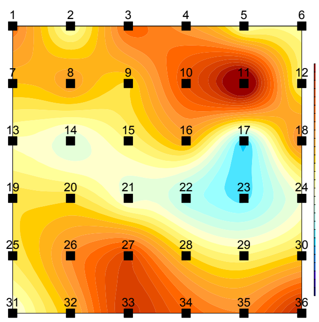
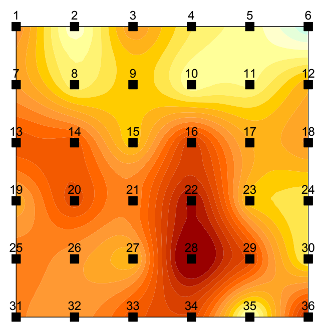
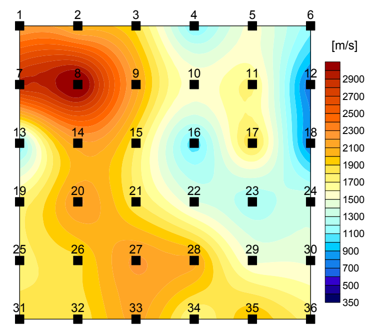
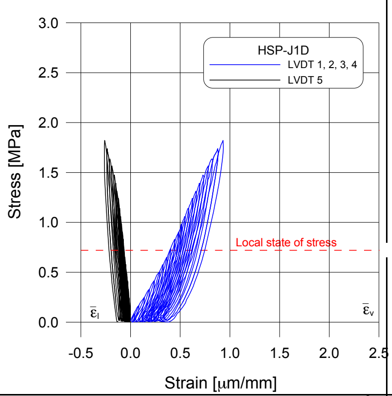
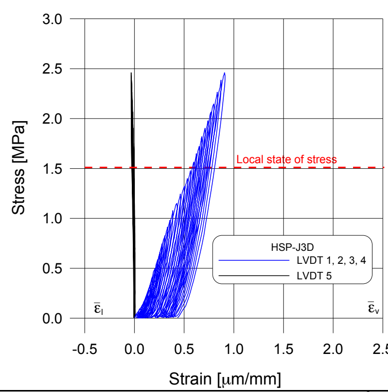
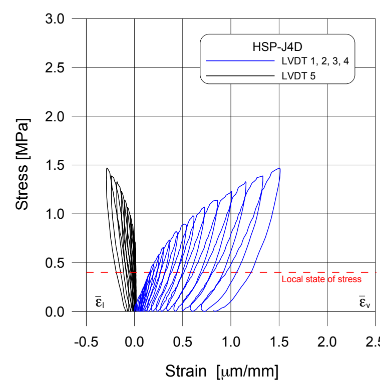
| | Ground floor (HSP – 1) | Ground floor (HSP – 3) | First floor (HSP – 4) |
|---|---|---|---|
| Masonry prospect |  |  |  |
| Direct Sonic Tests |  mean velocity: 1982 m/s |  mean velocity: 2185 m/s |  mean velocity: 1793 m/s |
| Double Flat Jack tests |  |  |  |
| | Mod.$E_{sec}$ (0.36-0.6)= 2310 N/mm$^2$ | Mod.$E_{sec}$ (0.36-1)= 33223 N/mm$^2$ | Mod.$E_{sec}$ (0.14-58)= 2124 N/mm$^2$ |

**Figure 7: Sonic and Flat jack tests results on the stone masonry of the Ground floor and at the First floor of the Savona ex-hospital.**

## CONCLUSIONS

The here proposed investigation procedure refers to the qualification of a masonry by means of surveys and local inspections, according to the knowledge level L1 and by means of sampling, laboratory and in situ tests according to the knowledge level L2 of the Italian Code, in order to better understand the characteristics of a masonry typology and to choose the most compatible repairing materials. This methodology allows to define the masonry quality aimed also to the most appropriate intervention. Data have to be collected in a survey form so to allow the comparison among different surveys.

In conclusion, the following criteria in the definition of the masonry quality should be remarked:

- The visual inspection only has some limits in the masonry quality evaluation. The masonry properties can be detected only experimentally in situ and in laboratory, as well as the mortar properties can be deduced only from samples taken out from the core of a masonry wall and not from the surface wall, where past re-pointing mortar can be found.
- The physical and mechanical characteristics of the masonry elements do not supply directly or indirectly the mechanical characteristics of a masonry as a whole when dealing with historic masonry.
- The elastic properties of a masonry can be achieved on site with a good reliability by means of the double flat jack test.
- The masonry cross section morphology should be surveyed on site; if the section is not visible it is necessary to disassemble a small masonry portion located in a representative area; investigation through borescope supplies only a very local stratigraphy without constructive characteristics.

In the end, before choosing an intervention technique, which should be able to improve the efficiency of weak masonry walls, such as the one surveyed in Abruzzo region, it is necessary to recognise the properties that helped them to arrive up to our time, despite the numerous small seismic events of the last centuries.

Sometimes one wonders if it is really necessary to alter radically these structures with invasive interventions in order to reach a working level that they have never had. Secondarily when a new intervention typology is found, laboratory tests should previously be carried out, before applying them directly on cultural heritage, in order to verify their effectiveness on the peculiar masonry.

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