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Investigations for the knowledge of multi-leaf stone masonry walls

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The use of stone masonry is very common in many historic constructions, both architectural monuments and whole urban centers. Such architectonical heritage is often located in areas characterized by a medium-high seismic hazard and frequently reveals mechanical damage due to the constructive peculiarities of masonry. It is characterized by scarce or no connection through the thickness and by a possible substantial presence of voids, being consequently affected by brittle collapse mechanisms. In order to understand the mechanical behavior of such masonry, to properly analyze it, to design the most suitable conservation strategies and the most effective consolidation interventions, it ought to start from a clear description of its typological and morphological characteristics.

Some different available walls classifications were used for this purpose, together with detailed data-bases, aimed to specific analyses. In particular, an existing extensive data-base was enriched with the analysis of other almost 100 walls sections. It was thus identified a wall «model» sufficiently representative of the existing typologies.

On the basis of those preliminary information, a comprehensive experimental research has been recently performed at the University of Padua. Seventeen physical models were built and tested with destructive and non-destructive techniques, before and after the application of different consolidation techniques. Results confirmed that grout injection is the most effective consolidation technique for this kind of masonry.

Some of the goals scored by the performed research and discussed in the present papers are: (i) the clarification of the current classifications of stone walls to identify some typical walls typologies; (ii) the design and the validation of a physical model sufficiently representative for laboratory researches. Finally, the use of non-destructive techniques (in particular, sonic waves and tomography), for a non-invasive evaluation of the conditions of stone walls, in order to have useful information for a proper design and control of the intervention, is discussed.

Introduction

The local and global behavior of masonry walls is affected by the type and quality of materials, the presence of connections through the leaves, the shape and dimension of the elements, the thickness of mortar joints and the constructive techniques (Binda et al 1999). The quality of masonry also depends on the workmanship of the constructors. In the case of «noble» buildings such as the gothic cathedrals, in fact, the constructive techniques were developed and their knowledge was handed down from father to son. Conversely, the so called «minor constructions» that constitute urban centers and rural dwellings, were seldom built in a workmanlike manner (Antonucci 1997). These elements that characterize masonry behavior are not easy to identify. In fact, the materials, the technique and the process of construction, in the case of multi-leaf stone masonry walls in particular, are dominated by uncertainties and irregularities.

Nevertheless, the knowledge of each masonry typology features can help in the choice of theoretical and physical models for analysis and experimental study of masonry. Similarly, the knowledge of features and typical faults can guide the choice of proper and effective repair interventions (Binda 2000). Therefore, the deep knowledge of the different stone masonry typologies is of basic importance and is necessary not only for historical and documental purpose, but also for scientific-technical research.

The morphological and typological characterization of multi-leaf stone masonry walls can be carried out by comparison with the available classifications of masonry. On the other hand, experimental tools such as on-site inspection of the sections, measurements, non destructive tests (sonic tests, thermographies, radar inspections, etc.) can be used. Minor destructive tests on masonry (single and double flat-jack, etc.) and laboratory tests on sample taken from the walls, finally, allow evaluating the mechanical characteristics of masonry and characterizing the materials, for a more accurate description of the walls.

To properly lay out the research on the effectiveness of various strengthening techniques for stone masonry walls, the available classifications of masonry were accurately studied. Due to the large variety of existing typologies and to the different approaches in their study, different kinds of cataloguing were found. Using information collected from data-bases and other literature sources, the most frequent stone walls typology and its characteristics were found. Only after these premises a physical model was designed and constructed, in order to create laboratory specimens representative of real conditions. Non destructive tests (sonic tests and tomographies) were also performed, and their reliability in evaluating masonry walls' morphology and conditions was checked.

AVAILABLE CLASSIFICATIONS FOR STONE MASONRY

As above mentioned, different classifications of masonry typologies can be found in literature. Three main groups of classifications were identified by the authors and were respectively named systematic, methodological and analytical, according to their aims, structure and results. A brief description, for each of them, is given in the following.

Systematic classifications of masonry walls

Systematic classifications are those that follow a fixed and strict order, subdividing masonry in several subcategories by specifying for each class more and more detailed characteristics. A typical cataloguing of this kind is often based on the characteristics of the elements that constitute masonry (stone, brick, adobe, etc.) and is generally adopted in handbooks of restoration. The classification given by De Cesaris (1996) is, in the authors' opinion, an example of systematic cataloguing. De Cesaris classifies stone masonry according to the shape of the elements (ashlars, roughly shaped stones, pebbles), to their assembly on the external leaves and through the section and to the presence of other materials (mortar, brick courses, wooden frames, etc).

In the case of stone masonry, due to the several different types, shapes and working processes of the elements, the classification of a wall according to these criteria is not always univocal. Very often, various classifications for the same wall are possible with reference to different parameters, such as the texture of the external leaves or the composition of the sections. The medieval town walls of Cittadella nearby Padua, Figure 1, are an example of this kind. They are a mixed kind of stone masonry, both for the characteristics of the external leaves and of the section (Figure 2 and Figure 3).

Figure 1
Example of cyclopean walls: overall view of the town walls of Cittadella (Padova), built in 1220

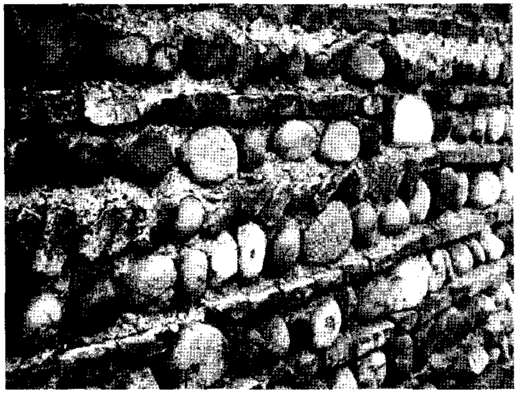

Figure 2
Detail of the town walls of Cittadella. From the external leaves, the wall can be classified as «stone masonry with brick courses» or «mixed masonry». They are made of pebbles and mortar with horizontal courses of bricks

Figure 3
Detail of a niche excavated inside the town walls of Cittadella. The internal leaf is different from the external ones. It is an «opus concretum», made of regular alternate layers of pebbles with brick pieces and thick mortar beds

Methodological classifications and development of mechanical models

Methodological classifications, on the contrary, are not based on groups of rules that allow cataloguing masonry by describing it. These classifications are more related to functional aspects of masonry than to its appearance; therefore masonry is not described and catalogued on the bases of physical, objective aspects, but analyzed with reference to constructive or mechanical principles. Giuffré (1991), for example, subdivides masonry walls into systems characterized by similar behavior. The development of mechanical models for masonry behavior is thus implicit in his classification. A first distinction between «cyclopean» masonry, such as that which constitutes the defensive system of medieval towns (see Figure 1), and masonry used for normal buildings, is made. In fact, even if very often the constructive techniques are similar, dimensions, ratio of dead to live loads and structural behavior are different.

In the case of normal buildings, two large classes of masonry are those corresponding to a popular and a noble tradition of building construction. Multi-leaf masonry walls, made of pebbles and irregular stones, belong to the class of «minor» constructions. Concrete masonry walls, made of a casting of stone elements bound together by mortar, like in the Roman «opus concretum», represent a development of popular construction techniques. Masonry made of well layered regular blocks, with elements perpendicular to the width of the wall that interconnect the different wythes, is typical of «noble» buildings.

Concrete and regular block masonry, to a certain extent, are characterized by similar collapse mechanisms. Concrete masonry, in fact, has a monolithic section that allows the redistribution of vertical loads and develops an overturning resistance under out of plane loads. The presence of interconnecting elements through the leaves of stone masonry walls makes the section act in a similar way. Furthermore, the presence of good connection among perpendicular walls, allows the transfer of horizontal loads from out-of-plane to in-plane loaded walls, which can develop higher strength (Giuffré 1991).

Conversely, multi-leaf stone masonry with scarce connections through the leaves and irregular texture of the section is characterized by instability under vertical loads due to the slenderness of the leaves, and by local crushing phenomena and detachment of the external leaves, due to the non-homogeneous distribution of loads (Giuffré 1993). Under out-of-plane actions, the absence of interconnection among leaves facilitates the development of independent kinematic mechanisms for each wythe and the expulsion of the external leaves (Figure 4). In this case, the out-of-plane collapse, with local or global overturning of masonry (Figure 5), happens for values of applied loads lower than those necessary on monolithic walls (Giuffré 1991).

Figure 4
Expulsion of the external leaf of a stone masonry wall after the Umbria-Marche earthquake (Italy, 1997)

Figure 5
Global overturning of a stone masonry wall after the Umbria-Marche earthquake (Italy, 1997)

Analytical classifications and development of masonry data-bases

Finally, analytical classifications are again based on ordering, on a descriptive base, the different masonry typologies, unlike methodological classifications, but they go from detail to general categories through the experimental and accurate analysis of representative masonry samples, unlike systematic classifications. Different characteristics of masonry are interlinked in order to reach a level of synthesis, where the single walls analyzed form themselves into groups distinguished by typical common features. An example of this kind, according to the authors, is the catalogue made by a group of researchers at the Politecnico of Milan, described in the following. More than 250 stone wall sections, found in different Italian Regions (Lombardia, Trentino, Friuli, Veneto, Liguria, Emilia Romagna, Abruzzo, Marche, Toscana, Umbria, Basilicata e Sicilia), were classified by defining the characteristics of four basic parameters. These parameters are: (i) the kind of stone element, (ii) the assembly of the elements, (iii) the wall section, characterized by the presence of one, two or three leaves (Figure 6), and (iv) the mortar used. On the bases of the information collected, five classes and eight typologies of stone masonry were identified (Binda 2000).

Besides classifying the stone masonry typologies, this cataloguing also creates a data-base of information on stone masonry. In order to collect homogeneous and comparable data, the walls were

Figure 6
Typical stone masonry sections: one, two, three leaves. From Binda et al. (1999)

analyzed following a procedure whose general structure is fixed in a form (Binda 2000). Not only the morphological characteristics of masonry, but also results of mineralogical, petrografic, chemical, physical and mechanical analyses on stones and mortars, plus mechanical and sonic tests results on masonry, are collected in these forms. If the analyzed wall is then consolidated, tests on masonry can be repeated before and after intervention. Also tests on the repair materials (such as tests on injection grouts) can be performed. This allows differentiating stone masonry typologies not only for the morphological characteristics, but also on the basis of mechanical parameters, giving possible information on the effectiveness of the interventions.

Problems related to stone masonry walls classification

The classification of stone masonry, due to its intrinsic complexity, deserves particular attention. For example, three-leaf stone masonry walls are generally called «a sacco». This name, which is usually misused, should define a particular type of three-leaf masonry walls, whose internal leaf is generally thicker than the external ones. In reality, three-leaf stone masonry walls are characterized by different construction methods that gradually changes from the actual «a sacco» walls, made with a completely loose internal core held by two separate external leaves, to the fixed concrete core masonry typical of the Roman age. In the first case the poor internal core, characterized by the presence of diffused voids, exerts a thrust on the external leaves. Friction is the prevalent resistant mechanism, while cohesion within the internal leaf and adhesion between the leaves is scarce. Complex crack patterns, detachment and expulsion of the external leaves characterize the collapse. In the case of concrete core masonry, the internal leaf is characterized by high cohesion, good mechanical properties and an actual load bearing capacity. The external leaves work as formwork for the concrete core casting and there is good adhesion between them and the internal leaf. Moreover, the wall sections are characterized by a monolithic behavior (Doglioni and Parenti 1994).

These walls typologies, which differ for construction techniques and mechanical behavior, are in general characterized by thick sections. For ordinary buildings, with load bearing walls 50–70 cm thick, the most common kind of multi-leaf section is built with an ill-shaped core, which is not cast but layered more or less accurately by the bricklayers. In such a context, different values of cohesion within the internal leaf and of adhesion between the leaves, possible presence of transverse elements, different percentages of voids, can leads to relevant differences in the walls (Doglioni and Parenti 1994).

Identification of a typical wall typology

Typological characterization

From the available data, the most frequent stone masonry typology is made of two or three leaves not interconnected, with the external leaves made of roughly shaped stones bonded in sub-horizontal courses. The average thickness is about 50 cm with a ratio of thickness between the external and the internal leaves of about 1:0.5. The highest frequency of voids percentage on masonry sections is distributed around two groups of values: from 1.13 to 3.8% and from 11.05 to 14.04 (Binda et al. 1999).

Also at a national scale it is stressed that one-leaf stone masonry is definitely rare (a part from Sicily, percentages of one-leaf stone masonry in different regions of Italy vary between 0 and 8%). Regarding the composition of masonry, stone constitutes at least 60% of the section, and average values are around 68.8%. Mortar constitutes 11 to 37% of the section, while voids are in general more than 2% (Binda et al. 1999). Other almost 100 multi-leaf stone wall sections described in literature were analyzed by the authors (da Porto 2000). Both existing walls and laboratory specimens were considered. Table 1 synthesizes the results found on three-leaf stone walls.

Both limestone and sandstone are common in existing constructions. The maximum dimension of limestone elements varies from about 15 to about 60 cm, and is in average equal to 30 cm. Dimension of sandstone elements varies from about 15 to about 25 cm. Average compressive strength for limestone is about 80 MPa, for sandstone is about 100 MPa. Most of the mortars are made of air-hardening lime. The consistence of existing mortars is, in general,

Table 1. Total thickness, ratio between the thickness of external and internal leaves and percentage composition of three-leaf stone masonry, measured on laboratory specimens and on existing walls

Wall section	Thickness		% composition		
	total (cm)	ext:int	stone	mortar	voids
Av. values physical models	40	1:1	—	—	12÷13,75
Av. values existing walls	53	1:0.55	67.87	28.39	3,74
Max values existing walls	66	1:0.78	84.5	36.46	11,05
Min values existing walls	36	1:0.4	55.61	12.6	0,38
Proposed values	50	1:0.78	68	22÷17	10÷15

powdery, with compressive strength between 1.2 and 8.7 MPa. The dimension of joints is irregular, due to the use of natural stone, and in average varies between 1 and 4 cm.

Mechanical characterization

Regarding typical mechanical parameters, an extensive study on values of strength and elastic moduli for multi-leaf stone walls was carried out. Data collected by nine research groups in Italy, Slovenia (Tomaževič 1992), Greece (Vintzileou and Tassios 1995), Belgium (Toumbakari et al. 2000) and Germany (Egermann 1993) were analyzed. Also researches performed in Canada, Egypt and other European countries were taken into account (da Porto 2000). Table 2 shows typical values of compressive strength, elastic modulus and shear strength for multi-leaf walls, before and after consolidation with grout injection.

EXPERIMENTAL PROCEDURES FOR THE STUDY OF THREE-LEAF STONE MASONRY WALLS

Design and construction of the physical models

The design of stone masonry specimens, to be tested before and after consolidation with different strengthening techniques, was based on the collected information. A three-leaf section was proposed. The specimens were designed 50 cm thick, equal to the average value found. The width of the walls was

Table 2. Average, maximum and minimum values of mechanical parameters for multi-leaf stone masonry, measured on laboratory specimens and on exiting walls on site, before and after grout injection

Multi-leaf stone masonry	Compressive strength (MPa)		Elastic modulus (MPa)		Shear strength (MPa)	
	original	injected	original	injected	original	injected
ZAG Ljubljana (lab. specimen)	0,635	1,57	293,5	1784,5	0,06	0,304
NTUA Athens (lab. specimen)	1,742	3,725	5073,8	7863,8	—	—
KU Leuven (lab. specimen)	2,354	3,367	4791,8	3466,7	0,349	0,65
Average on site values	1,113	1,408	367,8	756,4	0,134	0,108
Maximum on site values	2,243	1,596	1287,9	3012	0,227	0,237
Minimum on site values	0,639	1,37	166,8	351,7	0,029	0,049

chosen equal to 80 cm, that is to say, about three times the maximum dimension of the stone units (25 cm), while height was chosen equal to 140 cm, about twice the width. These dimensions were chosen to avoid scale and edge effects, in order to have uniformly distributed compressive stresses in the central area of the specimens under uniaxial compression loads, according to Gelmi et al. (1993). The external leaves were designed 18 cm thick and the resulting inner leaf was thus 14 cm thick. This thickness ratio 1:0.78, besides reproducing a typical ratio collected in the north-eastern part of Italy, is the average between the values detected in literature among existing walls (1:0.55) and laboratory specimens (1:1). With the same criteria, a proportion of 68% of stones, 22–17% of mortar and 10–15% of voids, on the volume of the whole wall, was considered typical for three-leaf stone walls (da Porto 2000). Figure 7 shows the designed specimens.

The specimens were built as a whole wall 13.60 m long by three experienced bricklayers (Figure 8). The long panel was cut into 17 parts with a wire saw, after 3 weeks curing. For the handling and the load distribution during the laboratory tests, two concrete beams, 20 cm high each, were built on the bottom and on the top of the specimens. The external leaves of the walls were made of rough-shaped limestone blocks, bonded in sub-horizontal courses, with mortar joints 1 to 4 cm thick. The internal core was built with mortar and limestone scabblings, derived from the rough-shaping of the stones, poured into not compacted layers between the two external leaves, so that a certain amount of voids was created. To reproduce the worst wall conditions, no transversal connection was provided through the leaves.

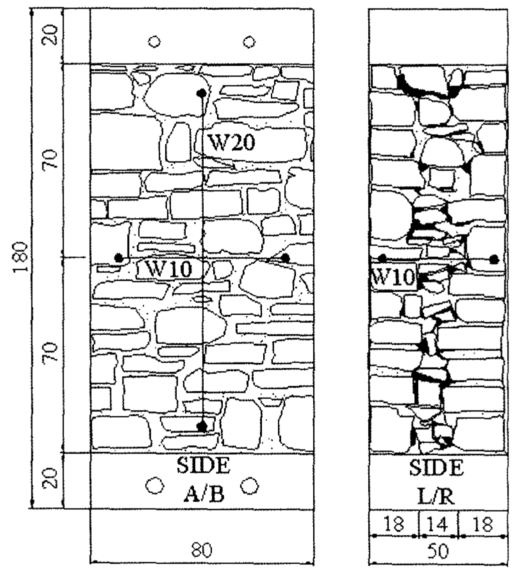

Figure 7
Geometry of the walls and position of the transducers during the compression tests

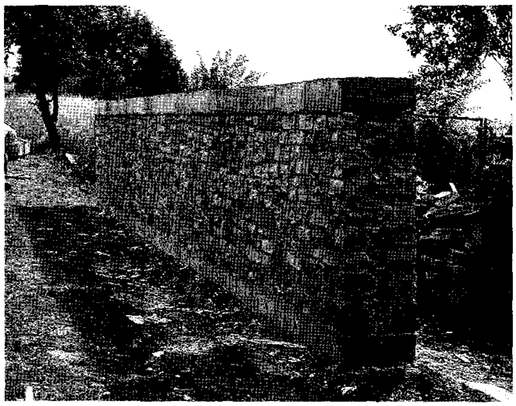

Figure 8
View of the entire wall built, before the wire-sawing

The material used for the construction combined the requirements of reproducing historical walls conditions (e.g. chemical and mechanical characteristics of mortar, composition of the internal core, etc.) and of using local and easy-to-find materials. The limestone was from the Cugnano quarry, located in the north-eastern part of Italy. The mortar was composed by a binder of natural hydraulic lime and lime putty (ratio 1:3); lime/sand ratio was equal to 1:3, water/lime ratio was 0.5 (ratios in volume) (da Porto 2000).

Experimental program

Nine walls were tested under uniaxial compression after 28 days of curing. Eight of these specimens plus the remaining eight were repaired with different strengthening techniques: injection of two different grouts, repointing, transverse tying, and their combinations. All the specimens were then re-tested about 60 days after construction, about 28 days after the execution of interventions. The intervention techniques are described in Valluzzi, da Porto and Modena (2001).

Tests were performed under force control at a load increment rate approximately equal to 0.25 kN/s. Six displacement transducers were applied to the specimens: four on the main façades of the wall, to register vertical and horizontal displacements, two on the transverse sections. Tests were performed with two loading cycles. Figure 9 shows a typical stress-strain diagram for an injected wall, before and after the intervention.

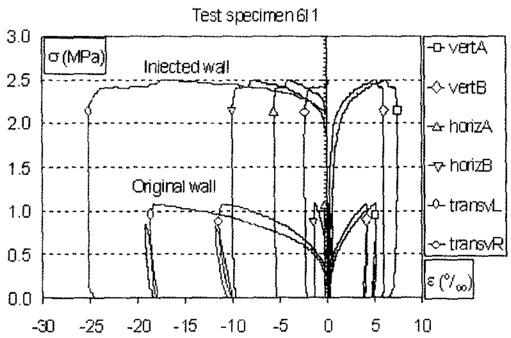

Figure 9
Stress-strain diagram (wall 6I1), before and after grout injections

Some of the walls were also subjected to sonic tests. These tests consist in generating an elastic wave by means of an instrumented hammer and registering the same wave in another position on the wall with a piezoelectric accelerometer. From the knowledge of the sonic pulse velocity, it is possible to draw some information about the current conditions of masonry. Different kinds of sonic wave transmission were used: direct transmission through the wall thickness, indirect transmission on the same walls surface, sonic tomographies, with measurements of sonic pulse velocities along different ray-paths on the same wall section.

Validation of the model

The compressive strength of stone, measured on cubes (71 mm for each side), was approximately of 164 MPa. Samples of mortar (40x40x160 mm prisms) were taken during the constructions of walls, and tested after 28 and 60 days. Their compressive strength was equal to 1.57 and 1.64 MPa, respectively. Thanks to the wire-sawing, the masonry panels were characterized by plane, easy to survey, transversal sections. The design assumptions, as regards the proportion of stones, mortar and voids were thus checked and confirmed.

Before the interventions, the maximum strength of the tested walls varied between 0.99 and 1.97 MPa; however, evident cracks patterns already started at a stress level varying from 0.55 to 1.09 MPa. The average value of the secant modulus of elasticity (calculated between the 30% and the 60% of the maximum strength) was of about 1700 MPa. The cracks had a vertical or sub-vertical trend, as expected for failure under compression, and most of them were located in the transversal sections, between the different leaves. The collapse thus occurred by detachment of the layers and out-of-plane expulsions.

In the walls repaired by means of grout injections, a quantity of grout corresponding to a percentage of about 14% of voids on the wall volume was introduced. After grouting, the average value of the maximum strength increased of 40% (about 2.5 MPa). Regarding the modulus of elasticity, it increased, in average, of about 35%, reaching the average value of 2347 MPa. Conversely, the transverse tying of walls strongly reduced transversal strains, of about the 50% at peak stress and of about the 90% at the same stress level.

Sonic tests

The original specimens showed values of sonic pulse velocities varying, in general, from 1500 to 400 m/s, which correspond to conditions of masonry from fair good to very bad (Berra et al. 1992). The lower part of the walls was characterized by higher values, corresponding to good conditions (Figure 10a). This reflected the construction process of the specimens, during which only the lower part of the internal leaf was compacted by the bricklayers. The lowest values of sonic pulse velocity were actually found on the inner loose leaf of the walls.

After the compression tests, a general decrease of sonic pulse velocities was detected. On the contrary, after grouting, the pulse velocities were about 3000 m/s, showing increments of even 1000%. During the injections, the quantity of injected grout and its propagation inside the walls was checked. It came out that the highest quantity of grout was injected where the previous lowest values and the subsequent highest increments of sonic pulse velocities were measured (Figure 10b).

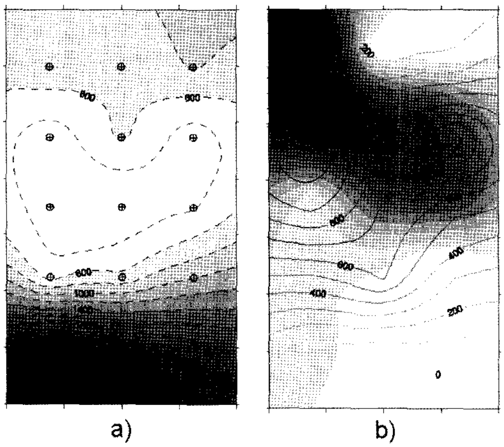

Figure 10
Vertical sonic tomography on the internal leaf of a wall after compressive tests (a). Quantity of injected grout on the same wall (background colours) and sonic velocity percentage increase after injection (foreground lines) (b). The darker colours stand for higher sonic pulse velocities (a) and for higher quantity of injected grout and higher velocity increases (b)

Conclusive remarks

The experimental simulation of the behavior of three-leaf stone masonry walls involves problems related to typology identification, materials, consolidation and diagnosis techniques. In the present contribution, the preliminary effort to define typological features and values of morphological and mechanical characteristics for stone masonry walls was described.

The various classifications of stone masonry walls found in literature differed for aims and structure. In general, it can be said that systematic classifications illustrate very well the morphological features of masonry. Due to their anthological and descriptive nature, they have a great historical and documental significance. Methodological classifications do not catalogue the characteristics of the different masonry typologies. However, they are very useful for an interpretative view of masonry. For example, the cataloguing of this kind here presented allows a qualitative evaluation of the mechanical behavior and the collapse mechanisms of walls. Finally, analytical classifications lend themselves to create data-bases of practical information, for operating on stone masonry walls. The simultaneous use of all of these classifications add complementary information to the knowledge of masonry typology, structure, behavior, and can avoid interpretative errors as those regarding the so called «a sacco» walls.

The accurate preliminary study of stone masonry walls led to the choice of materials, morphology and constructive techniques representative of existing walls. The compressive strength of the stone and mortar used was similar to those measured on real walls. Also the compressive strength of the masonry specimens showed an excellent fit with the results obtained on existing walls. The experimental values of the laboratory specimens, in fact, were all between the minimum and the maximum value measured on site. The modulus of elasticity measured on the specimens was higher than the real values (+30%, in average). However, a perfect fit between elastic moduli of real walls and physical models is not easy to obtain, as was found in literature. The use of lime based mortars, characterized by low compressive strength and modulus of elasticity if compared to cement mortars, limits the errors and allows reproducing the real conditions of historic masonry.

Also after the repairs it was possible to check the validity of the physical models built. The percentage increase of compressive strength for the injected walls was similar to that obtained on real walls. Also the final values of stiffness were still compatible with the elastic characteristics of existing stone masonry walls strengthened by injection. Very high increases of strength and stiffness found in literature, are related to laboratory research on three-leaf stone masonry specimens built with 1:1 thickness ratio between the external and the internal leaves. This proportion amplifies the effect of injection, but it is not typical of existing wall sections, according to the available data.

The original values of transverse strain and the restraint action carried out by the ties, in the specimens strengthened by means of transversal tying, confirm that collapse, in the physical models, occurs by detachment of the layers and out-of-plane expulsions. Therefore, not only the mechanical parameters, but also the observed collapse mechanisms demonstrate the validity of the physical models built. It is worth stressing that only a preliminary accurate study of existing walls and a proper design of the physical models allow the achievement of good results, that is to say the design and construction of laboratory specimens that are actually representative of existing walls.

Finally, the sonic test results well reflected the original poor condition, the damaged condition and the good conditions after consolidation of the specimens. It was also demonstrated the effectiveness and reliability of sonic tests in individuating areas characterized by the presence of voids and by lower density, and in detecting the change in masonry walls' conditions and consistency. Even if this kind of tests still need to be improved and calibrated with the mechanical parameters of masonry, it seems to be a useful and promising tool for a completely non-destructive evaluation of masonry conditions.

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