KNOWLEDGE OF THE BUILDING, ON SITE INVESTIGATION AND CONNECTED PROBLEMS

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ABSTRACT

Historic building, either famous monuments or “minor” architecture of historic centers need to be investigated in order to carry out repair aimed to their preservation. Non destructive techniques should be applied on site and destructive investigation limited to minor sampling. A methodology for investigation is outlined describing advantages and limits of the different techniques. Need for guidelines in Codes and Standards are also stressed.

KEYWORDS

Historic masonry buildings, diagnostic investigation, on site investigation, non destructive techniques.

1 INTRODUCTION

Historic buildings, no matter whether they are famous monuments or so called “minor” or even vernacular architectures, represent an important part of our cultural heritage. This patrimony which is the living memory of the country history and development must be preserved as much as possible as an historic document of our past. In the last decade the word “restoration” has more and more been substituted by the term “preservation”. Also in the case of damages due to earthquake or other calamities the expression “to adequate” was substituted by the expression “to improve by minor repair and strengthening”. Conservation of historic buildings requires a deep knowledge of structures and materials, of their characteristics, of the eventual state of damage and its causes. Prevention and rehabilitation can be successfully accomplished only if a diagnosis of the state of damage of the building has been formulated. The diagnosis should result from an experimental investigation on site and in the laboratory; it should also be clear that the investigation on site must be non-destructive as far as possible and give information with good precision. Besides the damage investigation before the intervention, the effectiveness of the repair techniques should also be controlled during and after the repair work, as well. The investigation also may require long-term monitoring of the structure.

The on-site experimental investigation is required and recommended also by Codes of Standards in several countries. The working group WG2- Working Item 001b: Diagnosis of building structures of the EC Technical Committee TC 346, prepare Standards for on site investigation. A RILEM TC (216 SAM, Structural Assessment of Masonry) is preparing guidelines for diagnostic investigation, following the results of a European Contract named ONSITEFORMASONRY.
2 DESIGN FOR THE DIAGNOSTIC INVESTIGATION

Historic buildings belong to different typologies to which a different behaviour of the structure corresponds: (i) isolated buildings, (ii) building in a row, (iii) complex buildings, (iv) towers, (v) palaces, (vi) churches, (vii) arenas. The modelling of these structures can be very difficult. In fact, when the structure is a complex one, only linear elastic models are easily usable. Non-linear models or limit state design complex models are difficult to apply, also because the needed constitutive laws for the material are seldom available. Furthermore when the complexity of the structure is given by its evolution along the centuries, starting from a simple volume to a more and more complex volume (Figure 1), then modelling has to take into account all the vulnerabilities accumulated during the subsequent transformations.

Figure 1. Complex building (aggregate) in Castelluccio di Norcia

The same difficulties can be found in choosing the techniques for repair and strengthening. Figure 2 shows which information can be available from in situ and laboratory survey and how they can constitute the input data for the structural analysis (Binda, 2007).

The structural performance of a historic masonry building can be understood provided the following aspects are known: (a) its geometry and historical evolution; (b) the characteristics of its masonry texture (single or multiple leaf walls, connection between the leaves, joints empty or filled with mortar); (c) the physical, chemical and mechanical characteristics of the components such as bricks, stones, mortar; (d) the characteristics of the masonry as a composite material; (e) the material decay; (f) the state of damage of the structure (Binda et al., 2009).

Several investigation procedures have been applied in the last decades most of them coming from other research field (e.g. medicine, aerospace engineering) or from application to the study of new materials (steel, concrete, composites). Nevertheless, to apply non destructive, although advanced, techniques to masonry which is a composite, highly non homogeneous material can be frustrating due to the difficulty of interpretation of the collected data. Most of the ND procedure can give only qualitative results; therefore the designer is asked to interpret the results and use them at least as comparative values between different parts of the same masonry structure.

It must be clear that even if there is a need of consulting experts in the field, it is the designer, or a member of the design team, who must be responsible of the diagnosis and must: (i) set up the in-situ and laboratory survey project, (ii) constantly follow the survey, (iii) understand and verify the results, (iv) make technically acceptable use of the results including their use as input data for structural analyses, (v) choose appropriate models for the structural analysis, (vi) arrive at a diagnosis at the end of the study.
In the following the methodology of investigation, as proposed by the author, also within the EU Contract “ONSITEFORMASONRY” developed between 2001 and 2004, and within GNDT and RELUIS contracts, is briefly described.

**Figure 2. Finalization of the experimental survey to the structural analysis.**

### 2.1 Historical evolution of the building
A preliminary in-situ visual survey is useful in order to provide details on the geometry of the structure and in order to identify the points where more accurate observations have to be concentrated. In the meantime the historical evolution of the structure has to be known (Cardani et al., 2008a) in order to explain the signs of damage detected on the building (Figure 3).

**Figure 3. Construction phases of a church (S. Michele Arcangelo at Sabbio Chiese, Italy).**

### 2.2 Geometrical survey
The geometrical survey can be carried out with simple tools or more sophisticated ones as photogrammetry or laser scanners surveys. The geometry of the structures has to be known in details, since it is the base both for the project of intervention and for the mathematical modelling.

### 2.3 Crack pattern survey
Especially important is the survey and drawing of the crack patterns (Figures 4 and 5). The interpretation of the crack pattern can be of great help in understanding the state of damage of the structure, its possible causes and the type of survey to be performed (Binda et al., 2007).
The crack pattern must be reported on prospects, and plans and even in 3D in order to better interpret it.

![Figure 4. Church of SS. Benedetto, Pompegnino (BS).](image)

![Figure 5. Church of St. A. Abate, Morgnaga (BS).](image)

2.4 Masonry morphology survey

The structural performance of a masonry wall can be understood provided the following factors are known: (i) the geometry; (ii) the characteristics of its masonry texture (single or multiple leaf walls, connection between the leaves, joints empty or filled with mortar), (iii) physical, chemical and mechanical characteristics of the components (bricks, stones, mortar); (iv) the characteristics of masonry as a composite material.

A direct inspection can be performed by removing few bricks or stones, surveying photographically and drawing the section of the wall. This can be more efficient than coring (See also Sec.4.1.1)

2.5 Laboratory test for material characterization

The aims of these tests are the followings: (i) to characterize the material from a chemical, physical and mechanical point of view, (ii) to detect its origin, (iii) to know its composition and content in order to use compatible materials for the repair, and (iv) to measure its decay and durability to aggressive agents.

2.5.1 Tests on damaged and new mortars

Physical, chemical and mineralogical-petrographic analyses are useful (and less expensive than other more sophisticated tests) to determine: the type of binder and of aggregate, the binder/aggregate ratio, the extent of carbonation, the presence of chemical reaction, which produced new formations (pozzolanic reactions, binder-aggregate reactions, alkali-aggregate reactions) (Baronio et al., 1991).

The grain size distribution of the aggregates can also be measured, particularly in the case of siliceous aggregates, by separating the binder from the aggregates through chemical or thermic treatments

2.5.2 Tests on damaged and new bricks and stones

When masonry is damaged by aggressive agents, chemical, physical and mechanical laboratory tests can give useful information for the choice of the appropriate material for substitution. The tests have to be carried out on deteriorated and on undamaged existing bricks and stones, and new ones.
2.6 **On site investigation techniques**

By definition the on site investigation should be carried out by using non destructive or slightly destructive techniques (Binda *et al.*, 2000), (Binda *et al.*, 2009).

2.6.1 **Minor destructive tests**

Several minor destructive tests are non used as the ponder drilling test, the penetration test and the Schmidt Hammer test for mortars. Nevertheless the flat jack tests are the only ones which give valuable mechanical results up to now.

*Flat jack test.* The method was originally applied to determine the in-situ stress level under compression of the masonry. The first applications of this technique on some historical monuments, clearly showed its great potential.

The determination of the state of stress is based on the stress relaxation caused by a cut perpendicular to the wall surface; the stress release is determined by a partial closing of the cutting, i.e. the distance after the cutting is lower than before (Binda *et al.*, 1999). A thin flat-jack is placed inside the cut and the oil pressure into the jack is gradually increased to obtain the distance measured before the cut (Figure 6). The displacement caused by the slot and the ones subsequently induced by the flat-jack are measured by a removable extensometer before, after the slot and during the tests. \( P_f \) corresponds to the pressure of the hydraulic system driving the displacement equal to those read before the slot is executed. The equilibrium relationship is the fundamental requirement for all the applications where the flat-jack are currently used: \( \sigma_f = K_j K_a P_f \) when: \( \sigma_f \) = calculated stress value, \( K_j \) =jack const (<1), \( K_a \) =slot/jack area const (<1).

The test described can also be used to determine the deformability characteristics of a masonry. A second cut is made, parallel to the first one and a second jack is inserted, at a distance of about 40 to 50 cm from the other. The two jacks delimit a masonry sample of appreciable size to which a uni-axial compression stress can be applied. Measurement bases for removable strain-gauge or LVDTs on the sample face provide information on vertical and lateral displacements. In this way a compression test is carried out on an undisturbed sample of large area (Figure 7).

![Figure 6. Single flat-jack tests carried out at the Monza Tower.](image)

![Figure 7. Double flat-jack test on West side of the Monza Tower.](image)

Proposals for Standards on flat-jack tests have been included in the Re-luis products in 2003.

2.6.2 **Non destructive tests**

Many authors have mentioned the importance of evaluating existing masonry buildings by non-destructive investigation carried out in situ. ND techniques can be used for several
purposes: (i) detection of hidden structural elements, like floor structures, arches, pillars, etc., (ii) qualification of masonry and of masonry materials, mapping of non homogeneity of the materials used in the walls (e.g. use of different bricks in the history of the building), (iii) evaluation of the extent of mechanical damage in cracked structures, (iv) detection of the presence of voids and flaws, (v) evaluation of moisture content and capillary rise, (vi) detection of surface decay, and (vii) evaluation of mortar and brick or stone mechanical and physical properties (Binda et al., 2009).

2.6.2.1 Thermovision
The thermographic analysis is based on the thermal conductivity of a material and may be passive or active. The passive application analyses the radiation of a surface during thermal cycles due to natural phenomena (insulation and subsequent cooling). If the survey is active, forced heating to the surfaces analyzed are applied.
A camera sensitive to infrared radiation collects the thermal radiation from the materials. The result is a thermographic image in a colored scale. At each tone corresponds a temperature range. Usually the differences of temperatures are fraction of degree. Applications can be to: (i) survey of cavities, (ii) detection of inclusions of different materials (Figure 8), (iii) detection of water and heating systems, (iv) moisture presence. In the diagnosis of old masonries, thermovision allows the analysis of the most superficial layers (Binda et al., 2003a).

![Figure 8. Investigation on hidden steel tie rods](image)

2.6.2.2 Sonic pulse velocity test
The testing methodology is based on the generation of sonic or ultrasonic impulses at a point of the structure. An elastic wave is generated by a percussion or by an electrodynamics or pneumatic device (transmitter) and collected through a receiver, usually an accelerometer, which can be placed in various positions (Binda et al., 2007b). The elaboration of the data consists generally in measuring the time the impulse takes to cover the distance between the transmitter and the receiver. The use of sonic tests for the evaluation of masonry structures has the following aims: (i) to qualify masonry through the morphology of the wall section; (ii) to detect the presence of voids and flaws and to find crack and damage patterns; (iii) to control the effectiveness of repair by injection technique in others which can change the physical characteristics of materials. The limitation given by ultrasonic tests in the case of very inhomogeneous material made the sonic pulse velocity tests more appealing for masonry. In general it is preferable to use sonic pulse with an input of 3.5 kHz for inhomogeneous masonry. Figure 9 shows the application of sonic tests to the detection of density in a stone walls.
2.6.2.3 Radar
Among the techniques and procedures of investigation which have been proposed in these last years, georadar seems from one hand to be most promising, from the other to need a great deal more of study and research (Binda et al. 1998) (Binda et al., 2008).
The method is based on the propagation of short electromagnetic impulses, which are transmitted into the building material using a dipole antenna. When the transmitting and receiving antennas, which are often contained in the same housing, are moved along the surface of the object under investigation, radargrams (colour or grey scale intensity charts giving the position of the antenna against the travel time) are produced. The choice of the antenna frequency must be made on a site basis. It is important to show results, as radargrams and graphics, which are significant to operators like architects and engineers.
When used for masonry, the applications of radar procedures can be the following: (i) to locate the position of large voids, cracks (Figure 10) and inclusions of different materials, like steel, wood, etc; (ii) to qualify the state of conservation or damage of the walls; (iii) to define the presence and the level of moisture; (iv) to detect the morphology of the wall section in multiple leaf stone and brick masonry structures.

2.6.2.4 Radar and sonic tomography
Among the ND applications the tomographic technique is quite attractive for the high resolution that can be obtained. Tomography, developed in medicine and in several other fields, seems to be a valuable tool to give two or three-dimensional representation of the physical characteristics of a solid. Tomography, from Greek "tomos" (slice), reproduces the internal structure of an object from measurements collected on its external surface (Binda et al., 2003b).

2.7 Static and dynamic monitoring
Where an important crack pattern is detected and its progressive growth is suspected due to soil settlements, temperature variations or to excessive loads, the measure of displacements in the structure as function of time has to be collected.
Very simple monitoring systems can be applied to some of the most important cracks in masonry walls, were the opening of the cracks along the time can be measured by removable extensometers with high resolution. This simple system can give very important information to the designer on the evolution of the damage.
In-situ testing using dynamic methods can be considered a reliable non-destructive procedure to verify the structural behavior and integrity of a building. The principal objective of the dynamic tests is to control the behavior of the structure to vibration. The first test carried out can be seen also as the starting one of a periodical survey using vibration monitoring inside a
global preventive maintenance programme. Acceptance of vibration monitoring as an effective technique of diagnosis has been supported by different studies (Niederwanger, 1997). These tests are very important to detect eventual anomalies in the diagnosis phase and to calibrate efficient analytic models (FEM).

The environmental excitation sources could be the wind, the traffic or the bell ringing in the particular case of towers. The forced vibrations could be produced by local hammering systems or by the use of vibrodines (Gentile et al., 2002).

3 DIFFERENT LEVELS OF INVESTIGATION

The importance of carrying out diagnostic investigations at different levels was clear after detecting the damages to the C.H. patrimony and to ordinary old buildings since the earthquake occurred in Friuli (1976). It was first of all observed that the damages caused by in plane and out of plane actions can occur according to typical mechanisms of failure recurrent for the same building typologies (churches, palaces, etc.). The experience of investigation in fact allowed to prepare special forms for the survey of damages by teams of expert referring to known failure mechanisms (Servizio Sismico Nazionale, 1998 and Civil Protection Department templates for C.H., 2006). It was so possible to extend the investigation to the whole historic centre instead of to single buildings. The study of the effect of the earthquake that struck the Umbria and Marche regions in 1997, showed how most retrofitting, carried out after the 1979 earthquake, mainly performed with upgrading interventions (substitutions of timber floors and roofs with r.c., jacketing of walls, etc.), provoked unforeseen and serious out-of-plane effects (large collapses, local expulsions), due to the “hybrid” behaviour activated from the new and the old structures (Binda et al., 2003a).

At the level of the single building (usually a listed monument), the on site investigation may be more complex due to the necessity of collecting the most possible number of data in order to help the designer preparing the project for the conservation of the building. More technologically advanced NDT can be applied to the details of the building so as more advanced techniques can be used for the geometrical survey (Binda et al., 2009).

3.1 Investigation at urban level

A research was carried out in Italy within the frame of a GNDT (National Group for Defence from Earthquakes) contract, involving Universities and Cultural Property Regional Offices. The main aim of the research was to set up systematic Data-bases for historic centres, able to store information useful for defining the seismic vulnerability of the buildings; preparing rescue plans; and, designing interventions for the preservation of the cultural heritage (GNDT contracts and Reluis contracts). The collected information deals with: i) the technological and constructive characteristics of the surveyed buildings; ii) the material and structure properties (with particular reference to the constructive techniques and to materials used for load-bearing masonry); iii) the materials and the techniques used for restoration before the earthquake; iv) the collapse mechanisms of buildings and structures due to the earthquake, considering also the ones already retrofitted (Binda et al., 2003a).

The object of the above mentioned research was not the single building, but the whole historic centre (even if small). The strategic aim was to define a methodology for the vulnerability analysis of built heritage, wrongly considered as “minor” in the past, that holds a meaningful testimony of cultural value. The research work aimed to produce a methodology of investigation which could be applied in the future by the authorities, at municipality, province or regional levels, to support the designers in choosing the right analytical model for the
safety definition and the appropriate intervention techniques for their projects, (Binda et al., 2007c).

3.1.1 A simple methodology for the quality survey of the masonry walls

The authors experience acquired on several types of Italian and European masonry structures, suggests that coupling flat-jack test with sonic test and with the observation of the masonry section by sampling, is a good and not too much invasive methodology to mechanically qualify the masonry (Binda et al., 2007a). This methodology was proposed with a document as a product of Re-Luis (line 1 and 10). A systematic investigation campaign was carried out on a sample of ten churches with the aim of supplying a good level of knowledge necessary to the structural analysis and to the proper strengthening and repair interventions (Cardani et al., 2008). According to the low budget allocated by the single churches, only few points could be chosen to detect the masonry quality, i.e. its morphology and stress-strain behaviour. Systematically, the testing points were chosen in the most representative parts of the bearing walls: taking into account that the façade of a church is usually made of better masonry, the lateral bearing walls were chosen. The tests were carried out mainly on the outer face of the wall, since the inner one was usually decorated with frescos and paintings which could not be damaged.

A complete characterization of the masonry in the chosen points was achieved by measuring: the sonic velocity, the state of stress, the modulus of elasticity, the coefficient of lateral deformation, the mortar and stones chemical, physical and mechanical properties. The morphology of the wall cross section was also surveyed in order to understand whether the masonry was made of one or two leaf and the leaves were connected in some way. This survey was carried out by sampling few stones in order to visually investigate the wall texture, redraw the inner aspect of the wall, sample stones and mortars for laboratory testing. In particular, four subsequent steps were followed in the same area: (i) sonic tests by transparency on a grid of 75x75cm, (ii) single and double flat-jack test, (iii) survey of the masonry morphology and material sampling, (iv) repositioning of the stones in the wall (Figures 11, 12).

Figure 13 shows the relationship between the sonic velocity and the modulus of elasticity, compared to other values previously obtained from tests on different stone-masonry walls in historic centres.

Figure 11. Results of sonic and flat-jack tests on the walls of three buildings.
3.2 Investigation of single buildings: complementary use of tests

When a complex investigation is carried out using different techniques, the highest difficulty is represented not only by the interpretation of the results of the single technique but also by the harmonisation of all the collected data (Binda et al., 2003c). To this purpose the development of new more appropriate software for the elaboration, interpretation and fusion of data particularly from NDT is needed (sonic, radar, flat-jack tests, static and dynamic monitoring). The production of guidelines for the correct application of investigation techniques to the different classes of masonries and of masonry structures, is also important.

The solution of very difficult problems as the detection of the morphology of multiple leaf masonry sections, the presence of voids and cracks in masonries, their mechanical characteristics, cannot be reached with a single investigation technique, but with the complementary use of different techniques (see also sec. 4.1.1).

Some typical problems were solved by the Authors with the combination of different techniques such as radar and sonic tests, flat-jack and sonic tests, sonic and radar tomography thermography, sonic, ultrasonic and radar tests, together with static monitoring. A good application and harmonisation of the results is presented in (Binda et al., 2007d) for the case of the Syracuse Cathedral.
4 CONCLUSIONS

A methodology for investigation on historic structures aimed to their preservation was outlined. Knowledge of the building details, materials and structural elements is essential in order to avoid past mistakes.

NDTs and MDTs are efficient only if their application is carefully calibrated on the studied building. Nevertheless the interpretation of the results is a difficult task and should be accomplished in a multidisciplinary approach.

Further research is needed on the complementarity of the techniques and on the development of appropriate software in order to obtain clear interpretations.

In absence of an immediate risk, the investigation can be: (i) prolonged in time and comprehensive, (ii) carried out to calibrate eventual mechanical models of the building behavior for long term actions or particular single events (hurricanes, earthquakes, etc.), (iii) set up to control the effectiveness of the intervention by monitoring of the parts, which were previously more at risk. Investigation is also needed in case of long term maintenance programs for repaired buildings.

Due to the possible high cost of MDTs and NDTs, an accurate choice has to be done by the designer, especially when diagnosis and search for vulnerability has to be applied at the level of to historic centres.

All the difficulties which have been described in the paper suggest that appropriate guidelines should be prepared within the National and International Codes and Standards (as in case of EC8 for seismic areas).

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6 REFERENCES


