Non destructive testing applied to historic buildings: 
The case of some Sicilian Churches

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ABSTRACT: The knowledge and diagnosis of the state of conservation of historic buildings can guide in the choice of appropriate mathematical models for structural analysis and in the proposal of repair and strengthening techniques.

After an introduction concerning to the methodology of investigation, three case histories are presented where NDT through sonic tests and minor DT (flat-jacks) were applied. Some comments were possible on the complementariety of the techniques.

1 INTRODUCTION

Historic masonry buildings, whatever use is made of them at present or in the future, have to show structural stability. From the point of view of the risk for human life, they may belong to the following categories, depending on the use of the building (Macchi 1992): (i) isolated and non accessible buildings, (ii) buildings belonging to the urban area, (iii) buildings open to the public, and (iv) buildings open to large assembles of people (cathedrals, theatres, etc.).

For each of the mentioned categories a certain amount of risk, as it is for new buildings, has to be accepted; the assessment of the structural state for several historic building has shown that for some of them the structural safety seems to be very low (Binda et al. 1997).

Certainly there exist some historic buildings whose stability is so precarious that they may collapse under slight earthquakes, strong winds, etc. (for example the Civic Tower of Pavia collapsed suddenly in 1989 without any apparent warning sign (Binda et al. 1992).

An appropriate and rational use of the structural analysis can help in defining the eventual state of danger and in forecasting the future behaviour of the structure. To this aim, the definition of the mechanical properties of the materials, the implementation of constitutive laws for decayed materials and of methods of analysis for damaged structures and the improvement of reliability criteria are needed.

The investigation is usually carried out where there is the intention of restore, repair or retrofit the building. Nevertheless exist cases when knowledge of the state of damage is in any case important for the safety of the building itself or to understand whether a maintenance intervention is needed. In some cases when the damage can be hidden or difficult to detect, an investigation campaign can save the situation as it happened in the case of the SS. Crocifisso Church in Noto.

Non destructive or slightly destructive techniques as complementary tests, can be reliable useful on side, provided that reliable interpretation of the data is made.

In the following the use of sonic tests and flat jack tests, together with other minor tests for the study of three similar cases of damage of church pillars are presented: the Cathedral and the SS. Crocifisso Church in Noto, the S. Nicolò l'Arena Church in Catania.
2 IMPORTANCE OF ON SITE INVESTIGATION TO DETECT THE STATE OF DAMAGE

The necessity of establishing the building integrity or the load carrying capacity of a masonry building arises for several reasons including: (i) assessment of the safety coefficient of the structure (before or after an earthquake, or following accidental events like hurricanes, fire, etc.), (ii) change of use or extension of the building, (iii) assessment of the effectiveness of repair techniques applied to structures or materials, and (iv) long-term monitoring of material and structural performance.

NDE can be helpful in finding hidden characteristics (internal voids and flaws and characteristics of the wall section) which cannot be known otherwise than through destructive tests. Sampling of masonry specimens is a costly operation, which also can lead to misunderstanding when the operation is not carried out in the appropriate way. When an overall knowledge of the wall is needed, ND tests can be useful.

The types of tests available at present are mainly based on the detection of the physical properties of the wall. The in-situ mechanical tests available are flat-jack, hardness, penetration and pull out tests. The flat-jack tests give local measurements and are slightly destructive: nevertheless they can give directly the values of mechanical parameters. In the case of ND tests, a correlation between the measured parameters and the mechanical ones is usually difficult, but they can give an overall qualitative response of the masonry. At present the most diffused ND techniques are represented by the sonic (or ultrasonic), radar and thermography tests.

Up to now 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 or by using different ND techniques.

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.

These operations can be accomplished with the help of experts in the field. Therefore information is needed for architects and engineers on the availability and reliability of the investigation techniques, which should be used taking into account limits and benefits, always compared to the cost.

2.1 Description of the problem

On site and laboratory investigation is the base for the knowledge of the structural behaviour and of the effectiveness of intervention.

The goal of these operations should always be clear before performing them in order to avoid high expenses with low benefits.

The level of the investigation should always be defined by a careful design; a preliminary investigation should be performed to choose more detailed and specific investigation in order to: check the reliability of hypothesis on damage causes and evolution, control the structure before, during and after the intervention, control the effectiveness of the repair and strengthening.

Different levels and complexity of investigation depend on the necessary level of knowledge, whether at urban scale or at the building scale.

2.1.1 Damage or weakness of Towers or pillars, columns in heavy construction: Churches, Cathedrals

Masonry load bearing elements of heavy historic structures frequently exhibit very typical mechanical deterioration phenomena like: a) formation of vertical or sub-vertical, thin but very diffused cracks, b) local detachment of the outer leaf in multiple leaf walls.

Such a peculiar crack pattern is often not attributable to common causes of damage like seismic events, foundation settlements, instantaneous increase of external loads (e.g. for added storey or building changing) or to chemical, physical and mechanical degradation of the basic materials. On the contrary, it is due to the prevalent effect of the dead load and to the connected
time dependent phenomena. Also wind, temperature variation and even earthquakes can contribute as far as compressive stresses develop during the event.

The most typical, and certainly the most critical, are masonry towers, very diffused in historic centres of Italy and Europe, and heavily loaded pillars; however, similar phenomena can appear also in masonry walls.

During their life, in normal conditions, such structures are subjected to dead loads (particularly high due to their considerable size), along with cyclic loads, like wind actions, thermal and hygroscopic excursions; moreover, bell-tower are interested by bell ring oscillations.

Due to the viscous behaviour of the masonry, high constant compression states of stresses can cause time dependent phenomena (creep) and consequent gradual degradation of the structure due to damage accumulation. Excessive state of deformation can be achieved, and an unexpected collapse can eventually occur. Cracks appear very thin until the failure, which happens suddenly, without any apparent warning (such as large cracks or spalling), even in close proximity of the collapse.

Because of the large weight of this sort of structures, wind and temperature loads do not cause substantial increase of stresses (shear and flexure) at the bottom. Nevertheless, they can act in combination with the previously mentioned condition and contribute to worsening the crack situation in the heaviest portions of the structure with their cyclic trend. In fact, close to the ultimate strength of the material, alternate cycles of loading and unloading can lead to fatigue damage, which can increase the failure hazard of the structure.

In the past, such problems were disregarded, because the presence of the above-mentioned cracking pattern was considered as a steady state of the structure. The sudden collapse of some of them induced to study the behaviour of those structures taking into account the dead load effects. Extensive monitoring programs and structural assessment are currently in progress to prevent other hazardous situations.

2.1.2 Detection of the masonry section morphology

The structural performance of a masonry wall structure can be understood provided the following factors are known:

− its geometry;
− the characteristics of its masonry texture (single or multiple leaf walls, connection between the leaves, joints empty or filled with mortar, physical, chemical and mechanical characteristics of the components (bricks, stones, mortar);
− the characteristics of masonry as a composite material.

In the case of multiple leaf masonry, the masonry texture, which strongly influences the bearing capacity of the wall, often can not be easily identified. Furthermore the characteristic strength of a highly non-homogeneous material is difficulty experimentally determinate being the strength and deformability parameters (Young modulus, Poisson ratio) of the components are not representative of the global strength and deformability of the masonry.

The worst defect of these masonry walls is that they are not monolithic in the lateral direction, and this can happen for instance when the wall is made by small pebbles or by two external layers well ordered but not mutually connected and containing a rubble infill. This makes the wall to become more brittle particularly when external forces act in the horizontal direction. The same problem can happen under vertical loads if they act eccentrically.

The survey of the sections allows to define some important parameters like: the percentage distribution of stones, mortar; the ratio between the dimensions of the different layers and that between the dimension of each layer and the whole cross section; the dimension and distribution of voids in the cross section. These parameters, together with the chemical, physical and mechanical properties of the materials give the possibility to better describe the masonry and constitute a fundamental basis of any conservative intervention (Binda et al. 1993).

2.1.3 Characterisation of the materials

If samples of the materials are needed for destructive tests they must be cored from the walls inflicting the lowest possible damage. The technique of sampling is very important, since samples must be as undamaged as possible in order to be representative of the material in situ.
The aims of these tests are the followings: (i) to characterise 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 the durability to aggressive agents from new materials used for restoration. Since it is very difficult to sample prisms representative of the walls, only single components or small assemblages are removed (Cardani et al. 2001).

2.1.4 Investigation on group of buildings on historic centres in seismic area

A proposed approach tackles the problem of the knowledge of mechanic of failure due to earthquakes in historic centres by considering different levels of analysis: history, materials, structural morphology of the wall section, observed damage mechanisms, effectiveness of retrofitting techniques. This analysis seems to be promising in relation to the homogeneity of the building peculiarities, both with reference to country houses and to buildings in historical centres (Binda et al. 1999a), (Penazzi et al. 2000).

As a first step of the knowledge process a survey procedure concerns the choice of the population of buildings to be investigated. This selection must be very accurate in order to limit the sample population to those buildings really significant. Information from each sample is collected in a data-base containing history, overall geometrical (plan, views etc.) and masonry data, representation of the structural system, eventual retrofitting, detailed description of the damage, and mechanical interpretation of the damage or collapse process.

The knowledge of the collapse mechanisms in the cases of non repaired and repaired buildings will help understanding the reasons for some failures, connect them to the construction and material characteristics and suggest more appropriate retrofitting techniques.

In this approach, a relevant phase consists in the survey procedure to inspect the internal composition of the masonry. At this level, the masonry of the building is investigated and classified with reference to its construction characteristics (i.e. by detecting the layout of the section) and to chemical, physical and mechanical characteristics of the components and of the masonry itself, by on site and laboratory tests.

The results provide the first information to be collected with those ones concerning the representation of the structural assemblage; in fact, it is well known that the type of masonry components and assemblages significantly affects the structural behaviour of the building.

The other critical phase concerns the qualitative identification of the damage process through data on crack, fissures, local or overall collapse etc. This phase, which is preliminary to the identification of a mechanical model, may be usefully carried out by introducing a catalogue or an abacus of the main mechanisms in common buildings.

The final aim of the analysis would be the proposal of mechanical models able to interpret and to forecast the observed damage and collapse modes. Even if this kind of structures are characterised by great complexities and uncertainties, nevertheless the results can be qualitatively acceptable, allowing to classify the damages and to critically consider the effectiveness of some techniques for repair and retrofitting when applied to a defined class of masonries.

2.2 Investigation procedures appropriate to detect the damage

A preliminary in-situ survey is useful in order to provide details on the geometry of the structure and on the visible damages (cracks, out of plumb, material decay) also in order to identify the points where more accurate observations have to be concentrated. Following this survey a more refined investigation has to be carried out, identifying irregularities (vertical deviations, rotations, etc.). In the meantime the historical evolution of the structure has to be known in order to explain the signs of damage detected on the building.

Especially important is the survey and drawing of the crack patterns. 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, provided that the development history of the building is already known.

Often the geometrical details of the structure need a special refined survey if they are complex or of difficult interpretation with the usual procedures.
Knowledge of the exact geometrical shape is of fundamental importance for the stability assessment of thin masonry vaults. All the irregularities of the geometry are detected in detail and can be given as input data to a structural analysis model.

Many authors have mentioned the importance of evaluating existing masonry buildings by non-destructive investigation carried out in situ (Binda et al., 1994), (Binda et al. 2000), (Forde and McCavitt 1993), (Suprenant and Schuller 1994). NDE 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 nonhomogeneity 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.

When a structural element can be accessed from all the sides as in the case of the pillars of churches, the indication can be more precise because the acquisition can be designed to ensure a dense and regular distribution of rays within the horizontal sections.

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 have to be collected. Monitoring systems can be installed on the structure in order to follow this evolution.

This type of survey is frequently applied to important constructions, like bell towers (e.g. to the Pisa leaning Tower, to the Dome of the Florence Cathedral in Italy) or cathedrals and the system may stay in place for years before a decision can be taken for repair or strengthening.

Very simple monitoring systems can be also 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 behaviour and integrity of a building. The principal objective of the dynamic tests is to control the behaviour of the structure to vibration.

A simple example of dynamic test is the control of the tensile stresses in tie rods.

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. An accelerometer net is installed in chosen significant parts of the structure.

2.3 Choice of the procedures according to the available budget and levels of investigation

The extension of the on-site and laboratory tests necessary for the building knowledge must be guided by parameters, which can be used to define the entity of the time and budget dedicated to these operation. The artistic value of the monument, the resources available, the entity of the damage and the type of intervention are some of these parameters. For the previous reasons, several levels of investigation can to be foreseen, depending on the type of building and on the aim of the research.

2.4 Different levels of investigation

Investigation needs to be carried out on monumental buildings but also more extensively on historic centres. Most of the historic centres are frequently characterised by a complex built environment of simple houses which constitutes itself an important part of the cultural heritage. This urban structure made of poorly constructed buildings eventually abandoned and with no maintenance is very vulnerable. The majority of this patrimony is often characterised by a poor level of material choice and construction technique, but worth of being preserved as it is an important part of the historic centre.

The required investigation, in these cases, has to be economic, due to limited resources. It is therefore important to define a "minimal" investigation program, which can support the designer in its project.
For large and important monuments, which were longer cared than poor constructions, the damage does usually not represent an immediate risk but a careful study is needed to understand their structural behaviour. Sometimes only a periodic control is needed.

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 behaviour for long term actions or peculiar single events (hurricanes, earthquakes, etc.), (iii) set up to control the effectiveness of the intervention and is characterised by monitoring of the parts, which were previously more at risk. Finally, investigation is needed in case of long term maintenance programs for repaired buildings.

3 THE COMPLEMENTARITY OF NON DESTRUCTIVE AND MINOR DESTRUCTIVE TESTING

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 these results.

Some questions arise when the designer or responsible of the building repair and maintenance receives the results of destructive and non-destructive tests.

When radar and sonic tests are carried out on the same wall or pillar, do the results harmonise, so that the same conclusions for both the tests can be the same?

Can sonic and double flat-jack tests be in some way correlate so that only few flat-jack, expensive and more destructive, can be carried out and sonic test allow a more extended at least qualitative interpretation?

Can core drilling and boroscopy help in sampling material for laboratory tests and detect the morphology of the wall section?

These and other questions are still open and a definite answer has not been given. The difficulties are due to the inhomogeneity of the material and complexity of the structures. A tentative of giving some answers was done in Binda et al. (2000).

Some examples of applying complementary investigation techniques are given in the following case history section.

4 CASE HISTORIES

The three cases reported in this section were chosen because the structures presented similarities of geometry, technique of construction or materials and damage.

The three Churches, S. Nicolò l'Arena, Noto Cathedral and SS. Crocifisso in Noto were all built after the earthquake, which hit Sicily in 1693 and damages by the 1990 earthquake. Furthermore the two last churches were nearly contemporarily built with the same type of stones and with similar mortars. Apparently the stones used for S. Nicolò were stronger being from volcanic origin.

The three buildings showed after the 1990 earthquake similar damages mainly on vaults, domes and arches. No or very low damages were visible on the pillars covered with plaster at least 20 or more years before.

After the collapse of the Cathedral of Noto, it was clear that plaster can hide dangerous crack pattern due to long term behaviour of the material and present since long time.

4.1 S. Nicolò l'Arena in Catania

After the 1990 earthquake, the structural elements of the Church of S. Nicolò l'Arena in Catania, as the dome and the vaults, were damaged and the appearance of vertical cracks on the original pillars were detected. It is not clear whether those cracks were already visible and were simply propagating during the earthquake.

An extensive investigation programme (including sonic, radar, flat jack, coring, boroscopy, etc.) has been planned (Fig. 1) to design the preservation and restoration actions (Saisi et al. 2001). Very interesting information were expected by stratigraphy of the section by coring, flat jack
tests and sonic tomography; also radar tests were applied. Sonic tomography is a powerful method to obtain information on the conditions of a structural element through the interpretation of velocity and attenuation maps. In general, the velocity distribution is an indication of the elastic properties of the element. The attenuation distribution is related to the non elastic behaviour of the material and so to the presence and importance of fractures.

The masonry texture appears characterised by two different typologies (Fig. 2): (i) a solid stonework built by large and regular blocks and filled with rubble masonry made with rather strong mortar; (ii) a highly inhomogeneous stone masonry surrounded by a cover more than 300 mm thick, made with tile fragments, stones and rather weak mortar, locally called "incoccio". Often the two typologies are present in the same structural element (Fig. 3). Apparently the second one was used as repair technique (Fig. 4).

The characteristic of the two masonry typologies (Figs. 5, 6) used for the pillars was controlled by double flat jack tests, which clearly revealed the two completely different mechanical behaviours (Figs. 7, 8). These characteristics are of primary importance in the numerical structure modelling for the safety control.

The stress strain diagrams of the second texture demonstrate the good characteristics of the pillars in terms of compressive strength and elastic properties (Fig. 8). Where the incoccio is
Figure 2: Main masonry typologies of the Church. Regular block masonry (a) and “incoccio” (b).

Figure 3: Regular stones and “incoccio”.

Figure 4: “Incoccio” probably used to widen the section of the pillars.

Figure 5: Masonry texture and localisation of the test MPD5.

Figure 6: Masonry texture and localisation of the test MPD1.

Figure 7: Stress strain curve of test MPD5.

Figure 8: Stress strain curve of test MPD1.
present, the double flat jack results seem very different from the ones obtained previously. First of all, the deformation is about 10 times the one of the other tested pillar for much lower stress values (Fig. 7).

To recognise the presence and the localisation of the two different masonries, sonic tomography was extensively applied. They show the velocity distribution of the elastic waves generated by an instrumented hammer in the sonic frequency band. The obtained results are very interesting and basically consistent with the external observations of the pillars and the extracted cores.

In Fig. 9 the sequence of the horizontal tomographies of pillar 2 are represented.

A typical distribution of the velocity on the pillars 1 and 2 shows average velocities relatively high at the base and at the top of the pillars and much lower velocities in the middle. This situation is very clear in the vertical tomography of both pillars even if the vertical sections have a lower density of ray.

The low velocities that have been found in the pillars 1 and 2 and the fact that these pillars show a dangerous crack pattern (Figs. 10, 11), confirm the need of urgent preservation actions. From an external observation, the masonry texture seems, in fact, very poor, characterised by the presence of the so called "incoccio".

From coring of the pillars it was also clear that the internal mortar is very weak.

The other pillars that have been investigated generally present much higher velocities indicating a less alarming state of conservation (Fig. 12).

In particular the pillar 6, the same of the double flat-jack test MPD5, seems characterised by a better quality material. The observation of the masonry texture reveals a large block stonework, rather regular, as external leaf.
4.2 The Cathedral of Noto

The authors applied systematically sonic tests and other diagnostic techniques on the remaining walls and pillars of the Cathedral of Noto (Binda et al. 1999b), (Binda et al. 1999c), (Binda et al. 2001a). In fact, the right main pillars and nave most of the dome of the Cathedral collapsed in 1996 (Figs. 13, 14). The aim of the research, carried out in strict collaboration with R. De Benedictis and S. Tringali, the designers of the reconstruction of the Cathedral, was to verify the state of damage and the possibility of conservation of the walls and pillars in view of the reconstruction of the damaged part of the Cathedral.

Furthermore the sonic tests were used to control the effect of grout injection used as a possible technique for repair of the damaged masonry. In the following the results will be reported and the reliability of the tests discussed as it was confirmed by the use of other complementary diagnosis techniques.

The masonry of load bearing walls and pillars, built according to a typical technique used in Noto, is characterised by an external leaf made with regular calcarenite or travertine blocks. The internal leaf consists of rubble masonry. Fig. 15 shows one of the collapsed pillars, revealing part of the section with the external stone leaf. A local calcareous sandstone was used for the external leaf in the lowest part of the pillar.

Figure 13: Plan of the Cathedral of Noto with the localisation of the tested pillars by sonic and flat-jack tests

Figure 14: View of the entrance of the Cathedral after removal of the ruins.

Figure 15: Detail of a pillar section.
The height of the blocks varies from 25 to 30 cm and the thickness, small compared to the pillar dimensions, is ranging from 25 (stretcher) to 40 cm (header). No really effective connection was realised between the external leaf and the core. The stones of the pillar strips supporting the arches have no connection either to the internal masonry or to the other parts of the external leaf.

The inner part of the pillars represents the 55% of the entire section, while in the pillars sustaining the dome it is the 58%. This part is a rubble masonry made with irregular stones and, up to the half of the total height, with large round river pebbles. The courses of these stones are rather irregular without any transversal connection or small stones to fill the voids and with thick mortar joints. Nevertheless every two courses of the external leaf (about 50 cm) a course made with small stones and mortar was inserted in order to obtain a certain horizontality (Fig. 16). Scaffolding holes were left everywhere, some crossing the whole section (Binda et al. 1999b).

The mortar appeared to be very weak made with lime and a high fraction of very small calcareous aggregates. Also the bond between the mortar and the stones was very weak; in fact it was possible to remove stones and pebbles from the interior of the pillars without any difficulty and with the stones being completely clean.

As a confirmation of the state of damage, and also a calibration of the procedure, sonic pulse velocity tests were carried out on the left hand side pillars and no remains of the collapsed pillars, as well. It is well known that ultrasonic frequencies can not be used on rubble walls due to the high attenuation caused by joints, voids and homogeneities. Nevertheless, being travertine and calcarenite so different the ultrasonic velocities measured in laboratory on single blocks, were very useful.

Measurements were taken at different heights (Fig. 17). It was impossible to position equal levels for all the pillars due to the presence of safety scaffolding (Binda et al. 1999c), (Binda et al. 2001a).

Low velocity values were systematically recorded in all the tested pillars of the Cathedral from about 1.00-1.50 m on, that is above the base. When part of the plaster was removed it was
clear that the external leaf was built with travertine blocks.

Fig. 18 shows the velocity distribution in pier P1A. The reduction of the velocity from the bottom to the top is clear. In Fig. 19 the distribution of the velocities in a pier section is represented showing clearly higher velocities in the external leaf.

The pillar P1B, the most investigated, shows the lowest values of the sonic velocities recorded at each level compared to the other P1 pillars. The pillar state is in fact characterised by a very serious damage, as described by the crack pattern of Fig. 20. The survey of the crack pattern was possible only after the removal of the plaster. Large vertical cracks had been filled with gypsum and lime mortar during the restoration carried out in the sixties. From Fig. 17 it can also be seen that the lowest velocities were measure around 3.00 m, where the crack pattern shows a very high damage. This is also confirmed by Fig. 20.

In order to check the extent of repair and reinforcement of the remaining damaged pillars by using the grout injection technique, some application were carried out on site.
Grouts were injected in the remaining parts of the collapsed pillars PC and PA and in the perimetral walls to control the applicability of the technique and to choose an optimal mix. Grout injections can be used for strengthening and connecting the leaves of a multiple leaf wall.

Four different types of grouts were used for laboratory and on site tests, and were called C, N, M, P: they were respectively lime + pozzolana, hydraulic lime, hydraulic commercial binder, microcement. The injection of each material was realised on approximately 1.0 m$^3$.

In the pillar PA the only mix C was used but the injection failed, in PC the mixes N, M, P while in the wall MB all of them. The sonic tests were carried out before and after the injection, at the same testing points.

As known, the success of the injection technique can have some limits connected to the masonry morphology, to the disaggregation and sedimentation of the grouts, to the mix characteristics (grain size distribution), to the operative technique.

The masonry behaviour was observed both during the injections and after 28 days. 28 days is the time necessary to reach the hardening of the grout. After this time, the collapsed pillars PA and PC were dismantled to observe the grout penetration and diffusion.

The sonic tests were carried out 28 days after the injection. A general increase of the sonic velocity was observed, as a consequence of the injection. Particularly the pillar PC. Fig. 21 shows consistent increases. It is interesting to observe that in some points the velocity values are similar to the ones initially acquired. This effect is easily explained because the section was not all injected, but only in one part. In the injection phases the grout penetration was limited to three areas (Fig. 21).

In order to have information on the elastic parameters and on the state of stress of the remaining structural elements, single and double flat jacks were carried out. The tests were very useful to study the state of damage of the remaining pillars of the Cathedral after the collapse.

In Fig. 22 three tests carried out on the external walls of the partially collapsed Cathedral of Noto are presented. Even in this case of highly non-homogeneous masonry, similar characteristics could be found; the masonry has a low strength and a high deformability.

![Figure 21: Results of the sonic tests carried out on the pillar PC at 25 cm, before and after the injection.](image-url)
In the case of the pillar P1E (Fig. 13) which sustained the dome, first the single and double tests were carried out on the external leaf of the pillar, then an other double jack test was performed on the internal rubble wall of the pillar after removing the external layer of regular stones. In Fig. 23 the two results of external and internal double flat jacks are compared together with the result of the single flat jack. As it can be seen, the internal part of the pillar is very weak compared to the external one. This result also explains the distribution of sonic velocities, which are lower in the internal part of the pillar. In the case of the Noto Cathedral it was possible to find that the crack pattern survey, the flat-jack tests and the sonic tests defined very well the masonry characteristics. The sonic tests were able to reveal the presence of the travertine in the upper part of the pillars.

4.3 SS. Crocifisso Church

The Church (Fig. 24) was damaged by the 1990 earthquake, especially in the transept and lateral naves domes and in the vaults, which were then supported by provisional structures. The pillars, apparently, did not show any damage.

During the on-site investigation, the plaster was locally removed, revealing an alarming state of damage due to compressive stresses (Binda et al. 2001b) as shown in Fig. 25.

The coring and the boroscopy observation, which together with the stone disposal survey gave information on the section morphology, revealed a multiple leaf masonry. The internal masonry is a rubble one, composed by a rather weak mortar, pieces of calcarenite and travertine (Fig. 26).

Sonic tests were carried out in order to detect the pillars characteristics. Fig. 27 shows typical sonic test results. The sonic velocities are higher in coincidence with the external stone leaves and lower in coincidence to the rubble material.

The lower average velocities concerns the pillar called D (Fig. 24), characterised by the worst crack pattern situation, as well. It is also possible to notice that in the case of highly cracked external leaf the velocity becomes much lower.

Flat jack, single and double, supplied interesting information. First of all the state of stress is lower and asymmetrical in the pillars supporting the dome, with a value of 0.76 and 1.04 -1.09 MPa, respectively in the apse pillar and in the pillar toward the transept (Figs. 28, 29). The lower stress in the apse pillar is justified by the presence of wall portions which support part of the loads.

Higher stresses values, 1.39 MPa, were measured on a pillar called E1 in Fig. 24, while the other pillars have a lower stress (0.83 - 0.99 MPa). The stress strain diagrams show consistent deformability of the masonry and rather low values of the strength, especially by considering the developing of cracks, which caused to interrupt most of the tests. The double flat jack-tests carried out within two stones and across a mortar joint, show a totally different deformation under the same stress when it is measured on the stones or across the joint. In Figs. 29, 30 these two different behaviour are shown in the stress-strain plot as average of LVDTs 1, 2, 3, 4 or 5, 6, 7 (Fig. 28). Therefore there is a major deformation of the joint when a certain state of stress is reached.
Figure 24: SS. Crocifisso Church plan and localisation of the double flat-jack tests.

Figure 25: Damages visible after the plaster removal.

Figure 26: Drilled core of pillar C and reconstruction.
The value of this state of stress is variable from the first load step up to the 45-50% of the maximum value.

The state of stress measured by the single flat-jack is in both cases greater than the above mentioned stress. This explains also the detected damages.

The used calcarenite, the Noto Stone, is in fact characterised by low mechanical properties especially in the case of saturated samples, as it was revealed by the compressive and brazilian tests. Tab. 1 shows the mechanical results carried out on stones sampled in the Church.
5 CONCLUSIONS

On site investigation techniques should be slightly or no destructive in order to avoid destruction as much as possible. Nevertheless the calibration of NDT on highly inhomogeneous masonry is very difficult.

Sonic tests proved to be successful in all the three mentioned case histories. They were effective when used in simple applications or in a much more refined application.

In the first case, it was very easy to understand which were the weak points of the pillar.

Flat-jack tests, besides giving the state of stress and the stress-strain behaviour help in the explaining given state of damages.

Coupling of sonic test and double flat-jack tests can give in the future a correlation between sonic velocities and modulus of elasticity.

AKNOWLEDGEMENT

The authors wish to thank L. Cantini, D. Penazzi, C. Tedeschi for their help in the survey of SS. Crocifisso, M. Antico, M. Cucchi, G. Cardani, for the technical assistance to the experimental investigation. The research was supported by the Prefettura of Siracusa, the Genio Civile of Siracusa (S. Messina), the Genio Civile of Catania (S. Cocina), by MURST Cofin 98 and by "Progetto Giovani ricercatori" of the Politecnico of Milan.

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