

# State of the Art of Research on Historic Structures in Italy

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## 1. INTRODUCTION

Many experiences in restoration and rehabilitation of damaged masonry buildings have been carried out in Italy during more than fifty years; in many cases the interventions were performed after a long period of misuse and lack of maintenance following the second world war. During this period also major earthquakes have taken place in most of the Mediterranean countries.

The intervention on the ancient masonry buildings should be inserted in the wider contest of the rehabilitation of the historic centres, which touches multidisciplinary aspects.

The intervention should take into account the modern restoration and conservation theories which interest both monuments but also all the historic buildings [Carbonara, 1996]. The preservation necessity was extended to the buildings previously considered as minor, but meaningful testimonies of the art of building. Then, an effective and coherent preservation of the historic centres should develop a deep knowledge of the materials and local technologies used in the "minor" buildings. These were often built by poor materials but with effective techniques, refined in the centuries with specific rules [Giuffrè, 1996].

Often the study of the building rules and structural details, such as the wall sections, has a great importance in the mechanic behaviour of a building. As an example, historic stone-masonry buildings present a peculiar structural and durability behaviour which is different from the one of the brick-masonry buildings [Giuffrè, 1991], [Giuffrè, 1993].

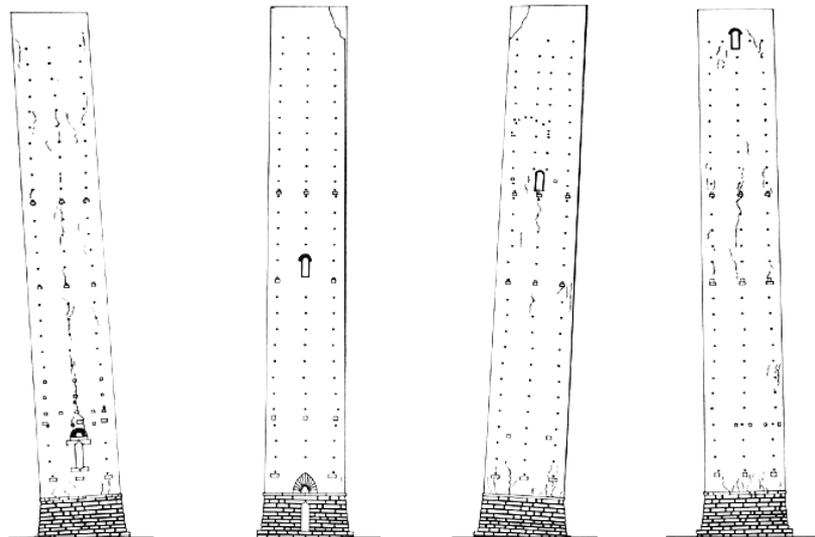


*Fig. 1. Damages after Umbria earthquake to a building repaired by introduction of concrete tie beams.*

In a urban scale, these studies should be extended to the analysis and classification of the main building typologies recognisable in the territory. 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 typologies and of the main mechanisms found in common buildings [Giuffrè, 1993]. The final aim of the analysis would be the proposal of mechanical models able to interpret and to predict 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. The studies are mainly finalised to the extensive evaluation of the structural vulnerability and to plan risk prevention or, at least, mitigation on a territorial scale [Giuffrè, 1991], [Giuffrè, 1993], [Carocci, 1996], [Giuffrè, 1997], [Bernardini,1998], [Anquillesi, 1999], [Bernardini, 2000], [Faccioli, 2000].

Prevention and rehabilitation can be successfully accomplished only if a diagnosis of the state of damage of the building has been formulated. How structural damage can interact with the performance of the structure to all the environmental actions and vice versa is not yet really completely known. From the point of view of the structural stability, the first concern for the conservation of a historic building should be a reliable diagnosis, to state its safety. Several unsuccessful results have underscored the need for adequate assessment prior to any restoration or rehabilitation. In fact, when neither the real state of damage nor the effectiveness of repairs are known, the results of the intervention are also unpredictable.



*Fig. 2. The Garisenda leaning Tower in Bologna.*

The symptoms of damages and their causes should first of all be known. In some cases the correlation is clear (Fig. 1, 2). Frequently the correlation between effects and causes cannot be done without an experimental and analytical investigation (Fig. 3, 4) [Rossi, 1982] [Binda, 1997], [Rossi, 1997].

Furthermore, modeling of a masonry structure is a difficult task, since masonry does not apparently respect any hypothesis assumed for other materials (isotropy, elastic behaviour, homogeneity), appropriate constitutive laws for the materials are still not well developed. The continued modifications happened in the building history produce several uncertainties in the model definition (geometry, materials, connection etc.).

In Italy the National Committee for the Seismic Protection of Monumental Building and Italian Cultural Heritage (CNPPCRS) has the institutional task of promoting research aimed to the systematic collection of data on the cultural heritage exposed to seismic risk, to the evaluation of its vulnerability and to plan hazard mitigation strategies.



*Fig. 3. The Bell Tower of Pavia after collapse*



*Fig. 4. The Cathedral of Noto (Siracusa)*

The discussion within the Committee on the ancient building preservation but increasing the their seismic safety produced many research and two official documents. The main conclusion concerned that for new constructions the safety is guaranteed by technical codes. These codes are mostly not applicable to existing buildings in masonry. Furthermore the ancient building has an identity and a value that should be preserved. When the safety is involved the different requests are in conflict [CNPPCRS, 1986], [CNPPCRS, 1989]. The intervention on ancient buildings should be inspired by specific principles and regulations, developed and defined on purpose [CNPPCRS, 1986], [CNPPCRS, 1989], [Corsanego, 1992], [Corsanego, 1993], [Gavarini, 1994].

.Then, a correct structural evaluation should be based on a deep knowledge of the: (i) building history and evolution, (ii) geometry, (iii) structural details, (iv) crack pattern and material decay map, (v) wall construction technique and materials, (vi) material properties, (vii) structure stability, is needed. This knowledge can be reached through an on site and laboratory experimental investigation, structural analysis with appropriate models and final diagnosis.

The debate on the previous problems rises in the last years in relation to the new law about the Public Works, called Legge Merloni [Ministry of Public Works, 1994], which explicitly requires a diagnosis phase on support to the design or to the maintenance of buildings.

Several investigation procedures have been implemented in recent years; the attempt is to use as much as possible non destructive (ND) techniques. Nevertheless, there is still a very little possibility at present to correlate non destructive evaluation (NDE) test data to masonry performance. Therefore when the designer is not sufficiently skilled to interpret them, a great amount of data can be inappropriately used or even not used at all.

Following the diagnosis and knowing the functional destination, the design for repair should be set up, remembering that there is usually not a unique way of repairing, consolidating, preventing.

The experience of the last decades in repair, strengthening and prevention for the preservation of masonry buildings in historic centres of seismic areas did teach that compatible or friendly techniques have to be chosen in order to obtain positive results.

The damages caused by dramatic events like earthquakes to historic masonry buildings which had already been repaired after previous similar events, applying traditional or modern techniques has given enough information to support the choice of compatible materials and

techniques. In some case, the need for rehabilitation and repair of damaged masonry buildings allowed for the application and experimentation of both traditional and advanced techniques; the later were used at first without previous control, because necessity and time were urgent.

Several techniques can be discussed and the optimal one chosen from the point of view of the most friendly intervention among the ones economically compatible with the available budget, but also respecting the safety necessities for the building [Modena, 1987], [Modena, 1997]. Also a project for a maintenance program to be applied in the long term should be set up, since no intervention can last for ever.

## **2. MATERIALS AND CONSTRUCTION TECHNOLOGY**

The structural performance of a masonry can be understood provided the following factors are known [Binda, 2000]:

- 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 ( stones, mortar);
- the characteristics of masonry as a composite material.

In the case of brickwork structures, and particularly in the case of new production masonry, the codes of practice can generally suggest some laws, which allow to calculate the strength of masonry as a function of that of the components.

In the case of stonework masonry, the problem is much more complex and some questions spontaneously rise. For instance, can the masonry texture, which strongly influences the bearing capacity of the wall, be easily identified? How can the characteristic strength of a highly non-homogeneous material be experimentally determined if sampling has to be enough numerous (for the results to be statistically representative) but in the same time non destructive? How can experimental tests be carried out and laboratory prototypes be built which are representative of real situations (think for instance to the great difficulty of building a wall made of river gravel in the laboratory)? Therefore, how can the physical-mechanical characteristics of stones and mortars be determined or be considered statistically reliable when sampling difficulties very often hinder the achievement of significant results? And again, can strength and deformability parameters (Young modulus, Poisson ratio) of the components, which indeed complete the mechanical characterization of the materials, be used to extrapolate the global strength and deformability of the masonry?

For these reasons, can the structural diagnosis of stonework masonry buildings be worked out from the knowledge of its components or can it be better performed through direct in-situ measurement of the mechanical characteristics of the masonry as a whole? How can the local and global behaviour of a stone masonry be determined under vertical and lateral loads? Provided good connections between the different structural elements in a stone masonry building have been introduced, how the behaviour of the wall is influenced by the construction technology under seismic in-plane or out of plane loads?

The worst defect of a masonry wall is to be 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 (Fig. 5).

The same problem can happen under vertical loads if they act eccentrically [Giuffrè, 1993].

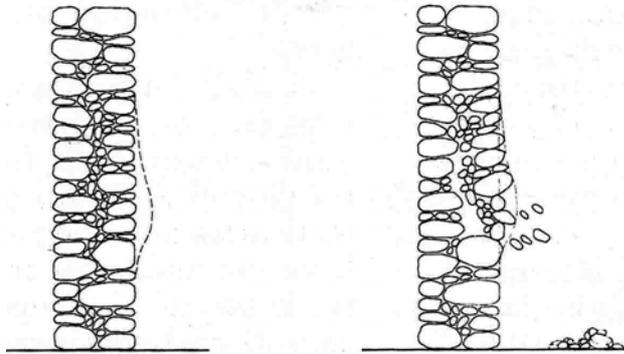


Fig. 5. Deformation and failure of a two leaves wall [Giuffrè, 1993].

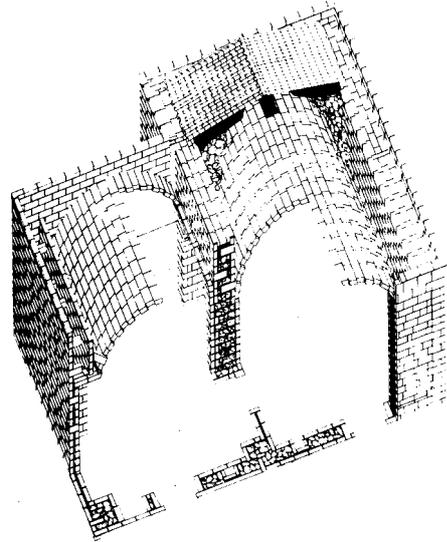


Fig. 6. Montescaglioso (Matera), single-story house (casa terranea) [Carbone, 1995].

Some indications on the mechanical behaviour of stonework masonry can also be given based on the research carried out [Abbateo, 1993], [Penazzi, 1997], [Binda, 1999]. First of all, given the great number of existing cross sections and the great influence of the building technique on the masonry behaviour, a systematic study on the mechanical behaviour of stonework masonry should begin from an extensive investigation of the different geometry and building techniques which takes into account the different layers constituting the wall and the kind of constraints which may or may not be present between the layers themselves. In fact, the ancient building techniques and particularly those adopted in the poorer architecture still need to be carefully investigated. In Fig. 6 the survey of an old single storey house (casa terranea) at Montescaglioso (MT) built in Gravina calcarenite is shown as an example of a correct analysis of the building. The survey is part of a final year thesis performed at the Department of Structural Engineering (D.I.S.) of Politecnico di Milano [Carbone, 1995].

Other researches were carried out in different Italian region [Abbateo, 1993], [Binda, 1995], [Binda, 1999] studying stonework walls of buildings the internal cross sections of which can be inspected; the operation can be more easily conducted in those areas where the buildings were damaged by the earthquake and have not yet been repaired. The survey consists of a graphic and photographic procedure which includes taking a photograph with a camera having the lens of 50 mm using a tripod which ensures the parallelism between the plane of the photograph and that of the wall; working out the metric survey of the walls first manually and then on a PC; creating a rich data-base organized in tables like that presented in Fig. 7 [Lodigiani, 1995], [Penazzi, 1997], [Binda, 1999].

The cataloguing has been carried out on 200 internal sections so far, belonging to different Italian regions (Lombardia, Friuli, Liguria, Basilicata, Trentino). The survey of the internal sections allowed to define some important parameters like: the percentage distribution of stones, mortar, voids which allows to make comparisons between the different regions (Fig. 8); 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 (Fig. 9). 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.

### 3. CLASSIFICATION OF MASONRY CROSS SECTION AND OF TYPOLOGIES OF HISTORIC BUILDINGS

The differences in the numerous types of masonry walls are not only given by the use of different materials according to the local possibilities (stones, bricks, earth, various types of mortars, etc.) but also according to the different construction technologies. Furthermore when modelling the behaviour of a masonry structure the complexity of its geometry and volumes makes difficult the choice of an appropriate model.

Therefore, given the great number of existing masonries, a systematic study of the mechanical behaviour of brick- and stonework masonry should begin from an extensive investigation of the different geometry and building technique taking into account the different layers or leaves often constituting a wall and the kind of constraints which may or may not be present between the layers or leaves themselves. In fact the ancient building techniques and particularly those adopted in the poorer architecture still needs to be carefully investigated.

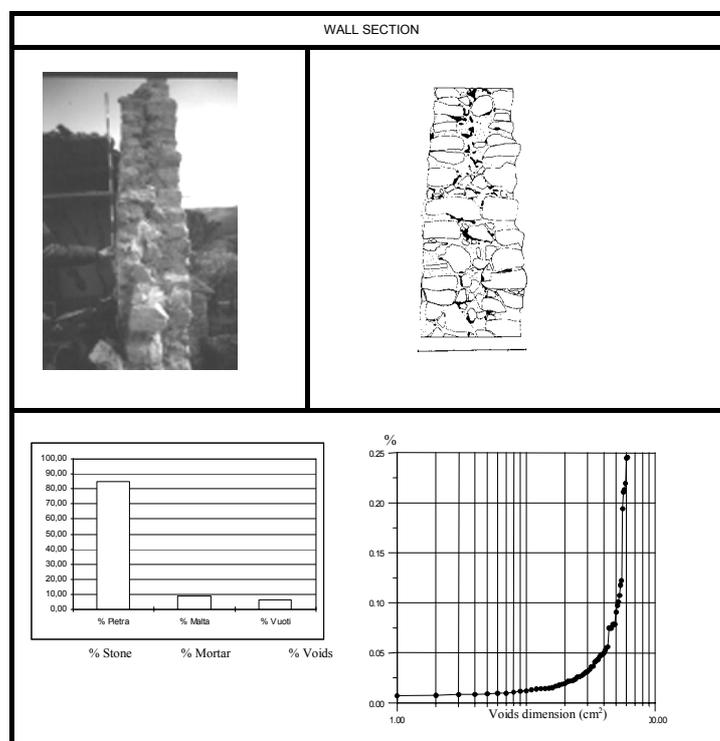


Fig. 7. Form representing the wall section and the void calculation [Binda. 1999].

A study like that presented above can be a good starting point for a classification of the different cross sections to be carried out, particularly of multiple leaf ones. In fact a correct structural analysis of these structures can only be performed provided some criteria are singled out in order to identify homogeneous groups of walls, not only on a geometric basis but also on a mechanical one [Gelmi, 1993]. To this respect many investigations are in progress not only in Italy.

Giuffrè carried out in the early '90s [Giuffrè, 1993] the first studies about the mechanical behaviour of the stonework masonry typologies based on visual inspection to recognise characteristics of the "rule of art" and, then, to the typology classification. The studies were part of a more general analysis on the vulnerability of some historical centres like Ortigia, Palermo) [Giuffrè, 1993], [Carocci, 1996], [Giovanetti, 1998], [Giuffrè, 1996], [Giuffrè, 1997], [Giuffrè, 1999], [Gurrieri, 1999]. In each case the local masonry typologies and materials are carefully studied are reported in abacus. The presence of some characteristic, like the

connection elements called diatons, can be a discriminating parameter for the evaluation of the wall mechanical behaviour (Figs. 10, 11, 12).

Other parameters can be: dimension of the elements, shape and workability of the stones, masonry texture, mortar quality, mortar quantity, presence of wedges, presence of horizontal courses, presence of leaves connections and diatons, characteristic of the section, homogeneity of the materials. Each masonry behaviour is then qualitatively evaluated (Fig. 12).

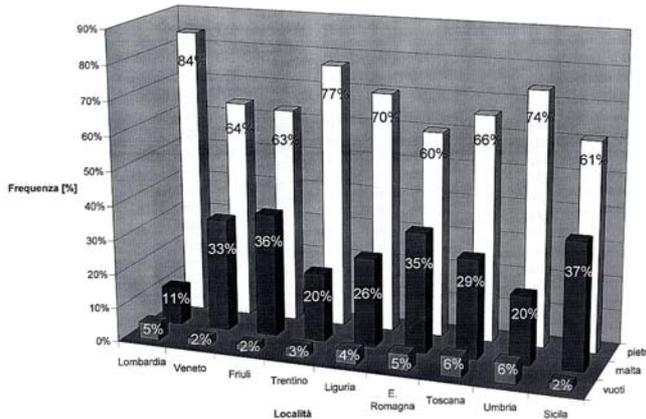


Fig. 8. Percentage of mortar vs. percentage of stones referred to the area of the cross section of stonework walls in various Italian regions.

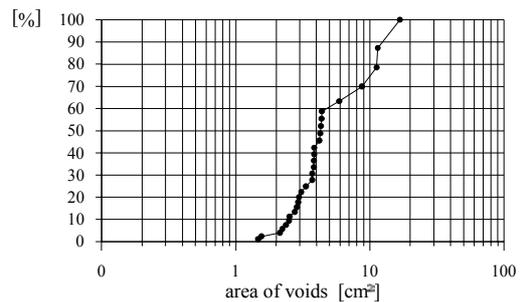


Fig. 9. Size and distribution of the voids within the section of the wall. [Binda, 1997]

Giuffrè' [Giuffrè, 1991], [Giuffrè, 1999], proposes in fact, a classification based on a parameter called  $\delta$  which indicates the ratio of the distance  $d$  between two subsequent diatons to the thickness  $s$  of the masonry wall. The parameter is representative of the bending resistance of the wall (Fig. 13).

Other interesting studies [Mannoni, 1976], [Francovich, 1988], [Mannoni, 1991], [Mannoni, 1994], [Della Torre, 1996], [Mannoni, 1998], [Peduto, 1998] concern the large scale analysis of the masonry typologies. They are mainly dealing with the prospect and section texture and do not enter into mechanical characterisations, but they are mainly direct to a classification with historic purposes. They represent rich and important data-bases especially of the Liguria and Toscana masonry typologies.

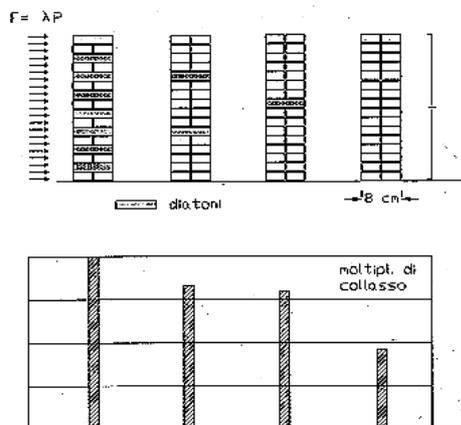


Fig. 10. Diaton influence and stability of the wall [Giuffrè, 1988].

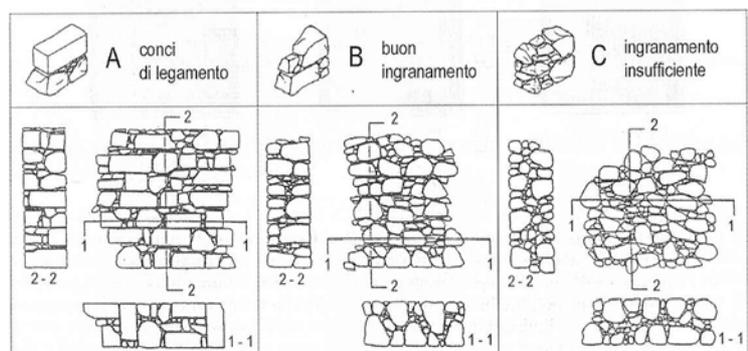


Fig. 11. Example of a section abacus, indicating very good, good and poor connections [Giuffrè, 1993].

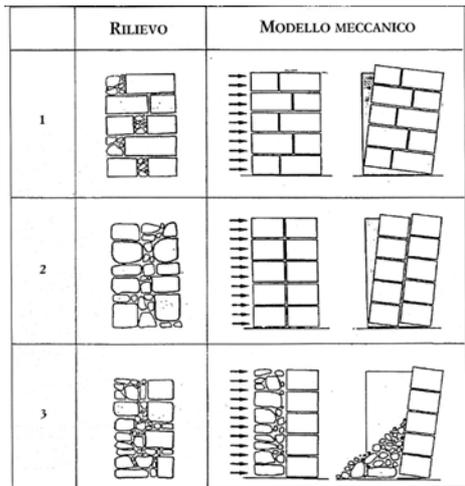
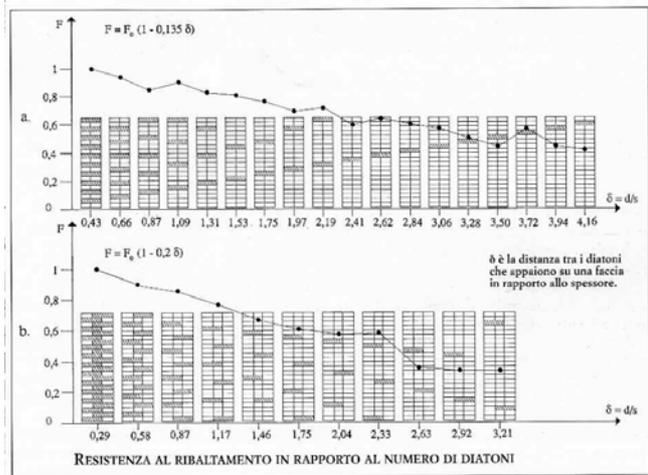


Fig. 12. Qualitative behaviour of a multiple leaf stone masonry [Giuffrè, 1999].



### 3.1 Masonry cross sections

The study described in section 2. leads to an initial cataloguing of multiple leaf walls based on the percentage of mortar, stones and voids measured on the area of the cross section and to a subsequent classification based on the number of different layers and on the type of constraint between them (Fig. 5). Whereas the first kind of classification allows to evaluate the injectability of the wall, as subsequently described in more details, the second one allows to formulate important hypothesis on the static behaviour of the masonry [Binda, 1994], [Binda, 1997].

#### 3.1.1 Brick masonry sections

Modern and contemporary masonries made with solid bricks are classified according to the thickness of the section corresponding to one or a multiple of the brick header; the type of section is then very easily detected by its dimension.

Old and ancient brick masonries had usually very thick sections (from 600mm on) with a much less homogeneous distribution of the bricks in the section; sometime only the external leaf of the masonry was made with whole regular bricks, while the internal part was made with pieces of bricks and large mortar joints for economic reasons.

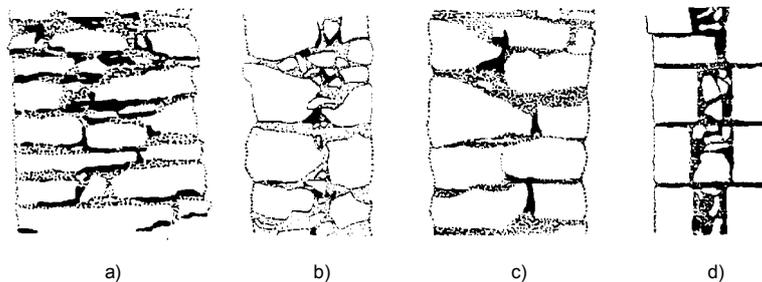


Fig. 14. Classification of the cross sections of stonework walls: a) a single leaf; b) two leaves without connection; c) two leaves with connection d) three leaves [Binda, 1994].

The joint thickness was usually much lower than the brick one in a ratio 1-2/5. Nevertheless this was not the case of late Roman architectures and of Byzantine constructions where the mortar joints were much thicker than before. From a survey carried

out on Milan Roman walls and on Ravenna Byzantine walls the following classification could be made (Fig. 15): (I) solid walls with thin joints, (II) solid walls with thick joints, (III) solid walls with multiple leaves (with different thickness of the leaves) [Binda, 2002]

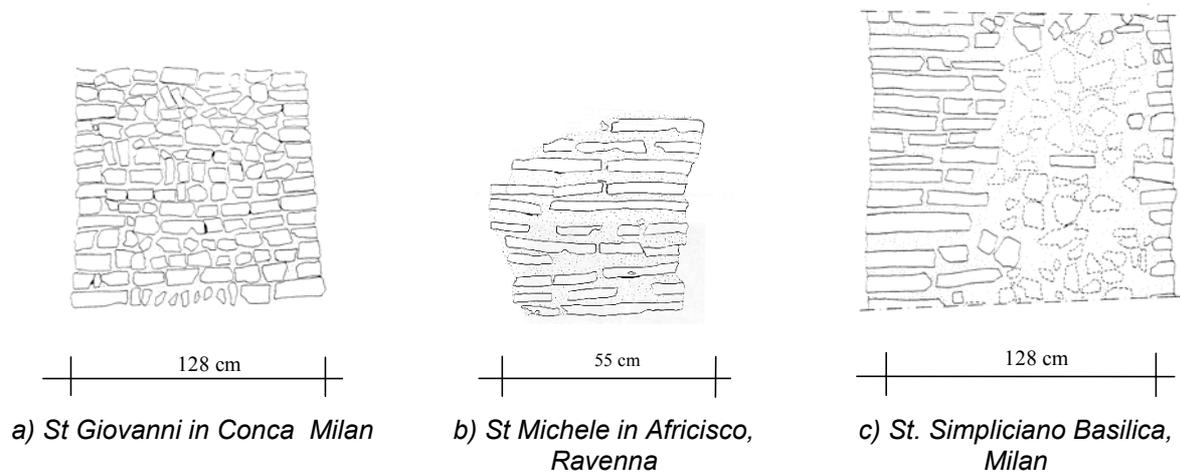


Fig. 15. Examples of brick masonry section [Binda, 2002].

### 3.1.2 Stone masonry sections

In the case of stone masonries more different types were found, also with more subclasses than in the case of brick masonry. In fact four large classes can be distinguish, each one having subclasses as follows: (I) one leaf solid wall, (II) two leaves, (III) three leaves, (IV) dry wall (Fig. 16). Each class can be further subdivided into two subclasses or even more [Binda, 2002].

### 3.2 Classification of building typologies

As in the case of masonry sections, the mathematical models used to detect the load carrying capacity of the masonry structures will have to take into account the many different types of masonry structures which are representative of the building function: houses (isolated, in rows, etc.), palaces, churches, towers, castles, fortifications, etc (Fig. 17).

The building and structure typology is so much important that a reliable approach to their restoration and preservation should refer to a methodology of investigation and choice for the most appropriate techniques applied to the special type of building and materials [Dolce, 1999], [Binda, 2002]. It has been shown during the earthquake, that even if the buildings belong to the same age and type of construction the isolated house or dwelling has a different failure mechanisms than buildings in a row [Giuffrè, 1993]. High rise towers and bell-towers suffer from similar long term damages which can bring them to failure even after centuries. So it is not possible to use the same investigation procedures, modelling and repair measures for Palaces, Churches, etc.

The approach for restoration should be done by classes of buildings and structures [Giuffrè, 1991], [Doglioni et. al., 1994], [Binda, 2002]. It is frequently impossible to apply techniques of intervention equal for every building class.

The researches carried out by Giuffrè and others on the historical centres enhance these necessities.

The survey of the historic centres produces interesting cataloguing of the building typologies but also of the typical transformation recognised. In fact, each typology but also each transformation (Fig. 18) can lead to specific damages due to the loss of continuity or to

bad connections. The mechanical behaviour of each typology is then summarised by an expected damage abacus.

Dogliani, Moretti and Petrini [Dogliani, 1994] carried out analysis, starting from similar basis, for the Friuli churches and bell-towers (Fig. 19), damaged by 1976 earthquake. The cataloguing of the typologies, structural details and damages was an important tool for successive researches and interventions on seismic area.

Similar analysis were carried out by Lagomarsino [Lagomarsino, 1997, 1998, 1999], on the Umbria and Marche churches, damaged by the 1997 earthquakes, to Catania Churches [Cocina, 1999], [Faccioli, 2000] and to the ones of Lunigiana and Gargagnana [Angeletti, 1997]. This study allowed the verify of simplified structural models.

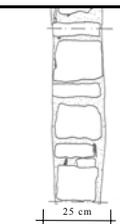
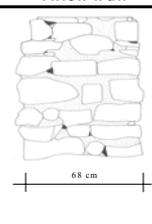
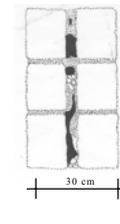
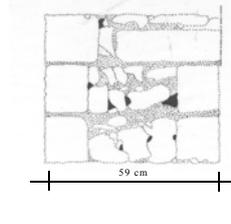
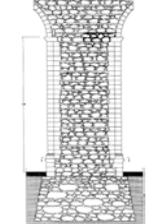
CLASS A: ONE LEAF SOLID WALL		
Single stone	Thick wall	
 Catania Ca5s2	 Valgrande 2.2 - Trento	 Bardello Bar25.2 - Como
CLASS B: TWO LEAVES		
Two leaves with no connection	Two leaves with simple connection made with overlapped stones	Two leaves with transversal connection made by long regular stones
 Portis Ud9 Udine	 Sant'Antonio ai Monti - Sam8.1 - Como	 Baiaro Ge8 - Imperia
 Carcente Ca27.1 - Como		
CLASS C: THREE LEAVES		
Three leaves with a thin internal leaf	Three leaves with thick internal leaf	Three leaves with thick internal leaf but referred to pillars and piers of churches and cathedrals
 Matera Montescaglioso 7	 Matera Montescaglioso 9	 Cathedral of Noto Pillar
CLASS D: DRY WALL		
 Erbonne Er1.2 - Como		

Fig. 16. Example of the stonework sections catalogue. [Binda, 2001].

#### 4. INVESTIGATION AS A NECESSITY FOR A RIGHT DIAGNOSIS

Prevention and rehabilitation can be successfully accomplished provided the diagnosis of the state of damage of the building has been carefully carried out. During the recent years, non-destructive and destructive evaluation procedures and techniques used in other fields (steel and concrete structures, medicine) have been discovered and widely applied [Binda, 1994]. Nevertheless, it is very often difficult to apply the results of an investigation, even a very good one, when the designer is not sufficiently skilled; in that case a great amount of data remains unused or can be used incorrectly.

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 to 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.

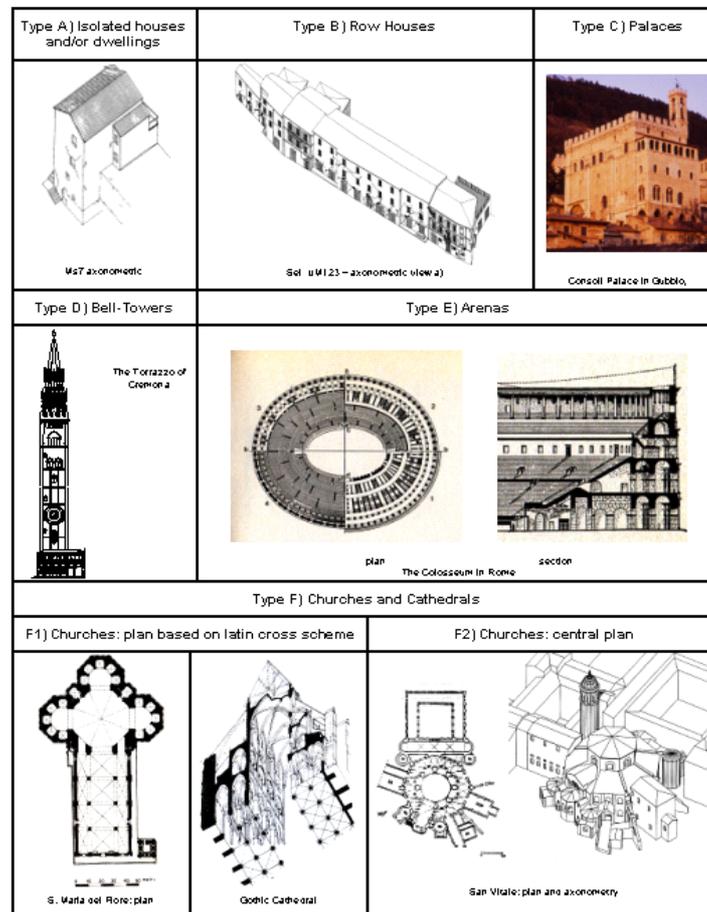


Fig. 17. Building typologies [Binda, 2002].

Several investigation procedures have been implemented in recent years; the attempt is to use as much as possible non-destructive techniques. Nevertheless, there is a very little possibility at present to correlate NDE test data to masonry performance especially in the case of multiple leaf stonework. Fig. 20 tries an attempt to describe the needs and the correspondent procedures [Binda, 2001], [Binda, 1994]. Unfortunately most of the

procedures 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 wall (e.g., qualify the different parts of a masonry structure or walls through the value of sonic velocities or wave forms, when sonic tests are applied).

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.

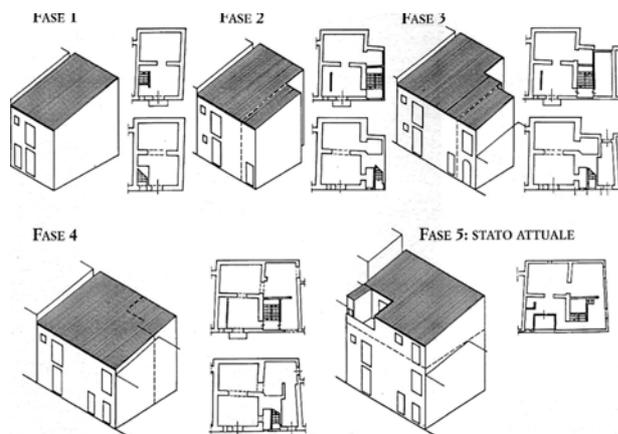


Fig. 18. Typical transformation of a building in Ortigia [Giuffrè, 1991].

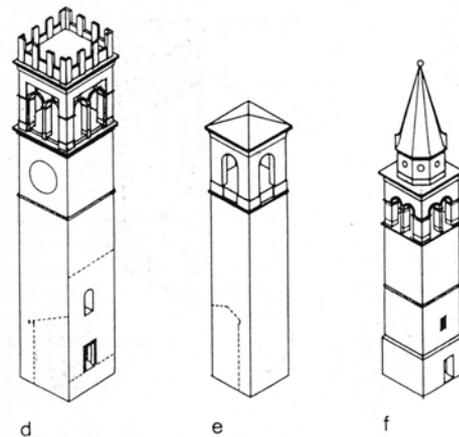


Fig. 19. Example of Bell-Towers in Friuli [Doglioni, 1994].

The geometrical survey, including a measure of the loss of verticality or horizontality in the load bearing elements and the type and distribution of cracks in the crack pattern is the first information to be collected; the type of cracks and their geometry can help understanding the causes of damage (Fig. 21). Furthermore the type of cracks and their direction help in interpreting even a mechanism of collapse (Fig. 22) [Doglioni, 1994], [Avorio, 1999], [Borri, 1999].

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 and deformations of the structure as a function of time have to be collected.

A monitoring system can be installed on the structure in order to follow this evolution [Bartoli, 1992], [Macchi, 1992], [Binda, 1994], [Bartoli, 1995], [Bartoli, 1996]; in some cases the knowledge of the crack pattern evolution can help preventing the collapse of the structure.

This type of survey is frequently applied to important constructions, like bell towers (Pavia Towers [Macchi, 1992, 1993] and Pisa Tower [Macchi, 1993, 2000]) or cathedrals [Macchi, 2001] and the system may stay in place for years before a decision is taken for repair or strengthening. Fig. 23 shows the evolution in four years of some of the main cracks of the dome in S. Maria del Fiore in Florence (Fig. 23) [Chiarugi, 1993].

The state of stress of a structure cannot be described experimentally like the state of deformation; nevertheless, indirect methods based on the stress relaxation, like the flat jack test or the shove test can be useful to measure locally the state of stress or the deformability of the masonry, providing not only a numerical value locally valid, but also the possibility of

calibrating the mathematical models through experimental measurements [Rossi, 1997]. Nevertheless, the use of flat jacks for stone masonries made with irregular stones is not so easy, due to the difficulty of finding regular joints; therefore the cut for the insertion of the jack is done directly in the stones courses [Gelmi, 1992]. It must also be remembered that the use of the flat jack test in the case of multiple leaf walls gives results concerning only the outer leaves.

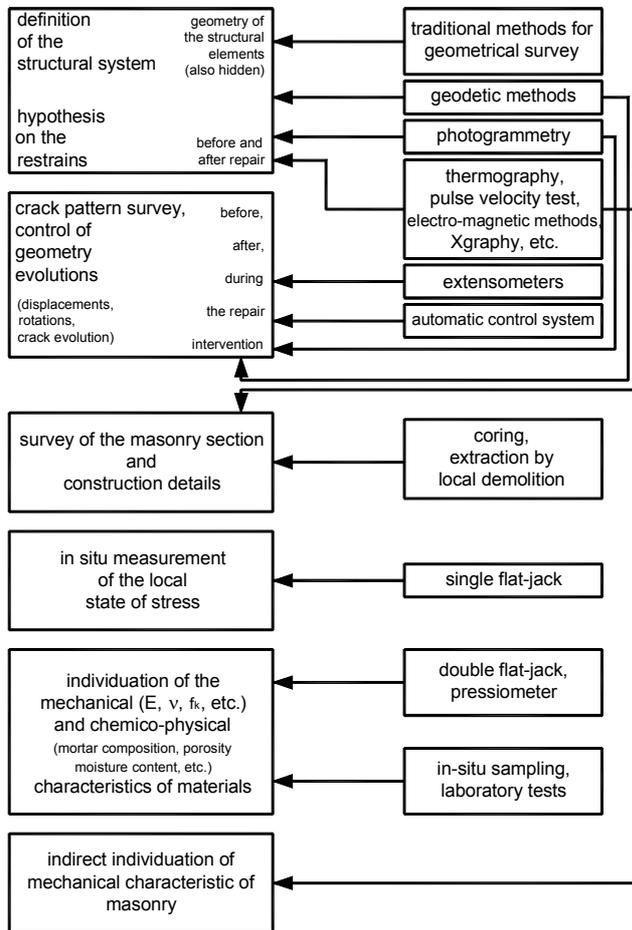


Fig. 20. Information required and correspondent investigation techniques [Binda, 2001].

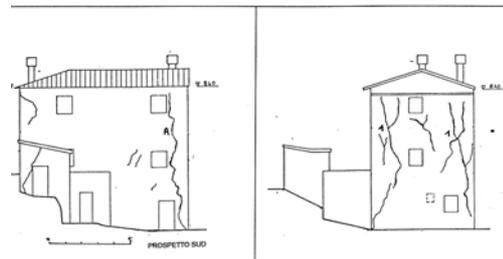
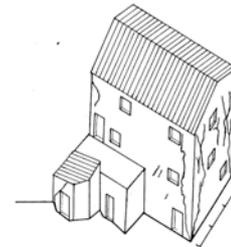


Fig. 21. Crack pattern survey of a Montesanto building damaged by the earthquake [Binda, 2001].

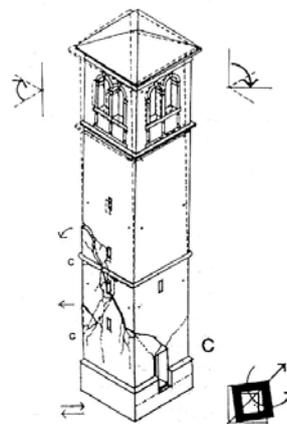


Fig. 22. Crack pattern of a bell-tower and interpretation of the damage mechanism [Doglioni, 1994].

Obviously the results obtained in situ have to be controlled with laboratory tests carried out on materials sampled from the construction. Non-destructive evaluation techniques can be applied for several purposes: (i) detection of hidden structural elements , like floor structures, arches and piers, (ii) qualification of masonry and masonry materials, (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 rise, (vi) detection of surface decay. Correlation of the ND data to mechanical or physical properties is very difficult in the case of masonry and particularly of stone masonry, mainly due to its non-homogeneity. Dynamic and estensimetric monitoring, infrared thermography, radar investigation, ultrasonic and sonic pulse velocity are the most sophisticated methods applied to in-situ investigation, but other simpler like the rebound hammer, the probe penetration, the drilling or pull-out tests, etc. have been tried with some success on brick masonry, but their results have a very poor reliability when they are applied to rubble masonries.

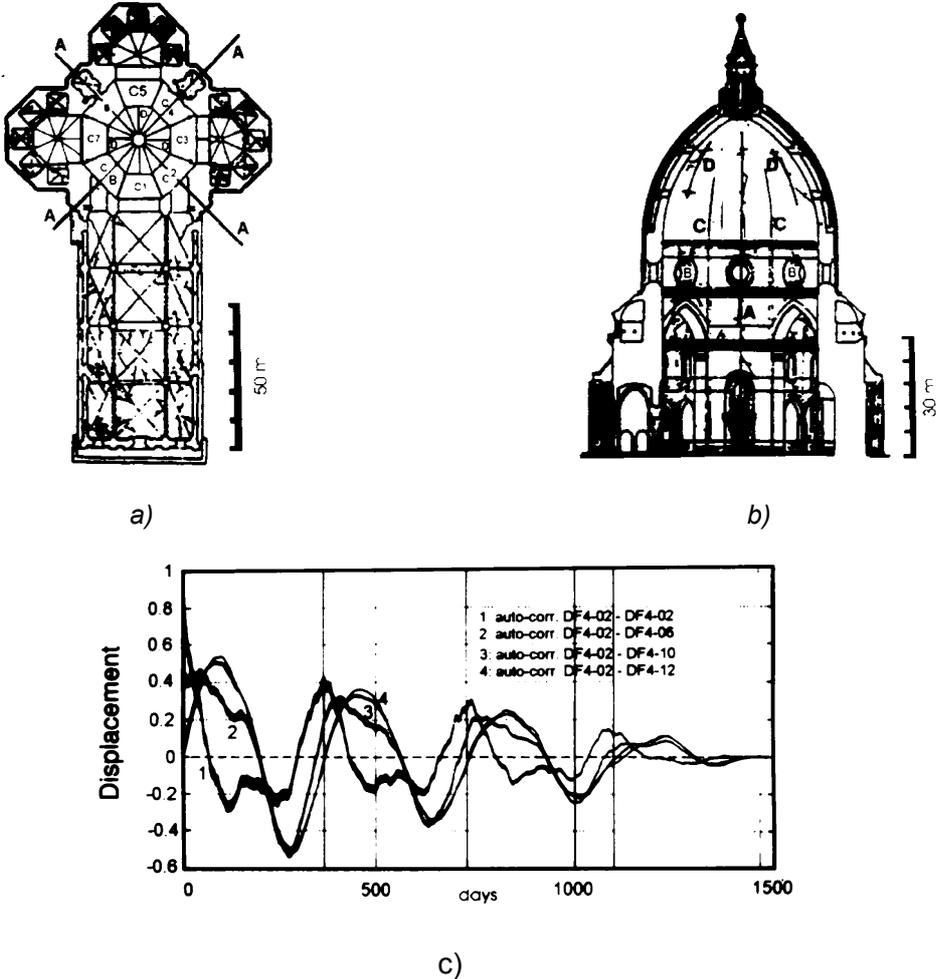


Fig. 23. S. Maria del Fiore, Florence, Italy: a) position of the major cracks denominated A,B,C,D on the dome; plan; b) position of the major cracks denominated A,B,C,D on the dome [Chiarugi, 1993]; c) curves displacement-time obtained as a correlation of the monitored [Bartoli, 1992].

#### 4.1 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.

#### 4.2 Investigation and diagnosis as multi-level application.

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.

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 (Fig. 24).



Fig. 24. The village of Campi (Umbria - Italy).

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* (Fig. 25), 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 particular 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.



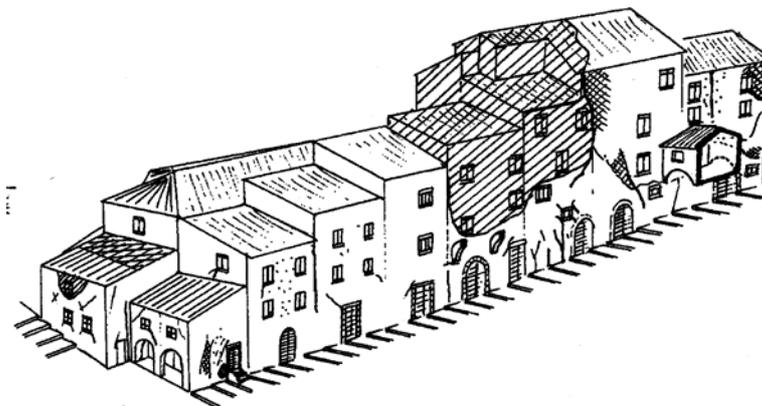
*Fig. 25. S. Vitale Church at Ravenna (Italy).*

#### **4.3 Approach for repair and prevention in seismic area.**

A proposed multilevel approach [Binda, 1999], [Penazzi, 2000] is at present applied to a population of masonry buildings in Umbria (central Italy). and Liguria (northern Italy).

This approach tackles the problem of the knowledge of existing buildings 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 of these two regions, both with reference to country houses and to buildings in historical centres. Nevertheless, some characteristics are very typical of constructions in other regions of Italy, so that some results could be extrapolated. 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 (Fig. 26), connect them to the construction and material characteristics and suggest more appropriate retrofitting techniques [Lagomarsino, 1998, 1999].



*Fig. 26. Failure of a row of buildings in a Umbria village after the earthquake [Penazzi, 2000].*

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.

#### **4.4 Investigation procedures.**

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 [Binda, 2000].

As said in Sec., the flow chart of Fig. 20 [Binda, 2001] schematically represents the needs to be fulfilled by the experimental investigation together with the techniques adequate to these needs.

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 [Riva, 1994, 1997], [Di Tomaso, 1993].

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. 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.

##### **4.4.1 Geometrical and crack pattern survey.**

A preliminary in-situ 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. 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 (Figs. 27, 28). 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.

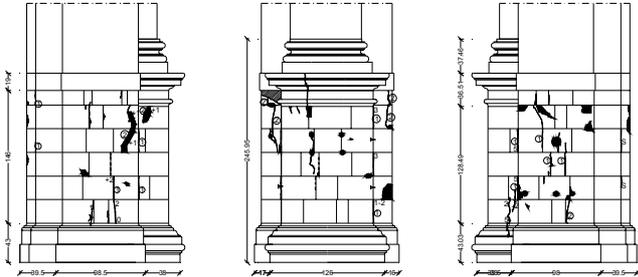


Fig. 27. Typical crack pattern of a pillar under heavy compressive stresses.

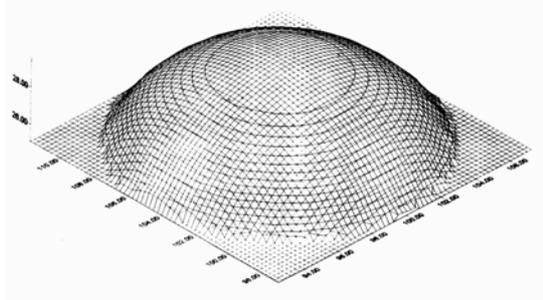


Fig. 28. Photogrammetric survey of the intrados of the dome of St. Vitale at Ravenna - Italy [Binda, 1995].

Often the geometrical details of the structure need a special refined survey if they are complex or of difficult interpretation with the usual procedures [Astori, 1992], [Binda, 1995]. Photogrammetry can be of great help in defining the geometry of vaults and arches. Fig. 28 shows the photogrammetric survey [Binda, 1995] of the dome of St. Vitale in Ravenna (V cent. A.D.). 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.

**4.4.2 Minor destructive techniques for masonry.**

To understand the morphology of a masonry wall it is important a direct inspection. Sometimes it could be performed by removing few bricks or stones and surveying photographically and drawing the section of the wall (Fig. 29).

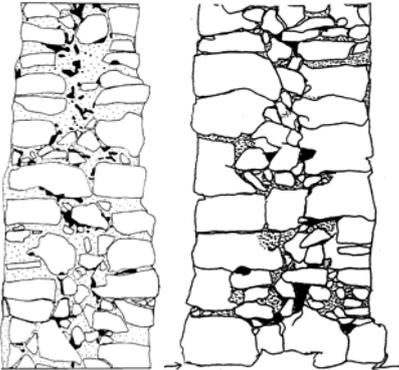


Fig. 29. Survey of stonework sections [Binda, 1999], [Penazzi, 2000].

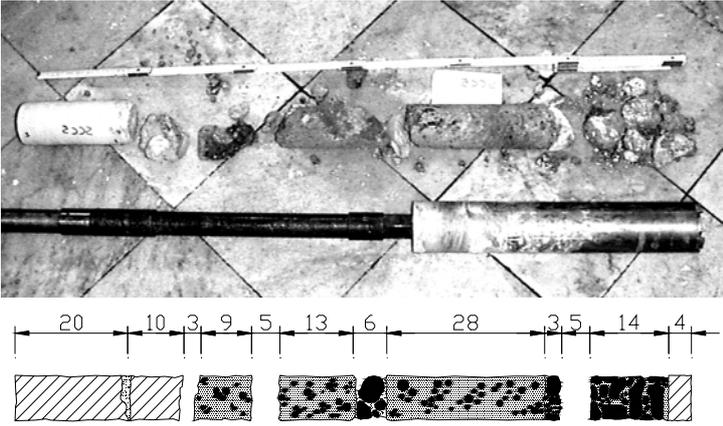


Fig. 30. Drilled core and reconstruction.

In some cases it is possible to core boreholes in the most representative points of the walls. Coring should be done with a rotary driller using a diamond cutting edge. This operation is rather simple but has limits. The drilled core is usually very decohesioned (Fig.

30) so it is almost impossible to detect the quality of the original materials. Inside the boreholes additional investigations can be made by the use of borescopy. A small camera may be inserted into the borehole allowing a detailed study of its surface and try a reconstruction of the wall section.

Nevertheless the interpretation of the results is a very difficult operation, sometimes hopeless; it should be remembered that boroscopy can only give a general stratigraphy of the section.

Other slightly destructive tests can be used to give more information on site about masonry and masonry components. They can be considered as surface or small penetration techniques, which can be used for a preliminary investigation. Some of them can be remembered here:

1. the Schmidt hammer rebound test to detect the quality of mortar joints, has some limits in the present equipment which was set up to be used on cement mortar and can have too high energy for a lime mortar;

the penetration tests proposed in different ways, like probes, drillers, etc. correlate the depth of penetration to the material mechanical properties. Unfortunately a correlation is impossible to the real strength of ancient mortars; so the calibration of these tests is very difficult.

2. Furthermore the depth of penetration is low, so only the repointing mortars are usually detected;
3. the pull-out tests can only be used on bricks and stones, very rarely on mortar joints, unless they are not very thick.

Other surface tests have been proposed so far; all of them can be useful to have an overall rough idea of the masonry condition on the surface and they can be meaningful for a preliminary survey of the structure, but they only give the possibility of qualitative interpretation of masonry condition. All these tests can be really useful for the quality control of new masonry [TC 127-MS, 1998].

#### **4.4.3 Flat jack test.**

The method was originally applied to determine the in-situ stress level of the masonry. The firsts applications of this technique on some historical monuments [Rossi, 1982, 1985, 1987], clearly showed its great potential. The test is carried out by introducing a thin flat-jack into the mortar layer, in masonry with regular and thin joints. The test is only slightly destructive [Binda, 1999].

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 [ASTM, 1991]. A thin flat-jack is placed inside the cut and the pressure is gradually increased to obtain the distance measured before the cut. 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. The pressure of the hydraulic system driving the displacement equal to those read before the slot is executed is measured (Fig. 31), [ASTM, 1991]

The test can also be used to determine the deformability characteristics of a masonry (Fig. 32, 33) [Ronca, 1997], [Binda, 1999], [Bartoli, 2000]. A second cut is made, parallel to the first one and a second jack is inserted. 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 tests is carried out on an undisturbed sample of large area.

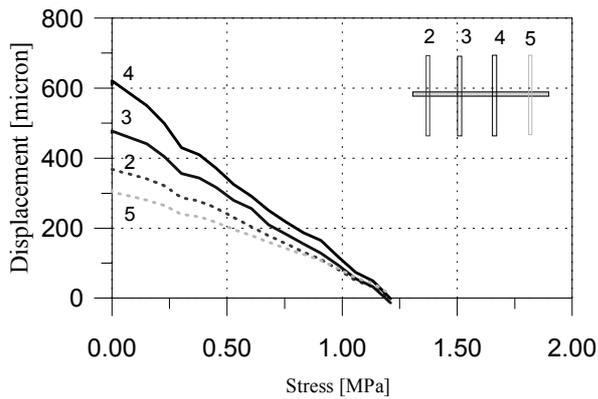


Fig. 31. Single flat-jack tests carried out at the Monza Tower [Binda, 1999].

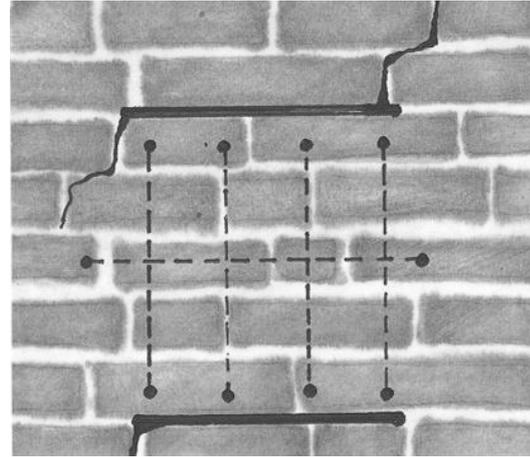


Fig. 32. Double flat-jack test.

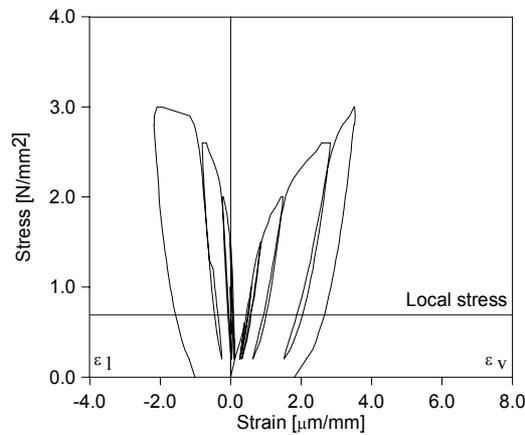


Fig. 33. Double flat-jack test on West side of the Monza Tower [Binda, 1999].

#### 4.4.4 Laboratory tests.

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.

*Sampling of bricks, stones and mortars:* the method of sampling depends on the characteristics of the materials in situ. Some simple principles have to be applied:

1. sampling must be carried out respecting the existing building;
2. the quantity of sampled material must be consistent with the scope and the requirements of the test procedures;
3. if determination of the type and the extent of damage is involved, sampling must be carried out on different portions of the building in order to study all the types of degradation;

4. sampling has to be carried out dry in those portions of the building not subjected to the action of rain or by a previous repair, especially when mortar binder and aggregate characteristics are needed;
5. the number of samples should be quite high, in order to represent statistically the situation of the existing masonry.

*Tests on mortars:* at present there are no standardised tests to define the composition and the chemical-physical and mechanical characteristics of mortars sampled from an existing building. It is often very difficult to drill samples having the consistent dimensional tolerance needed to conduct mechanical tests; then the only useful information, which can be obtained concern the mortar composition and the state of decay. Chemical and mineralogical-petrographical 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) [Binda, 1988].

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 [Baronio, 1991]. The above mentioned tests allow the determination of the composition of the existing mortars and permit the reproduction of mortars and grouts for repairing the masonry.

A RILEM Committee ONM, which includes Italian delegates, as well, is working on the proposal of recommendation on methods of testing mortars.

*Tests on damaged and new bricks and stones:* when masonry is damaged by aggressive agents the decay is never uniform; if maintenance is needed and only some bricks or stones or decorations are affected by the damage, the best remedy is frequently the substitution of the most decayed elements. In this case, laboratory tests can give useful information for the choice of the appropriate material for substitution.

When substitution is not possible and/or the decay is very extensive, a surface treatment may be required; again laboratory tests are needed for the right choice of the treatment. The tests have to be carried out on both deteriorated existing bricks or stones, and on undamaged and new ones. The following tests are suggested: (i) mechanical compressive and indirect tensile (splitting) tests; (ii) physical tests to study the porosity of the material (volumetric mass, water absorption by total immersion, water absorption by capillary rise, initial rate of suction, X-ray diffraction, mercury porosimetry; (iii) chemical tests: tests for alkaline sulfate can be conducted on material samples taken at different depth of the masonry in order to detect the presence and quantity of these very aggressive salts; (iv) optical and mineralogical analysis; (v) durability tests: freeze/thaw and salt crystallisation tests are needed for new bricks and stones in order to determine their performance under aggressive agents.

The concern for standardising methodologies for laboratory testing on stone and brick conservation has been steadily growing since at least the 1970. In the 1977 born the Commissione NorMaL (Normativa Materiali Lapidei) finalised to define unified methods in the study of the stone decay and to verify the effectiveness of surface treatments. The Commission prepared several Documents and Recommendation to standardise the test procedures, sampling materials but also defined common lexicon and description of the damages.

In Italy several other researches are carrying out on the evaluation of superficial decay and treatments of stones and bricks [Rossi Doria, 1981], [Alessandrini, 1986], [Lazzarini, 1986], [Laurenzi Tabasso, 1989], [Baronio, 1993], [Rossi Manaresi, 1995], [Alessandrini, 1996].

#### 4.4.5 Non destructive techniques for masonry.

Many authors have mentioned the importance of evaluating existing masonry buildings by non-destructive investigation carried out in situ [Riva, 1994, 1997], [Di Tomaso, 1993], [Marchisio, 2000]. 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.

##### 4.4.5.1 Thermovision.

Thermovision is a NDT, which has been applied since several years to works of art and monumental buildings. 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 analysed are applied.

A camera sensitive to infrared radiation collects the thermal radiation. In fact each material emits energy (electromagnetic radiation) in this field of radiation; this radiation is characterised by a thermal conductivity, that is the capacity of the material itself of transmitting heat, and its own specific heat. The result is a thermographic image in a coloured or B/w scale. At each tone corresponds a temperature range. Usually the differences of temperatures are fraction of degree.

Thermovision can be very useful in diagnostic; in fact it is used to identify areas under renderings and plasters that can hide construction anomalies. It is particularly interesting for studies on frescoed walls [Ludwig, 1996], [Lenzi, 1997]. Other applications can be: (i) survey of cavities, (ii) detection of inclusions of different materials, (iii) detection of water and heating systems, (iv) moisture presence. In the presence of moisture, the camera will find the coldest surface areas, where there is continuous evaporation (Fig. 34).

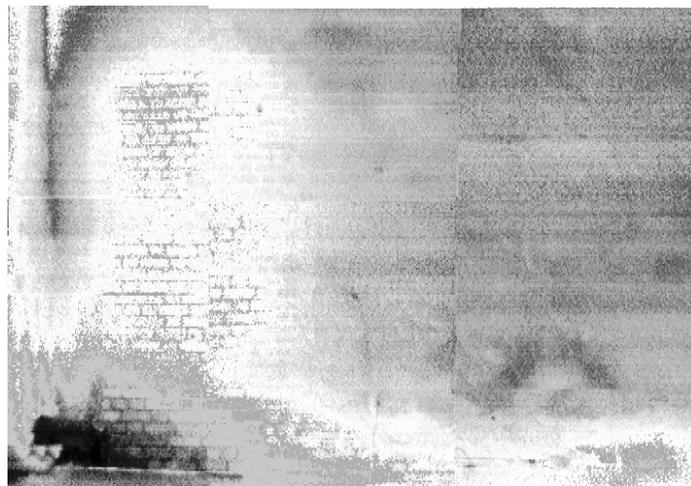


Fig. 34. Moisture detection by thermovision [Binda, 1998].

In the diagnosis of old masonries, thermovision allows the analysis of the more superficial leaves. It is necessary to point out that the penetration depth of this technique is limited, so it is unable to locate anomalies, which are hidden in the inner part of the masonry. The technique is often sensible to the boundary condition of the tests. Sometimes shapes are detect, caused by different local emissions and not by effective variations.

#### 4.4.5.2 Pulse sonic 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 electro-dynamics or pneumatic device (transmitter) and collected through a receiver, usually an accelerometer, which can be placed in various positions.

The elaboration of the data consists 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:

- to qualify masonry through the morphology of the wall section, to detect the presence of voids and flaws and to find crack and damage patterns [Binda, 1998], [Binda 2001];
- to control the effectiveness of repair by injection technique in others which can change the physical characteristics of materials [Abbaneo, 1996].

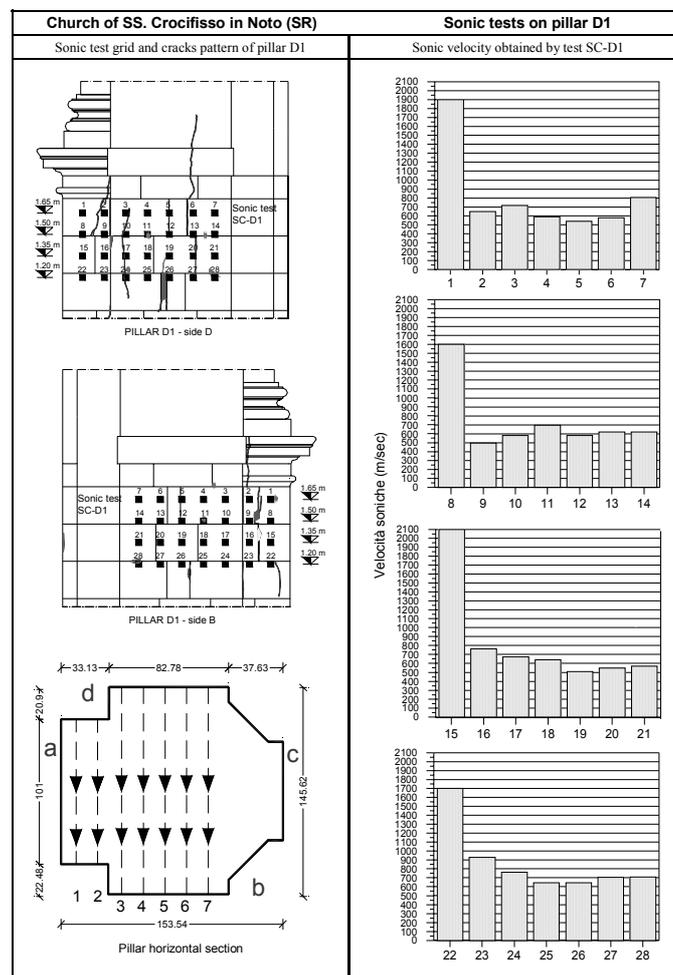


Fig. 35. Crocifisso Church at Noto (Italy): results of sonic tests applied to a pillar

The first applications of ultrasonic tests to the evaluation of masonry materials and structures have been carried out on long time ago in the sixties. Several efforts have been put in the tentative of interpretation of the data from sonic and ultrasonic tests [Riva, 1994, 1997], [Di Tomaso, 1993].

The limitation given by ultrasonic tests in the case of very inhomogeneous material made the sonic pulse velocity tests more appealing for masonry. Efforts have been made by

the authors to correlate the sonic parameter to the mechanical characteristics of the material, but this correlation seems difficult [Riva, 1994, 1997].

It is important to stress that the pulse sonic velocity is characteristic of each masonry typology and it is impossible to generalise the values. The tests, then, have to be calibrated for the different types of masonry directly on site.

Fig. 35 shows the results of sonic tests applied to a pillar of the Crocifisso Church at Noto (Sicily - Italy).

#### 4.4.5.3 Georadar.

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 [Bernabini, 1994], [Lenzi, 1997], [Binda, 1998, 1999], [Cardarelli, 2001]. In recent years, commercial radar systems like ground penetrating radar (GPR) or specifically developed radar systems have been applied to non-destructive testing of historical buildings. The great majority of these experiments has been conducted by executing 2D profiles with the system in the echo configuration (transmitter and receiver on the same side) and using frequencies normally in the 500 MHz – 1 GHz range.

When applied to masonry, the applications of radar procedures can be the following: (i) to locate the position of large voids and inclusions of different materials, like steel, wood, etc. (Fig. 36); (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 (Fig. 37).

Georadar seems to be a powerful tool to detect the presence of voids and structural irregularities, the presence of moisture and hopefully the presence of multiple-leaves in stone masonry.

The method is based on the propagation of short electromagnetic impulses, which are transmitted into the building material using a dipole antenna. Measuring the time range between the emission of the wave and the echo, and knowing the velocity of propagation in the media it would be possible to know the depth of the obstacle in the wall. In the real cases, the velocity is unknown because it changes from one material to the other or in the presence of voids. Furthermore the velocity is higher in dry walls, and lower in wet walls [Binda, 1998].

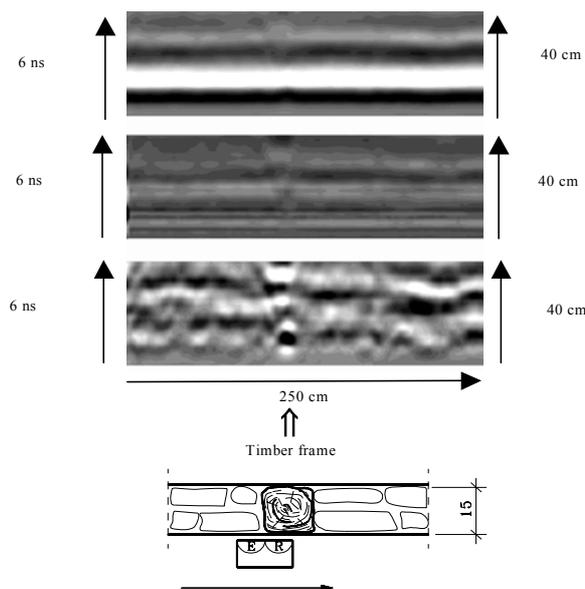


Fig. 36. Localisation of a wooden element in a frescoed wall [Binda, 1998].

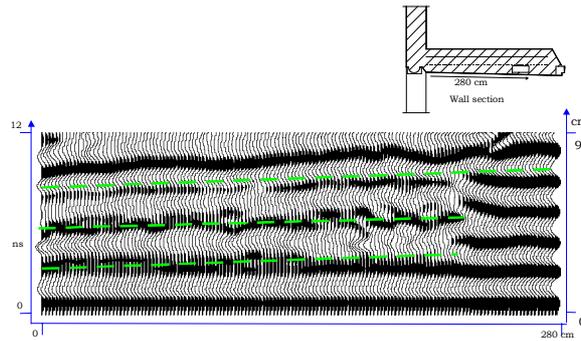


Fig. 37. Radargram of the wall section at the Malpaga Castle. The leaves positions and the presence of a void on the right side are recognisable [Binda, 1999].

Radar tests need always a preliminary calibration in order to verify if the emitted signal is enough powerful to detect the opposite side of the wall and the wave speed. This step allows to calibrate the relationship between the time and space scales. Some types of equipment give directly this transformation by setting up a value of the dielectric constant of the masonry. The value is an average of the characteristics of all the materials crossed by the wave. The choice of the antenna frequency must be made on a site basis. During the test it is important to control the radar potentialities in relation to the frequency used.

One of the limits of the technique is the low readability of the results. In fact usually radar data are clearly readable only by experts. It is important to show results, as radargrams and graphics, which are significant to operators like architects and engineers.

#### 4.4.5.4 Radar and sonic tomography.

Among the ND applications the tomographic technique is quite attractive for the high resolution that can be obtained [Valle, 1997, 1998], [Cardarelli, 1999, 2001], [Zanzi, 2001, 2002]. Tomography, developed in medicine and in several other fields, seems to be a valuable tool to give two or and 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.

Tomographic imaging is a computational technique, which utilises an iterative method for processing a large quantity of data. Standard pulse velocity data or radar data [Zanzi, 1995], [Valle, 1998, 1998], [Saisi, 2001] could be used to reconstruct a velocity distribution within a solid material, thus providing an "image" of the masonry interior. The testing technique gives a map of the velocity distribution on a plane section of the structure under investigation (Fig. 38). The result of the tomographic inversion is a map of a property of the materials. In case of travel time tomography (TT) the measured quantity is the traveltime of the signal and the map is the distribution of the propagation velocity within the object. In case of amplitude tomography (AT) the measured quantity is the amplitude of the signal and the map is related to the distribution of the absorption coefficient.

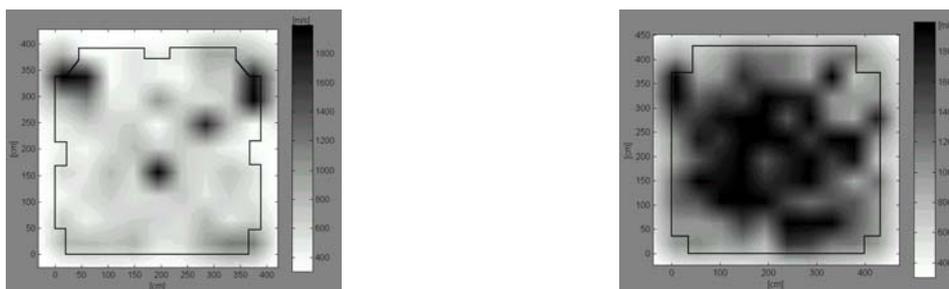


Fig. 38. Pulse Sonic Tomography of a S. Nicolò l'Arena pillar at difefrent heigth [Saisi, 2001].

**4.5 Structure control by 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 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 [Macchi, 1993, 2000], to the Dome of the Florence Cathedral in Italy [Bartoli, 1992], [Chiarugi, 1993], [Bartoli, 1995, 1996]) or cathedrals [Binda, 1995, 2000] (Fig. 39) [Macchi, 2001] and the system may stay in place for years before a decision can be taken for repair or strengthening.

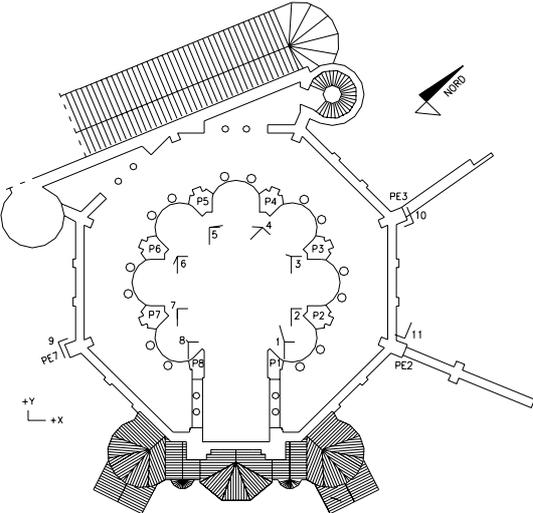


Fig. 39. S. Vitale Church at Ravenna. Total variation of the out of plumb (November 1998-November 1999) [Binda, 2000].

Very simple monitoring systems can be also applied to some of the most important cracks in masonry walls, where the opening of the cracks along the time can be measured by removable extensometers with high resolution (Fig. 40). 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 environmental excitation sources could be the wind, the traffic or the bell ringing in the particular case of towers [Chiarugi, 1993], [Binda, 2000], [Beconcini, 2001].

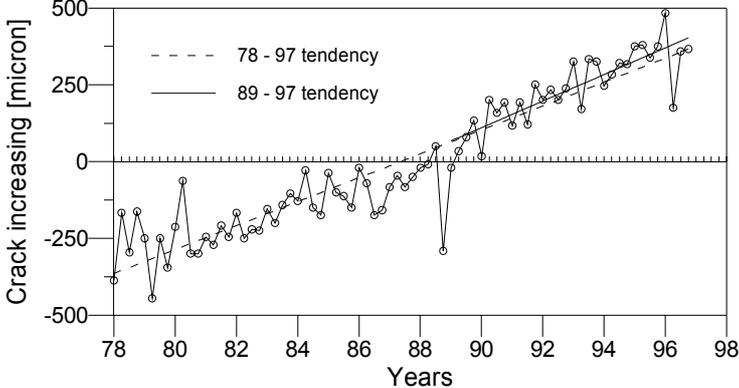


Fig. 40. Crack monitoring made with a removable extensometer at the Monza Tower [Binda, 1998].

The principal objective of the dynamic tests is to control the behaviour 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 [Modena, 1992], [Chiarugi, 1993], [Macchi, 1993], [Binda, 2000], [Beconcini, 2001], [Modena, 2001]. These tests are very important to detect eventual anomalies in the diagnosis phase and to calibrate efficient analytic models (FEM). In this way it is possible to verify the effectiveness of the computational methods used in the analysis and control of the structure. The availability of an efficient numerical model allows for checking and predicting the structure behaviour to dynamic actions like, for example, strong winds effects and seismic actions.

#### **4.6 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 [Riva, 1994, 1997], [Rossi, 1997], [Saisi, 2001].

Some questions arise when the designer or responsible of the building repair and maintenance receives the results of destructive and no destructive tests.

When radar and sonic tests are carried out on the same wall or pillar, do the result harmonises, so that he 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, 2000].

### **5. MATHEMATICAL MODELS FOR THE STRUCTURAL ANALYSIS**

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 [Macchi, 1992]. 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, 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. Nevertheless, when the structure is a complex one, only linear elastic models are easily usable. Non-linear models or limit state design models are difficult to apply, also because the needed constitutive laws for the material are seldom available. The designer, who is in charge of the selection between the available techniques and procedures, and between the technically and economically most correct

method to define the state of preservation or damage of the structure, faces several difficulties.

**5.1 Elaboration and use of the survey results, choice of the analytical model to calculate the carrying capacity of the structure**

The structure geometry, the crack pattern survey and monitoring and the local slightly destructive and non destructive tests results should be concretely used to choose the appropriate analytical model for the detection of the safety of the structure and its load carrying capacity. Having all these information it will be clear that a choice has to be made among all the available models, taking into account the typology of the structure and of the masonry.

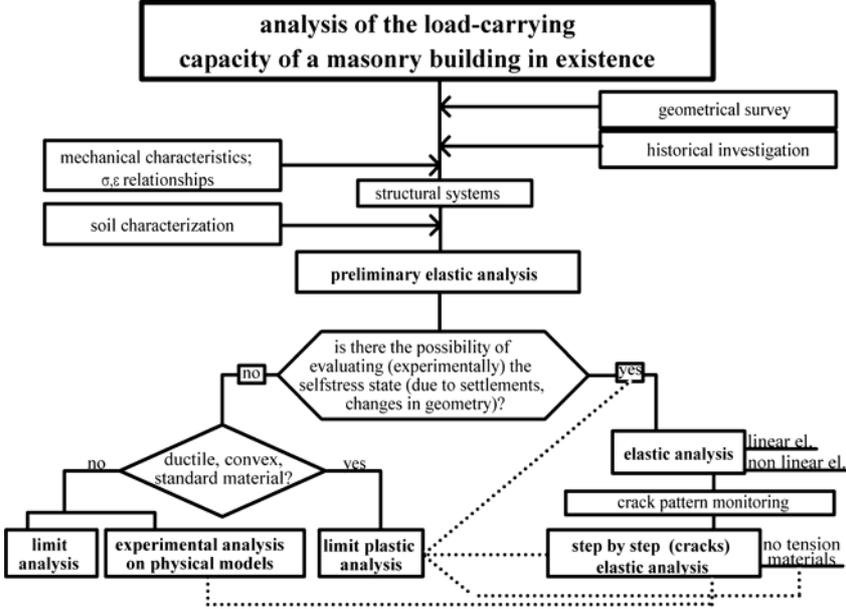


Fig. 41. Phases and alternatives of numerical analysis for an existing structure [Binda, 1983, 1994]

This previous description of available techniques and procedures illustrates the difficulty faced by the designer who must select the technically and economically correct method to define the state of preservation or damage of the structure to be restored. When the results of the survey are previously available, then conclusions from the experimental and numerical investigation will bring to the diagnosis the real state of the structure. Fig. 41 shows the possibilities available to a designer when dealing with the structural analysis, from the elastic to the inelastic or limit analysis, provided that one can obtain enough information from the experimental survey; nevertheless, appropriate constitutive laws for the masonry materials are still not well developed [Binda, 1994].

The aim is to assess the load carrying capacity of existing buildings, and hence to determine a safety factor which can assure to the building an acceptable performance given the function assigned to the building. This function is frequently different from the original one for which the building was designed, due to a modification of the loads (e.g. stone- or brick masonry bridges under the modern traffic) or of the destination (e.g. a convent transformed into a University building). Therefore a safety coefficient should be calculated taking into account also the possible seismic loads. It is now clear that the safety coefficient of these structures cannot be calculated as easily as in the case of contemporary concrete, steel or even masonry structures due to all the uncertainty concerning the material, the construction technology of the walls, the geometry, etc.

Then the following questions have to be answered: once the experimental data have been collected on-site and in laboratory, which mathematical models should be adopted to

calculate the state of stress and strain in a masonry structure? Knowing that the structure was not designed according to the contemporary analytical methods but to simple geometrical or static rules, would it be better to assume simple engineering models or sophisticated models? Do we really know the constitutive laws of any type of masonry, since they differ so much from one to another (e.g. solid brick and stone masonry from multiple leaf walls, rubble walls)? Which is the role played by the elastic model and how reliable is it for an existing old masonry structure? How reliable are non elastic or limit analysis models implemented for other materials? How can we take into account the long term behaviour of a masonry structure and the synergetic effect of loads and environment?

Modeling of a masonry structure is a difficult task [Bartoli, 1997], since masonry does not apparently respect any hypothesis assumed for other materials (isotropy, elastic behaviour, homogeneity).

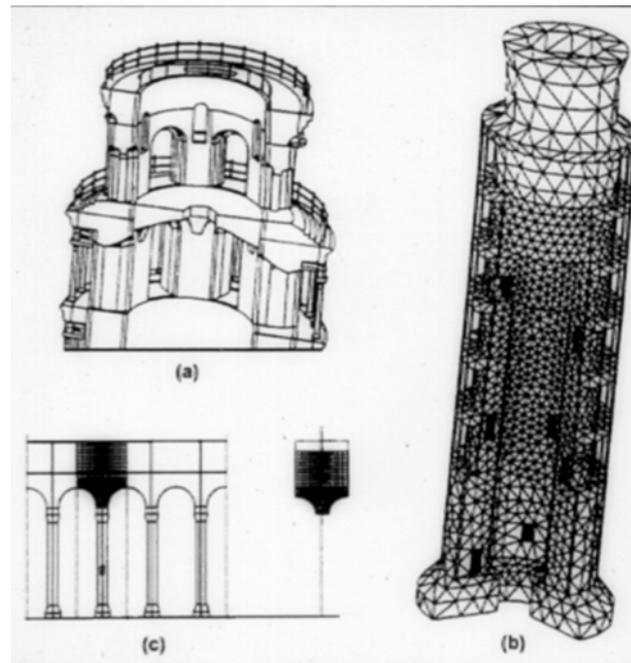


Fig. 42. Modeling of the Pisa Tower [Macchi, 1993]

In the past decades several attempts have been done to assume models used for other materials, but the results were very poor. Elastic models can give an indication on the mechanical behaviour of the structure but they cannot follow the behaviour beyond the elastic range. Nonlinear models can be very heavy to handle and costly. In the case of badly damaged and complicated structures several elastic computations can be carried out; this methodology was followed for the leaning tower of Pisa (Fig. 42) under different hypotheses of collaboration of the various parts of a structure [Macchi, 1993]. Sometimes the calculation has to be based on engineering considerations and the structure subdivided into substructures before a FE analysis is carried out [Ronca, 1992].

In other cases, like for domes and vaults, understanding the deformations occurred during the construction can be interesting; this is the case of the Dome of S. Vitale in Ravenna, built with light clay tubes, for which Mirabella Roberti et al. [Mirabella, 1995] have assumed an axisymmetric FE model and simulates the increment of stress and strain during the construction.

Fig. 41 [Binda, 1983] tries to give some guidelines. Since then, new proposals were made on computer methods adapting them to the lack of continuity, anisotropy, non-homogeneity, non elastic behaviour and large displacements, typical features of the masonry structures. Distinct Element Models (DEM) and its new formulation as Discontinuous

Deformation Analysis (DDA) both used for rock mechanics problems which in some cases are very similar to the problems of masonry have now been proposed together with the more traditional FEM and BEM. [Mirabella, 2001] analyses the Nuraghe mechanical behaviour by DEM. The method is able to model the peculiar typology of the masonry, built by large stone blocks, without mortar.

Nevertheless, most of the models have still to be calibrated with experimental parameters and research still needs to be done even if a great improvement has been reached in the last five or six years.

In the last two decades the historic building process has been reconsidering. The inadequacy of the structural engineering codes applied to the historic buildings has been demonstrated.

In the Italian contest, this experience was peculiarly aimed by problems of intervention and hazard mitigation of the historic centres.

## 5.2 Modelling of stone masonries in seismic areas

The sequence of earthquakes in 1997 which stroke the Umbria and Marche regions show the necessity to develop new structural models for the old masonry buildings and code requirements for the intervention [Borri, 1999], [D'Ayala, 1999], [Magenes, 2000], [Valluzzi, 2001]. The code requirements were oriented previously to a concept of seismic adequacy of the structures [Ministry of Public Works, 1996]. The damages showed after the Umbria and Marche regions interest also “adequate” buildings.

The seismic code moves from theories of “adequacy” to “improvement”, which implicates more compatible are respectable interventions on the historic building patrimony [Corsanego, 1992, 1993], [Gavarini, 1994].

Experimental testing and damage modality of real structure show as the masonry walls are less resistant for actions perpendicular to their medium plane rather than parallel to this plane [Regione Autonoma Friuli-Venezia Giulia, 1977]. The stiffness in the first case is sensibly less of the other. A general good behaviour of a masonry building, than, should involve all the walls to resist to the action parallel to them, avoiding inflections and overturnings.

This philosophy considers the building with a box behaviour. The walls should be connected, by stiff joints to the floor, even stiff and resistant in their plane. The floor should be able to distribute the seismic actions between the walls in function of their stiffness.

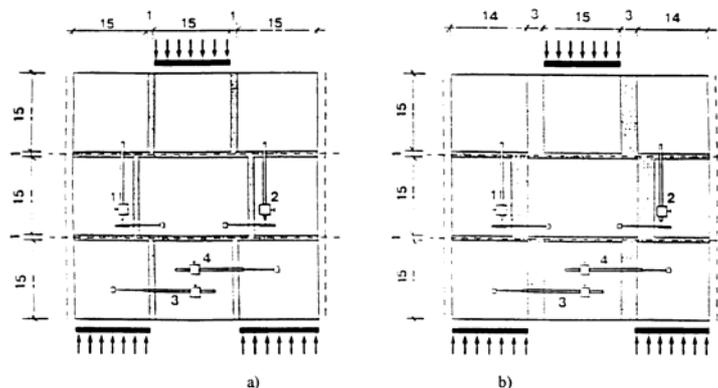


Fig. 43. Specimens subjected to shear tests: a) with blocks offset, b) without blocks offset [Binda, 1993].

The intervention procedures based on this philosophy generally involve the demolition of vaults or wooden floors, the building of a tie beam and a new concrete floor.

A different level of structural control was proposed by Liberatore and Spera [Pesenti, 2001], considering a deformable wooden floor.

The actions which more compromise the stability of stonework masonry are the horizontal ones.

To this respect some works [Binda, 1993; 1994] have to be mentioned aimed to study, on an experimental and a numerical basis, the stress distribution between the different layers of a three leaf masonry panel. During the research, tests have been performed to study the shear behaviour of the interface between the different layers and to interpret it numerically. Simplified models were built to analyse the mechanical behaviour at a local level, trying to reproduce the type of bonds between the layers (with and without offset between the stone blocks) which are shown in Fig. 43.

The samples (Fig. 43) were then subjected to shear tests obtaining interesting results (Fig. 44). Samples built with the weaker stone (limestone) showed a higher interface shear strength, probably because of the high porosity which gave a better adhesion with mortar. In the cases of panels having a block offset, the vertical joint turned out to be stiffer than in absence of the offset, and the load was mainly transferred through the stone block. Looking at the crack pattern after failure it appeared that in the specimens made with the weaker stone, the upper block collapsed well before the mortar joint failed. This was probably due to the excessive strength of the mortar used, compared to the stone's one.

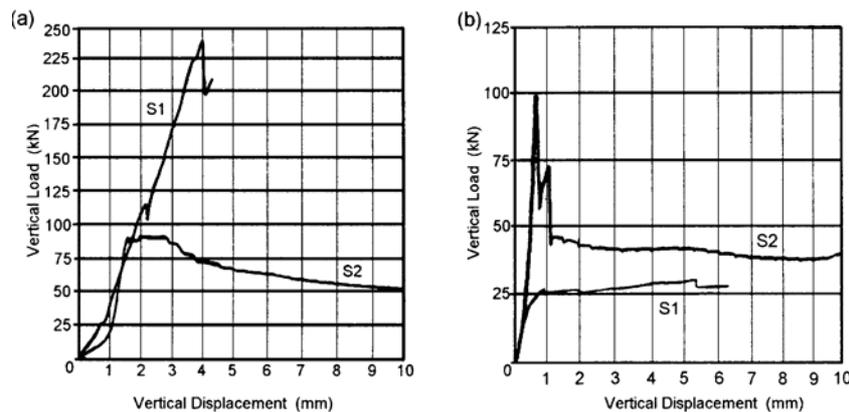


Fig. 44. Results obtained from shear tests on specimens a) with blocks offset, b) without blocks offset: S1 sandstone, S2 limestone [Binda, 1993].

Chiostrini et al. [Chiostrini, 1994] carried out compression tests and compression-shear tests in situ on masonry walls characterised by very different textures, sometimes made with bricks together with stones. They obtained results in terms of elastic parameters and strength values under different loading conditions. In the case of the compression tests more regular walls showed higher strength values whereas in the case of shear tests no particular effects were observed due to the different textures.

Beolchini and Grillo [Beolchini, 1992] carried out in situ vertical and diagonal compression tests on stonework panels isolated from the walls and made by two leafs of rounded limestone blocks connected with a very poor mortar. They observed that the texture has a great influence on both values of the stress and of the strain at failure in compression and that the ultimate shear stress value corresponds to the onset of a significant diagonal crack.

Bettio et al. [Bettio, 1993] carried out a series of in situ tests on stonework walls in the area of Trento including compression tests on big panels and flat jack tests. This technique,

initially adopted in rock mechanics, is now largely used also for studying the mechanical characteristics and the state of stress of brickwork masonry. As far as the stonework masonry is concerned, the research of Bettio et al. [Bettio, 1993] is basically innovative and can be looked at as a sort of calibration of this technique with respect to its application to stonework masonry. The results obtained, in terms of stress-strain relationship, can well be compared with those given by compression tests on big panels and allow to consider this technique particularly promising.

In the years 1998/2000 the Ministry of Researches and Technologies (MURST) financed a research on these topics [Pesenti, 2001].

When some stones cannot fulfill the local equilibrium because of an insufficient mutual contact, a local mechanism can rise which suddenly evolves in a total collapse of the structure. This possibility is generally easier when the wall is subjected to non-vertical actions; in fact, with respect to the vertical ones, equilibrium had to be assured since the beginning of construction otherwise, without a sufficient horizontal constraint between the stones, the wall could have never been built [Giuffrè, 1991], [Carocci, 2001].

Some answers to the above problems can be looked for in the literature on stonework masonry, although not much has been done up to now.

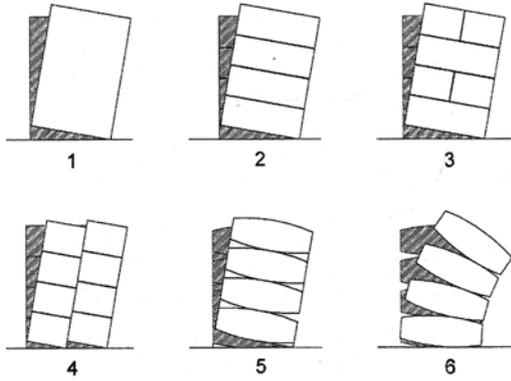


Fig. 45. Failure mechanism of a wall [Carocci, 2001].

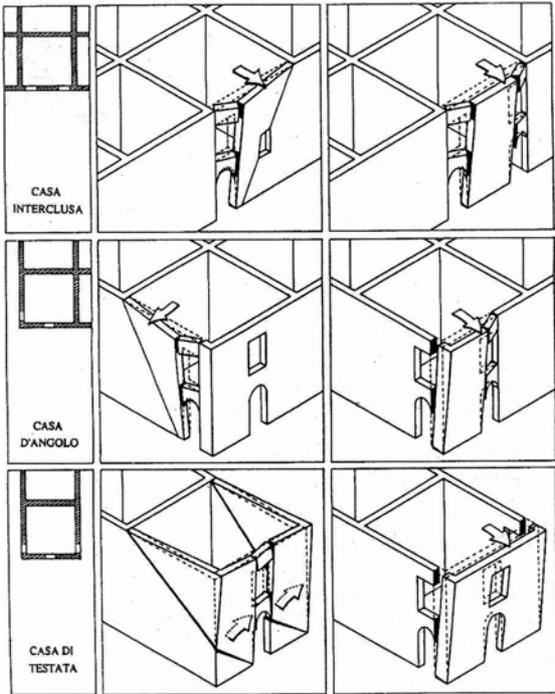


Fig. 46. Failure mechanism of a building inside a row [Giuffrè, 1993].

Giuffrè [Giuffrè, 1991, 1993] proposes to first evaluate by visual inspection some aspects of the mechanical behaviour of a stone wall, looking for the presence of particular characteristics which allows to consider the wall as built according to "the rule of art". There is in fact a complex of rules, which were precisely formulated in the treatises of the XIX century, although they were already known previously, which deal with the lay out of the stones and are aimed to guarantee a good response of the wall toward the external actions. A masonry wall built according to these rules should behave monolithically, and reach the collapse for instance under seismic loads through the formation of cylindrical springs, whereas the portions of the wall which do not crack keep a behaviour like "rigid body" [Giuffrè, 1991, 1993] (Fig. 45, 46). Such a mechanism of collapse has the advantage to be predictable and possibly prevented through suitable interventions (Fig. 46).

The control algorithms are, then, based on equilibrium relationships of the structural elements or portions (Figs. 47 and 48). It is a limit state control.

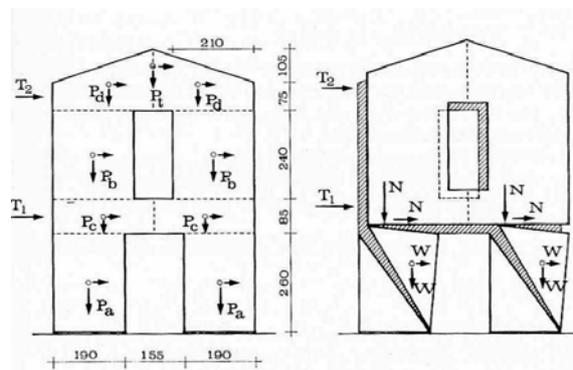


Fig. 47. Macroelements of a facade [Giuffrè, 1991, 1993].

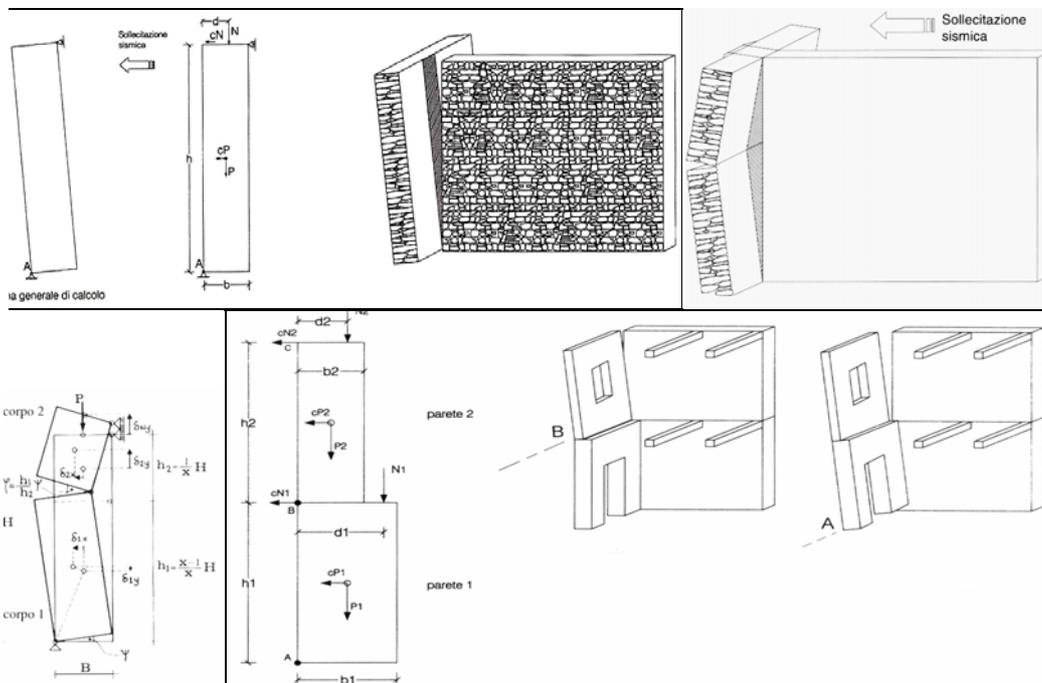


Fig. 48. Macroelements of a facade [Giuffrè, 1991, 1993].

Starting from these researches, several other studied were carried out, recognising even more complex mechanism and interpretative algorithms (e.g. Italian Conference of Seismic Engineering, 1999 and 2001).

An interesting research (financed by the Marche region) carried out by Lagomarsino et al. [Lagomarsino, 1997, 1998, 1999] has developed a software for the control of the seismic vulnerability of the Churches and to verify the effectiveness of the intervention (<http://www.diseg.unige.it/ricerca/gruppi/vulnerabilita/Marche/Marche.htm>).

The software analyses the main church elements (Fig. 49) and their collapse mechanisms for the seismic actions (Fig. 50).

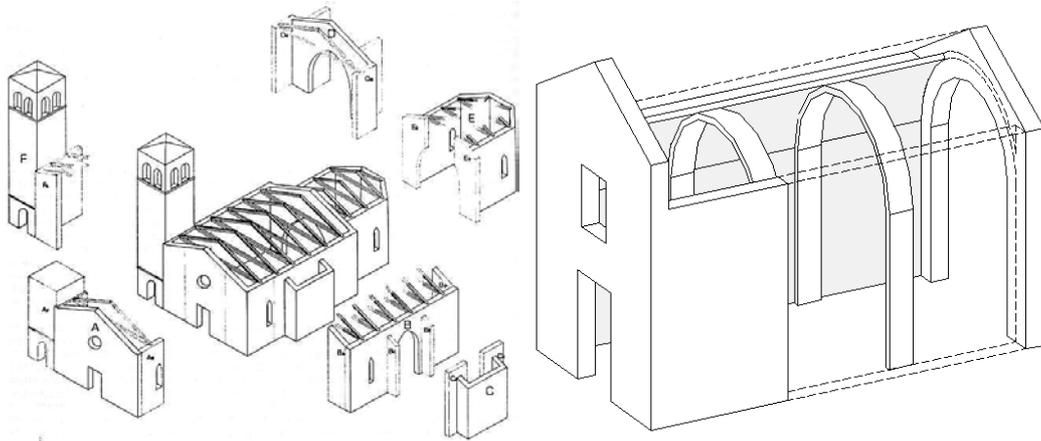


Fig. 49. Church macroelements [Doglioni, 1994] and [Lagomarsino, 1997,1998,1999].

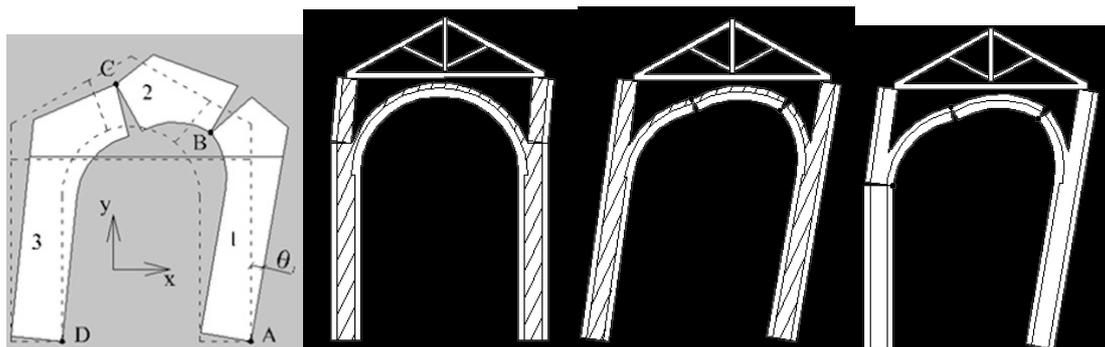


Fig. 50. Failure mechanism of a Triumph Arch macroelements and [Lagomarsino, 1997,1998,1999].

A similar project carried out by Bernardini and others [Bernardini, 2000] and financed by GNDT developed a software for the evaluation of the vulnerability of buildings. The seismic behaviour principles are common, starting from the recognition of wall portions and considering their overturning (Figs. 51 and 52). Even in this case the repair effect are easily computed.

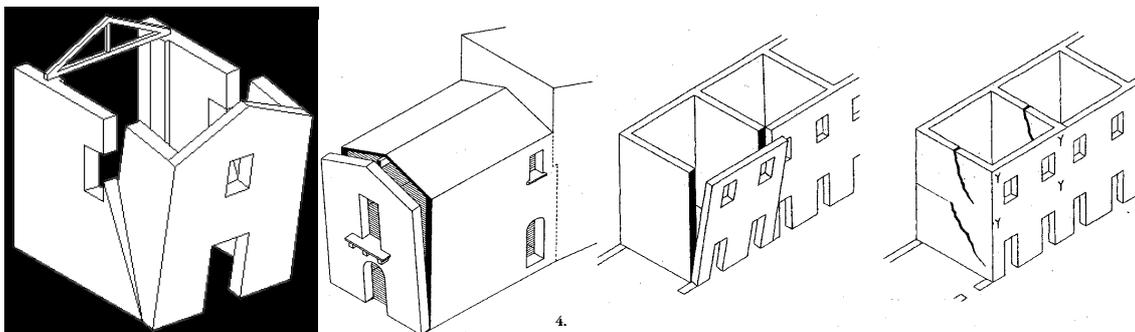


Fig. 51. Failure mechanism of the facade, in a church [Lagomarsino, 1997,1998,1999] and in common row buildings [Giuffrè, 1991, 1993].

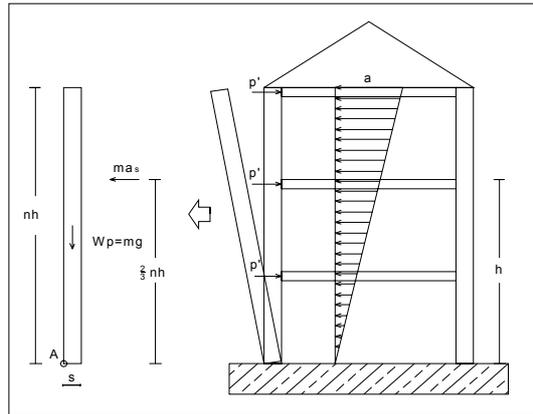


Fig. 52. Overturning mechanism of a facade [Bernardini, 2000]

Fig. 53. Information requested by the software Chiese, developed by Lagomarsino and others [Lagomarsino, 1997, 1998, 1999]

In both the previous cases, analysing the limit state of the structures, the requested information (Fig. 52 and 53) deals mainly to geometric characteristics of the buildings, presence of ties and to qualitative evaluation about the monolithicity and the texture of the masonry. The specific weight and the resistance of the material if unknown are suggested in the help menu taking into account the Italian seismic code [Ministry of Public Works 1996] (L.219/81 art. 10 " Istruzioni relative alla normativa tecnica per la riparazione e il rafforzamento degli edifici in muratura danneggiati dal sisma). They are powerful tools but with a easy and user friendly interface.

### 5.3 A peculiar behaviour of masonry: long term damage due to heavy deadloads

Apparent viscosity beyond the elastic range for masonry under heavy compressive loads has been extensively investigated only recently [Lenczner, 1965], [Lenczner, 1969], [Shrive, 1981], [Binda, 1991], [Binda, 1992], [Shrive, 1997]. The experimental research carried out on the materials of the Civic Tower of Pavia, suddenly collapsed in 1989 [Binda, 1992], stimulated subsequent studies. In fact, the results achieved the identification of the time-dependent behaviour of the material as the cause of the collapse.

The experimental data available up to now, only developed by L. Binda and others in Italy, concern both long term creep tests and accelerate tests under subsequent step of constant load tests [Binda, 1993]. Constant load step tests turned out to be a suitable procedure for analysing creep behaviour [Anzani, 1999, 2000, 2001], having the advantage of being carried out more easily than long term tests. Primary, secondary and tertiary creep phases, in fact, were clearly detected also during this type of tests (Fig. 54).

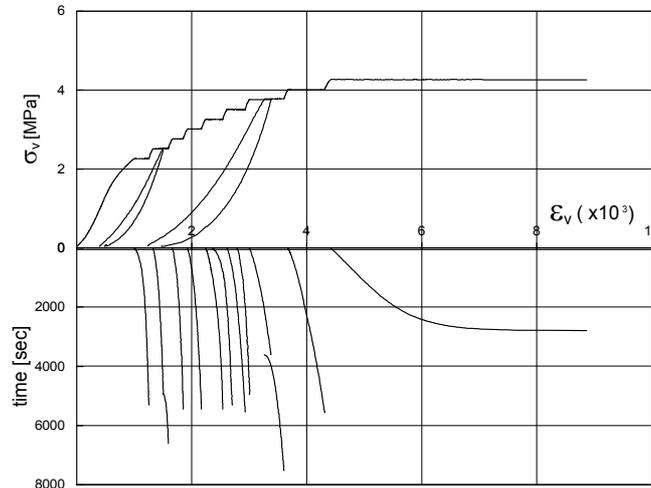


Fig. 54. Result of a test with subsequent load steps carried out on a prism (200x200x500) mm belonging to the crypt of the Cathedral of Monza (Italy) [Anzani, 1999]

The time dependent behaviour of the masonry is a phenomenon of great interest, especially with respect to ancient buildings such as towers or massive masonry structures, which have been bearing constant heavy loads for centuries. It has been shown that the damage of the masonry under the action of persistent loads can evolve in a relatively long time until collapse; this under lower stress values than those corresponding to the nominal material strength, obtained by a standard monotonic compression test. The phenomenon can start at 45-50% of the strength value.

The available experimental data collected up to now tend to show an evident increase of lateral deformations developed in time. This dilation phenomenon can lead to collapse due to crack propagation.

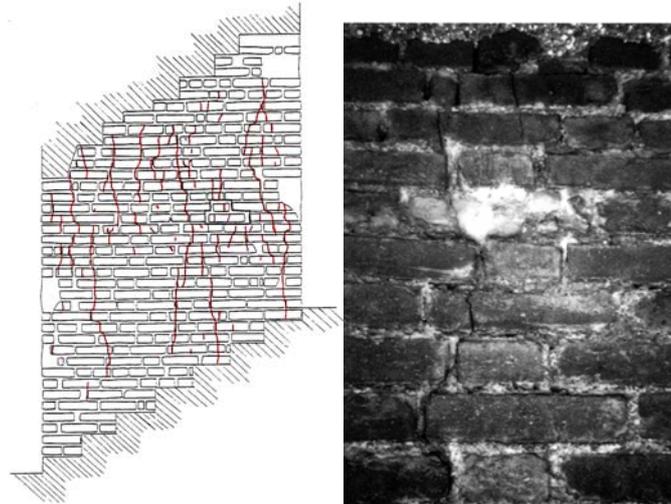
From an experimental point of view the following aspects have been particularly highlighted:

- the material dilation under severe compressive stresses with high values of the horizontal strain developing before failure;
- the development of creep strains depending on the stress level, with secondary creep showing even at the 40% of the estimated material peak stress and possibility that tertiary creep shows at about the 70%;
- a slow crack propagation and failure developing in a relatively long time. This aspect suggests that the evolution of vertical cracks, which might appear on the external walls of a building should be carefully analysed. In fact, the possibility of continuous damage with the consequence of a future sudden collapse cannot be a priori ruled out;
- the combination of cyclic actions with the effect of a heavy dead load turns out to be a particularly critical situation, which is able to induce material damage.

The collapse of Tower of Pavia, was not an isolated case; through the literature, other similar cases appear, some of which are famous like that of the Bell Tower of San Marco in

Venice, the Bell Tower of St. Magdalena in Goch (Germany) or, more recently, that of the Cathedral of Noto (Italy).

Several case histories show that significant crack patterns, clearly due to vertical compression (dead load), often appear on the walls of ancient towers or on church pillars, indicating structural damage (Fig. 55). Tower, as well as particularly slender or heavily loaded elements like columns, pillars, etc., turn out to be overloaded by heavy persistent compressive stresses. Moreover, significant concentrations of stress can take place in some portions of the material due to non-uniform stress distributions.



*Fig. 55. Thin cracks at the entrance wall of the Tower of Monza [Binda, 1996, 1998]*

Sometimes around major cracks there may be a net of vertical flaws, cutting the bricks, or stones, and proceeding through the mortar joints (Fig. 55). Unfortunately, they these are in most cases considered superficial and not particularly worthy of care.

The effects can also be coupled with synergetic stresses caused by cyclic wind action and temperature variation induced stresses. Additional minor shocks, like storms, low intensity earthquakes, etc. may contribute to increase the damage. Of course the study of these phenomena is fundamental from the point of view of safeguarding of the architectural heritage and of assessing the safety of ancient masonry structures. The traditional stress-strain analysis is not prepared to take into account this particular aspect, which has been only recently revealed crucial to ancient buildings.



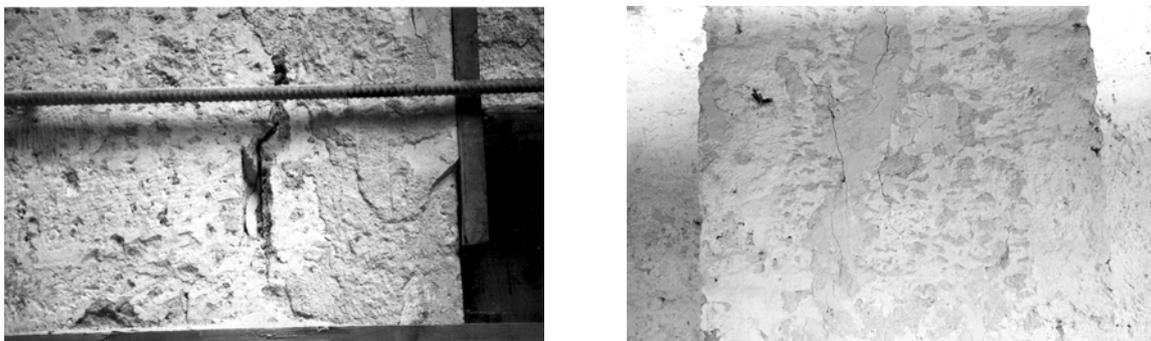
*Fig. 56: The Cathedral of Noto after the collapse [Binda, 1999]*

After the partial sudden collapse of the Noto Cathedral on March 13, 1996 fortunately without any casualty (Fig. 56), the Noto community astonished by the loss of one of its most famous buildings, decided to rebuilt the Cathedral as it was. The Cathedral was damaged as many other buildings in Noto and in other cities of Sicily by the earthquake which occurred on December 13, 1990. For a certain time it was closed to the public until some provisional structures were built while waiting for the necessary repairs. The Cathedral was built in different phases from 1764 over a previous smaller church opened in 1703 to the public and demolished in 1769/70 as the new Cathedral was growing. The Cathedral was opened in 1776. In 1780 the dome collapsed and the church was reopened in 1818. In 1848 the dome collapsed again under an earthquake and then it was rebuilt and the church reopened again in 1862 but the dome was not completely finished until 1872. In 1950 the Cathedral was restored with new renderings and paintings and the timber roof substituted with a concrete structure; the work continued until 1959.

The losses caused by the collapse were the following: 4 piers of the right part of the central nave and one of the 4 piers sustaining the main dome and the transept, the complete roof and vault of the central nave, three quarter of the drum and dome with the lantern, the roof and vault of the right part of the transept and part of the small domes of the right nave.

The collapse certainly developed starting from one or more of the right piers of the central nave. As in the case of the ones sustaining the dome, these piers consisted of a multiple leaf structure in which an external leaf made with regular stones confined a central core in masonry made with calcareous stones of different dimension and shape. The external leaf, except for the base of the piers, was made with regularly cut blocks from the "local travertine" also called calcareous tuff. The compressive strength of this material is very low and can vary from 4 to 6 or more N/mm<sup>2</sup>.

The mortar appeared to be very weak made with lime and a high fraction of very small calcareous aggregates.

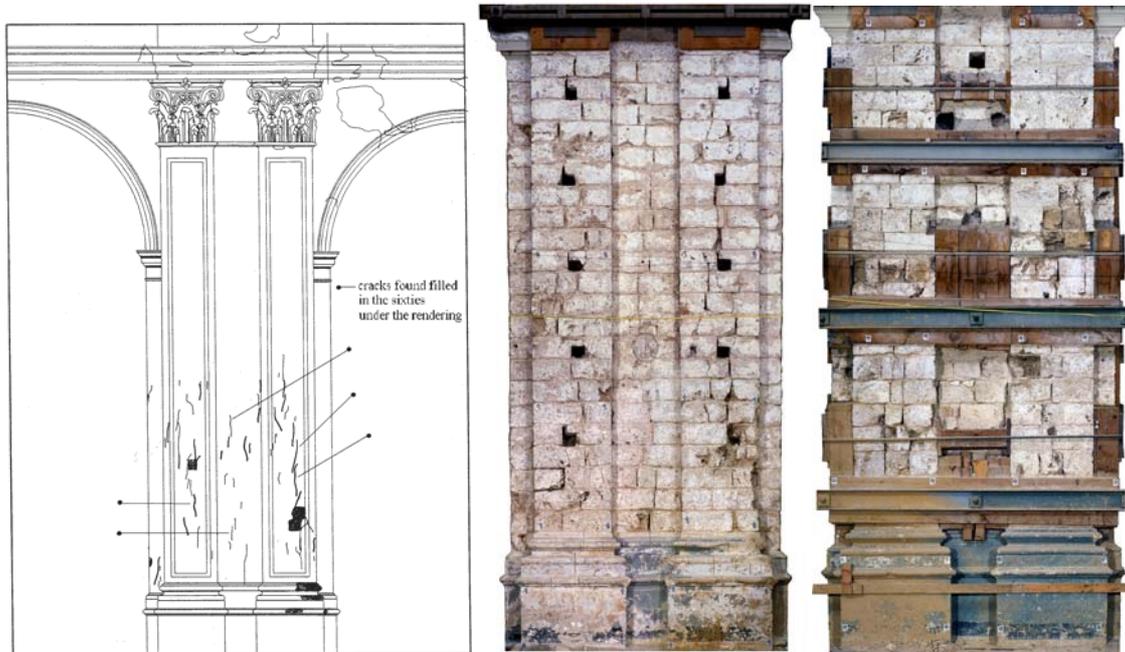


*Fig. 57. Large crack found in a pillar of the Cathedral of Noto and example of a crack filled with gypsum mortar in the sixties [Binda, 2001]*

The left piers, still covered with a thick plaster, seemed to have minor damages, but the doubt that the damage could be inside and perhaps even present before the 1990 earthquake, suggested to subject these piers to a more accurate survey. As the plaster made in the sixties was removed a series of vertical large cracks were found, some of which filled with the gypsum mortar used for the plaster (Fig. 57 and 58). This finding proves that the damage was already present in the sixties. The pre-existing crack pattern was clearly a damage from compressive stresses, hence a long range damage dating probably even long time before the rendering. This damage would probably progress even without the earthquake, which only accelerated the collapse.

After the collapse of the Noto Cathedral careful investigations are being carried out on similar churches, all built approximately in the same period after the 1693 earthquake which

struck the oriental part of Sicily [Binda, 2001]. In fact the ancient Noto, which was destroyed by that earthquake, was abandoned and rebuilt on a hill near the sea in no more than 50 years. The same was for other cities in the eastern part of Sicily; one of them is Ispica situated in the most southern part of the island. In the following, two cases of damage similar to the Noto Cathedral are analysed; they were discovered by removing the plaster from the pillars of the central nave in both cases. This was suggested by the experience carried out on the Cathedral of Noto where the existing damage of the pillars was hidden by the plaster. In fact as in that case, the presence of diffused thin cracks had never been considered as dangerous before the investigation [Binda, 2001].



*Fig. 58. Crack pattern survey of a pillar of the Noto before and after the removal of the plaster.*



*Fig. 58. The appearance of a crack on the plaster and underneath it [Binda, 2001]*

## 6. CONCLUSIONS

An attempt was made to report on the State of the Art of research carried out in Italy in the field of Cultural Heritage restoration and conservation. This report is not intended to be exhaustive on all the multidisciplinary subjects involved in Conservation. Nevertheless it is possible to find lines of research which still need strong work and collaboration among different researchers and countries involved for their historic patrimony. Some needs for research in the future, compared to the work already performed can be listed as follows:

- a great deal of research has been carried out on stone and brick damages due to the environment (air pollution, frost-defrost action and salt crystallization), particularly in the field of chemistry, physics and petrography. Most of the best research was carried out also in the frame of EC Contracts. Nevertheless the main efforts were made to understand the behaviour and durability of surface treatments on the single units (stones and bricks). Only few research has been dealing with the durability and effectiveness of treatments on the masonry as a composite. In this direction more effort has to be made;
- the on site investigation procedures have been applied before testing their effectiveness and particularly the possible application to masonry problems. A great deal of research is still necessary for the interpretation of the NDT results and for their correlation with the masonry characteristics. Since no test can give alone the requested information also the complementarity of the different tests (thermovision, georadar, flat-jack, etc.) has also to be studied for the definition of the necessary physical and mechanical parameters of masonry;
- the possibility of using NDTs in the detection of the effectiveness of some repair techniques (e.g. grout injections, re-pointing, etc.) is also a matter of future research;
- the static and dynamic monitoring systems applied to different classes of structures and damage situations, need great implementation;
- the calibration of appropriate mathematical models according to the masonry and building classification needs certainly great efforts in the future;
- the choice of appropriate repair and improvement techniques and materials has to be investigated;
- the study of the behaviour and compatibility of new modern materials and techniques with the original materials is important before extensive applications are carried out.

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