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ASSESSMENT OF HISTORICAL MASONRY BUILDINGS: RESEARCH ON APPROPRIATE NON-DESTRUCTIVE DIAGNOSTIC TECHNIQUES

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Dedicated to

Anna, Silvio,

Bianca and Mario

Abstract

This study focuses on the complexity characterising the design process in the conservation field. The historical architecture consists of complex systems of materials, elements which generate religious, social and political values. Its preservation does not only realize the protection of a historical memory, but guarantees the immanence of an aesthetical value; this value has been turned into shape and substance by using materials and imagination. Innovative technical solutions have been developed to support the conservation of the buildings of the past, but the complicated nature of the issue does not allow for unique solution that can be suitable for the different problems affecting the historical buildings.

The study is organised following a specific methodology: the relationships between theoretical models and empirical experiences is used to outlined the influence of the theory in the practical applications of its principles and the way the praxis can affect the theory.

Following the criteria coming from the existing technical specifications, a solution to establish a compromise between conservative and safety requirements cannot be found. By studying the last experiences in the application of innovative techniques, the research proposes new guidelines to support the conservation design. This was the aim of implementing an investigation methodology for the choice of appropriate interventions.

Summary

Introduction

Premise:

The contraposition between the substantial aspects of the predominant visual culture influenced the debate concerning the safeguard of the architectural heritage. The role of the historical centre in the contemporary city has been widely studied and published in several treatises, but the defence of the material authenticity of the historical buildings has always been a problematic component of the discussion. First of all the complexity of the problem has often been reduced to the preservation of the documental value of the historical buildings (above all buildings with artistic values). Other aspects, such as "living" or life quality, are usually not taken into account and the final design privileges visual/superficial aspects. According to Paolo Torsello, one of the well known Italian theoreticians of architectural restoration, culture must be intended as knowledge that produces other knowledge, induces thinking and arouses doubts.

Since the appearance, in the second half of the XVIII century, of the A. G. Baumgarten's treatise on the *Aesthetica,* the issue of the perception of the beauty has influenced the interpretation of the work of arts. This kind of influence has deeply affected the conservative approach towards historical buildings and compromised the correct preservation of the instances typical at the architectural heritage. In the praxis of conservation, the designer is forced to take decisions: choices can drive to strategic solutions, able to combine different demands (conservative, historic, documental, etc.), or to failure, if one instance (usually the aesthetic) prevaricates the others.

Considering the role of the historical centres for the life quality, outlined by experts like L. Benevolo or M. Cacciari, the importance of their protection cannot be limited to visual perception, but must be extended to the use of the buildings and the technologies which ensured their existence. According to Ernesto de Martino (anthropologist), *living* is connected to ritual manners. The origins of living, in the Western culture, are the cathedral, the bell-tower, the home, the fireplace: living is organized following the rituals of certain behaviours which, time by time, produced an artificial habitat.

The design for the preservation of aesthetical, material, and functional characteristics of historical buildings requires a balance between *venustas*, *firmitas* and *utilitas*. This is a complex problem that offers more than one solution and needs specific research for the definition of the strategies which can address the designer to its complete comprehension.

This study focuses on the complexity characterising the design process in the conservation field. The historical architecture consists of complex systems of materials, elements which generate religious, social and political values[1]. Its preservation does not only realize the protection of a historical memory, but guarantees the immanence of an aesthetical value; this value has been turned into shape and substance by using material and imagination. Innovative technical solutions have been developed to support the conservation of the buildings of the past, but the complicated nature of the issue does not allow an unique solution that can be suitable for the different problems which affect the historical buildings.

Development of contents:

According to the cultural materialist, the development of technical aptitudes needs a connection between “the hand and the head” [2]. The design activity itself, according to a diffused opinion, must develop a sort of connection between sketch, drawing, model, on-site reality and back to the drawing. The study is organised following a path: the relationships between theoretical basics and empirical experiences is used to outlined the influence of the theory in the practical applications of its principles and the way the praxis can affect the theory.

Taking into account some significant examples coming from the area of the so called “technical craftsmanship”, this study considers new innovative approaches to the questions connected to building restoration. The assessment of ancient buildings, strongly recommended through national and international regulations, represents a step connected to the design process. Anyway, it is a fundamental step that combines different demands: knowledge, above all, deepening of the hidden characteristics of the building and interpretation of its state of conservation and its properties.

1 Giovanni Carbonara, Trattato di restauro architettonico, UTET, Torino, 2007 (Carbonara, 2007)
2 Richard Sennett, L’uomo Artigiano, Feltrinelli, Milano, 2009 (Sennett, 2009)

The concept of "loss" is the initial subject of the research. By considering the decay processes of ancient buildings which drive to the loss of such a patrimony, the study takes into account the results obtained in the field of the conservation theory. The conservation design follows rules that have been set during their empirical application: restoration, as a discipline, has received considerable supports from the practical and technical experience. Following the study of many examples, it is clear that the conservation design, if based on a wrong or limited knowledge, can sometime be the cause of the loss of the above mentioned aesthetic/historic/material values built in the architectural heritage.

The research is divided into different parts, according to these steps:

- A short review of the main approaches concerning the restoration praxis and the relationship between restoration design and knowledge;
- A study in depth of the relationships between the conservation theory and the recent regulations for the protection of the historical buildings in seismic areas;
- An original approach to the issue of the nowadays living: the role of the historical centers in the life quality; the strategic preservation of the structural characteristics of the ancient buildings for the conservation of the resource;
- A methodological approach to the on-site and laboratory investigation;
- Innovative applications of non-destructive testing techniques.

The first part of the work presents the development of the main theoretical contributions in the field of conservation. The first chapter is a short review of the main theories concerning architectural restoration, also showing the evolution of the concept of restoration. This issue is discussed at the scale of the building and at the scale of the historic centres. The application of the theories to real cases (at building and urban scale) had several effects in the definition of the complexity that characterises the design for the architectural patrimony. Theoretical principles, from Boito's to Giovannoni's thinking, through the works of other protagonists of this field, had defined several indications for the same question: the rescue of the material culture. This e requirement that characterized the various areas of the conservation field: archaeological sites, ancient buildings maintaining their original functions, ancient buildings with new destinations; historical centres; improvement for historical buildings in seismic areas, etc. For each case, the problems are always related to the identification of a compromise between preservation and improvement /transformation of the existing; compatibility and reliability between historic and new structural elements. The variety of the building typologies and the large amount of different building technologies do not allow an univocal interpretation of the problem. The ambiguity, depending to the lack of knowledge concerning the architectural heritage, is origin of the complexity that characterizes the conservation field.

The second chapter takes into account, more in detail, the evolution of the debate concerning the protection of historical buildings in seismic areas. The problem of the safety of ancient buildings represents an open question in the field of conservation: the technical solutions set to reinforce and adapt the existing structures showed in time disastrous results. A critical discussion taking into account the main available regulations provided for the protection of the architectural patrimony in seismic area is presented, in order to remark some contradictions which increase the complexity of the problem. For the designers, regulations, national and international standards are the supports for the comprehension of the problem. In Italy, being a seismic country, a peculiar attention for the development of specific regulations promoting seismic mitigation was found since the pre-unitary period. After recent seismic events the evolution of the debate around the technical principles for historic buildings in seismic areas registered new important contributions: critics to the national standards provided new changings in the approach to the problem. Experts belonging to the research field (Laboratories and Universities) improved the methodology for studying the ancient buildings in order to obtain information related to their state of conservation. The identification of their vulnerability was based on a detailed study of different characteristics of the building structures and the so called "path to knowledge" became one of the central issue for supporting the quality of the project addressed to existing buildings.

The second part of the work is composed by a progressive deepening of the issue. The third chapter reports the state of the art of the main experimental methodologies for the study of the building structures. The original contribution of the work is related to the study of some testing techniques previously developed in different scientific areas, not only in restoration field, but afterwards modified or refined to be suitable for the protection of ancient buildings, according to the practice of the craft mastery. This a sort of state of the art of the main diffused techniques used to investigate the existing building heritage. The applied procedure generates the following path: from the theoretical model to its application in reality and back to the design supported by an informed judgment. The presentation of this practical activity takes into account some case-studies showing that calibrated experimentations provided valid indications for the final design.

The fourth chapter shows the results of the on-site and the laboratory research through applications of innovative testing techniques. Thermovision and sonic direct and indirect tests have been studied in order to improve their effectiveness when applied to existing buildings. These diagnostic techniques are widely used in conservation field, but their potentials can be largely improved. They are two aspects of the assessment methods which provide the knowledge requested for the comprehension of historical buildings. At the same time they are also real non-destructive tests, whose application maintains the integrity of the structures and respect the materials. For this reason thermovision and sonic tests are suitable for large applications even on wide surfaces. Both tests provide qualitative results and their interpretation can be sometimes ambiguous. Following the indications contained in international recommendations and standards, thermographic tests were applied to masonry and timber structures in order to support the study of the construction techniques. Sonic tests were applied by using different configurations and proposing an innovative interpretation of the results. According to pragmatism, this phase of the research was based on the synthesis of complex and simple actions. The experimental activity was carried out following cognitive dissonances: from doubts, through curiosity, to the final perceptive leap.

Considering even the thickness (the third dimension) of the architecture as an element carrying cultural and aesthetical contents, the research points out some complexities generated by the problems connected to the vulnerability of historical buildings. Following the criteria coming from technical specifications, a solution to establish a compromise between conservative and safety requirements was not found. By studying the last experiences in the application of innovative techniques, the research proposes new guidelines to support the conservation design. This is a sort of diagnostic approach to define the methodology of intervention for the final design.

The fifth chapter presents the connection between the detailed study and the methodology described in the second part of the work and their role for the definition of the conservation design mentioned in the first part. Through the examples of some significant projects, the relationship between past and present, material integrity and structural improvement, building scale and urban scale is investigated. The application of the diagnostic approach represents a chance for the conservation of the building heritage, according to the idea of sostainability.

Chapter 1. Cultural heritage and sustainability of the conservative strategy

1.1 The conservation design. Evolution of the concept of preservation for historical buildings

The history of building restoration shows that several differences can be found between theoretical postulates and the realization of the intervention on the existing buildings. As a result of a debate lasted centuries with relevant discussions, the theory of conservation of ancient building produced different interpretations. The practical consequences introduced by the design processes on ancient buildings can draw away the results from the original conservative purposes.

An idea representing the complexity of this subject is offered by Salvatore Boscarino[3]: he recognized the synthesis between history and technology in the restoration. In his opinion it produces a praxis based simultaneously on the historical/critical judgement and on the technical/scientific opinion. According to this point of view, humanistic studies cannot leave out from scientific-technical knowledge. The research of a valid methodology for restoration has always been looking for this balance between theoretical and technical knowledge.

The combination of theory and practice supports nowadays the idea that the design for conservation is an integrated activity, through the participation of several professional profiles, belonging to different disciplinary spheres. The conservation design is the product of experts interactions, through the comparison of their different skills. This methodology was developed by widening the collaboration between different scientific experts, in order to analyse the problematic afflicting the historical buildings. These collaborations take into account different aspects of the existing buildings in order to preserve its characteristics: identity, cultural values, historical evidences, material integrity and technological aspects. The contributions offered by the theory of conservation propose a series of procedures to arrive to the conservation design. In this sense, basic graphic printout for the conservation design includes these analysis: geometrical surveys, material surveys, decay surveys, crack pattern survey, together with historical studies of the building. These fundamental aspects can be studied in depth by the mean of diagnostic techniques. Since the recommendations contained in the historical treatises of architecture (from

[3] G. Carbonara, *Restauro e consolidamento: una riflessione sulle tecniche*, in "Restauro e consolidamento", a cura di A. Aveta, S. Casiello, F. La Regina, R. Picone, Mancosu editore, Roma 2005, pp. 23-26. (Carbonara, Restauro e consolidamento: una riflessione sulle tecniche, 2005)

Vitruvius to Palladio and Serlio, explorative demonstrations to test the quality of the materials were taken into account), the use of diagnostic techniques has been modified and refined by several experiences and are now considered as a specific phase of the design process. As mentioned by Caterina Giannattasio in her introduction to the international workshop *Ancient Scars and new Meanings*[4], multiple approaches to the problem of conservation, considering both the urban scale and the building scale, have a significant common point: the phase of the research of the basic knowledge. This is considered to be the starting point for a correct approach to the pre-existences, at architectural and urban scale.

1.1.1 A short review: from Restoration to Conservation

The modern idea of conservation is reported in recommendations and standards promoted by international authorities and organizations. After the declaration of Amsterdam (1975), which recalled assumptions contained in the previous Venice Charter (1964), the discipline of restoration has been defined as an integrated activity, addressed to the preservation of the integrity of the architectural works[5].

The Italian acts introduced in 1939 (Act no. 1089 and Act 1497) the roles for the preservation of the architectural heritage and the landscape[6]. After these basic rules new standards and recommendations were set up to improve the acts for “the protection of natural beauties” (Act. 1497) and the “protection of the goods having artistic or historic interest” (Act. 1089), in order to take into account new contributions derived by other authorities involved in this topic.

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[4] Giannattasio, C., *Antiche ferite e nuovi significati. Permanenze e trasformazioni nella città storica*, Proceedings of the International workshop on Architectural and Urban Restoration, September 14-15 2007, Cagliari (Italy), pp. 9-22, Gangemi Editore, Roma, 2009, ISBN 978-88-492-1613-4. (Giannattasio, 2009).

[5] *The Declaration of Amsterdam*, Charter promulgated by the Committee of Ministers of the Council of Europe, Congress on the European Architectural Heritage, 21-25 October 1975, Amsterdam. This document was widely based on the previously *International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter 1964)*, set up in the 2nd International Congress of Architects and Technicians of Historic Monuments, Venice, 1964, adopted by ICOMOS in 1965. (Europe, 1975)

[6] The first Act for the preservation of the historical and cultural heritage was introduced in Italy in 1939 with the *Legge 1° giugno 1939, n. 1089: Tutela delle cose d’interesse artistico o storico. (Gazzetta ufficiale 8 agosto 1939, n. 184)* (Legge 1° giugno 1939, 1939). The first organic act for the protection of the environment is (Legge 29 giugno 1939, 1939). *(Gazzetta ufficiale 14 ottobre 1939, n. 241)*. Both acts were coordinated later by the government decree issued under parliamentary delegation *Decreto Legislativo 14 dicembre 1974, n. 657* for the establishment of the Ministry for the Cultural Heritage and the Environment. (Decreto Legislativo 14 dicembre 1974, 1974)

International institutions like UNESCO and ICOMOS, since the second half of the last century, focused on the study of the criteria for restoration. Promoting cultural exchanges between different experiences in restoration field, the work of these organizations was useful to develop the concept of restoration. Also the subject of this discipline was gradually extended from the monuments to the diffused historical patrimony. The definition of "cultural heritage" was introduced with the intention to overcome the old distinction between monuments and the so called minor architecture. This passage showed an evolution of the sensibility concerning the preservation of historical artefacts.

Another important contribution reached by the interactions between experts, promoted by international organisms, was obtained with the extension of the protection from the single building to the entire historical centres. This step drove later to the preservation of the landscape, interpreted as the sum of natural and anthropomorphic traces.

This evolution of the concept of restoration, shortly described above, had a great influence for the definition of the differences between the terms restoration and conservation. The ambiguity in the word "restoration" gave rise to many definitions of the aims of the discipline. Since ancient times, the respect for the evidences of the antiquity has been documented. Chronicles from Latin writers of the Roman Empire described the first documented attempts to preserve the heritage of the past: usually important pieces of sculpture, as reminded by Manfredo Tafuri in his "Ricerca del Rinascimento"[7]. For either works of art or buildings, the praxis of restoration was not a codified procedure and its definition had always been influenced by cultural and political trends. The following points summarize the main interpretations of the problems connected to the preservation.

- Since XVIII century, the western thought had not elaborated a shared opinion on the restoration. Since the rediscovery of the lesson left by the past masters, during the Renascence period, several activities for the protection of the ancient building was documented. The

[7] Manfredo Tafuri, *Ricerca del Rinascimento. Principi, Città, Architetti*, Einaudi, Torino, 1992. (Tafuri, 1992)

archaeological areas in the papal Rome were object of first documented reintegration of monuments of the classic age[8].

- Before the unification of Italy, the different states in which the peninsula was divided experienced peculiar approaches to restoration. The attention showed by the Austrian government towards the monuments belonging to the classic age in north-east Italy (Lombardo-Veneto State) reveals the will of connecting the Austro-Hungarian administration to the Roman Empire domain. On the contrary, the protection of the past which goes back to Medieval Age (mainly Romanic churches) was increased in the new unified state. In this case the recovery of local and regional traditions was seen as the statement of a principle of independency against the standardization of the signs produced by supranational entities (like the Austrian Empire).

- Between the XVII and the XIX centuries, the deep transformations imposed by the Industrial Revolutions amplified the development of the urban areas and increased the pollution in the atmosphere. New problems, as effectively represented by Pugin's work (Figure 1.1) for the preservation of ancient buildings appeared for the first time.

The problem of the protection of the past evidences became urgent and the debate related to the methodologies to ensure it grew up. On one side decay processes of traditional materials increased due to the pollution of the industrial towns, whilst the renewal of the city centres corresponded to the demolition of ancient buildings and to the isolation of few landmarks. Deep changes gave place to a fruitful matching between theoricians. In Europe the opposition between Eugene Viollet le Duc, promoter of the stylistic restoration, and John Ruskin, resolute supporter of the integral conservation of ancient buildings, created two main philosophies about the role of the restoration activity[9]. In Italy, personalities like Camillo Boito or Andrea Beltrami[10] became the

[8] Marcello Vannucci, *Lorenzaccio. Lorenzino de' Medici: un ribelle in famiglia*, Newton Compton, Roma, 1984, pp. 99,100. (Vannucci, 1984) The event of the destruction of the restored decorations of the Costantino's arch made by Lorenzino de' Medici is described as an attempt to eliminate the fake elements from the original work of art.

[9] John Ruskin's thinking about the consequences of the restoration of ancient buildings is reported in his works *The stones of Venice* and *The seven lamps of architecture*. (Ruskin, 1983) Eujene Viollet le Duc was a deep expert of the architecture of mediaeval age and left his main notions in the ten volumes of his *Dictionnaire raisonnè de l'architecture francaise du XI au XVI siècle*, 1868. (Viollet le Duc, 2002) Ruskin, in *The stones of Venice* (Ruckin, 2000), underlined his relationship with the tactile feel produced by the contact with the old and decayed stones of the venetian monuments. Each component of the buildings is marked by the signs of the time and the sensation of the ineluctable process of aging produces the feeling of sublime, according to a romantic view of the world. On the

main exponents of two opposite tendencies, during XVIII century: one supporting the philological interpretation of the ancient building (Boito) and one devoted to the ideal of a formal uniformity for historical buildings (Beltrami), based on historical research.

Figure 1.1: A. W. Pugin, "Contrasts, or a parallel between the architecture of the 15th and 19th centuries", 1841 (from L. Benevolo, "La città nella storia d'Europa", 1996, (Benevolo L. , 1996) p. 169).

- Boito, promoter of the first Italian Charter for Restoration in 1883[11], had eminent masters: his slogan "better first reinforcing than repairing, rather repairing than restoring"[12] recalls the lessons

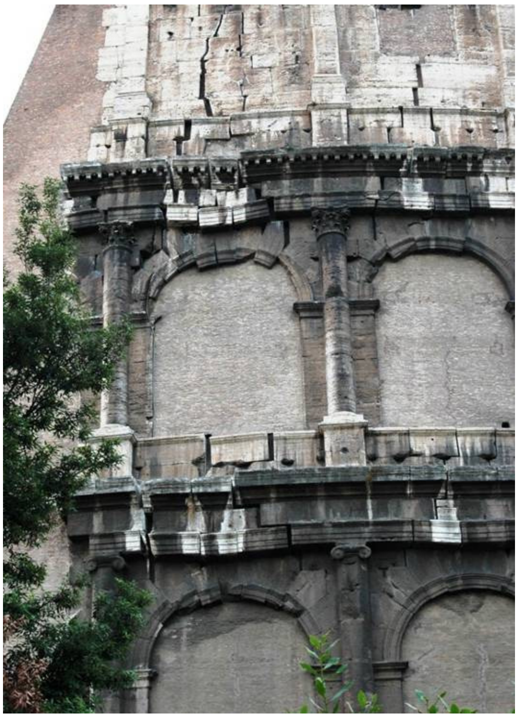
contrary, Viollet le Duc emphasized the research of a unitary stylistic vision of the ancient buildings. According to his opinion, each building ruin contains the "inner feeling" or "art feeling" which provides the indications to complete the building, reaching a phase of perfection that could not be existed either before.

[10] Camillo Boito, referent from Italy of Ruskin and Morris' Arts and Crafts, and Luca Beltrami, important member of the superintendence office in Milan and known for his restoration works, played an important role in the debate around the restoration of ancient buildings, in the second half of XIX century. A synthesis of their theories is contained in G. Carbonara, *Avvicinamento al restauro*, Liguori, Napoli, 2002. (Carbonara G. , 2002)

[11] The so called First Italian Restoration Charter was set up in 1883 during the conference *Congresso degli ingegneri e architetti italiani*, where Camillo Boito played a decisive role in the composition of the document. Camillo Boito gave an important effort to define the principles of the charter. Here the main assumptions are reminded: a) Boito proposed a new approach related to the conservation of ancient ruins: by the technique called *anastylosis*, the single collapsed pieces of a structure can be reassembled together (referred in particular to Greek-Roman ruins); b) the uniformity of the style is not the final attempt of the restoration design: the new attention focuses on the complexity of the historic building. Boito introduced the bases for the philological conservation of the ancient buildings.

left by Raffaele Stern and Giuseppe Valadier who, respectively, in 1086 and 1823, reinforced the Coliseum in Rome avoiding mimetic interventions. Stern's design, above all, represents a masterpiece with the solution of a travertine buttress incorporating two spans of the three orders (Figure 1.2a). The choice to leave the visible damages of the arches (Figure 1.2b), shattered by the 1823 earthquake that compromised the stability of the monument, showed a deep respect for the signs of the time on the buildings.

a)



b)

Figure 1.2: View of the Stern's buttress a) incorporating two spans of the external ring of the Coliseum and b) detailed view of the shattered arches blocked in a sort of snapshot of the history (pictures of the author).

- The designs presented during the XIX century for the restyle of important churches of Italian towns, such as the Romanic church of St. Sepolcro renewed by Gaetano Moretti in 1895 (Figure 1.3), show a deep-rooted tradition for the stylistic revival. The definition of restoration was still ambiguous: sometimes it was intended as a preservative activity of the existing conditions of the monumental buildings (as shown by Stern and Valadier) and in other cases it was considered a

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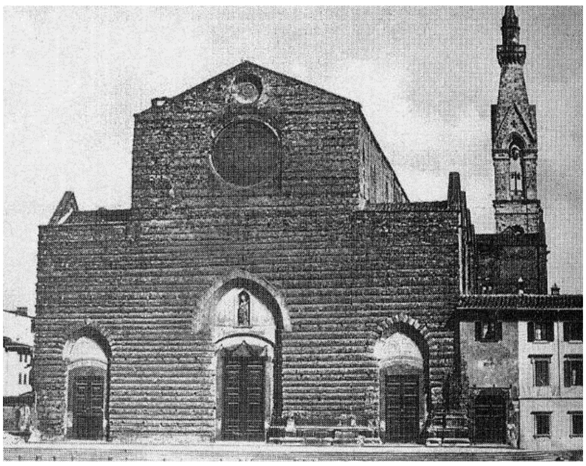
[12] From the first point of the so called First Italian Restoration Charter, 1883, in *Voto finale del terzo Congresso degli Ingegneri e degli Architetti Italiani*, Roma, 1883. (Terzo Congresso degli Ingegneri e degli Architetti Italiani, 1883)

pure exercise of architectural composition. This is the case of the completion of incomplete works, such as the façade of the Florentine church of Santa Croce (Figure 1.4), where the addition of a new façade in an hypothetical Italian gothic style was proposed as restoration design.


a)


b)

Figure 1.3: The mediaeval Church of St. Sepolcro in Milan, a) with the main facade in baroque style and b) the restored façade (after 1908) designed by Gaetano Moretti in neo-Romanic style (from G. Carbonara, "Avvicinamento al restauro", 2002, p. 245).


a)

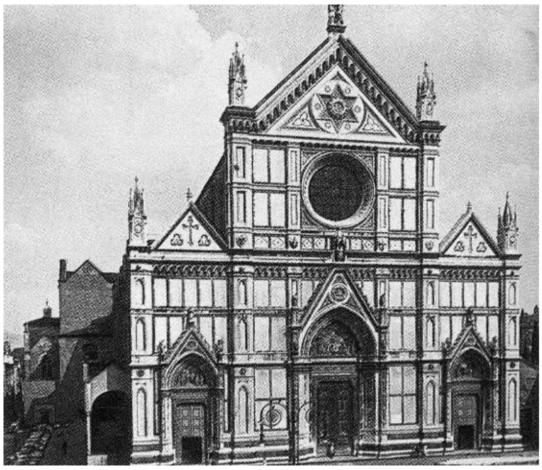
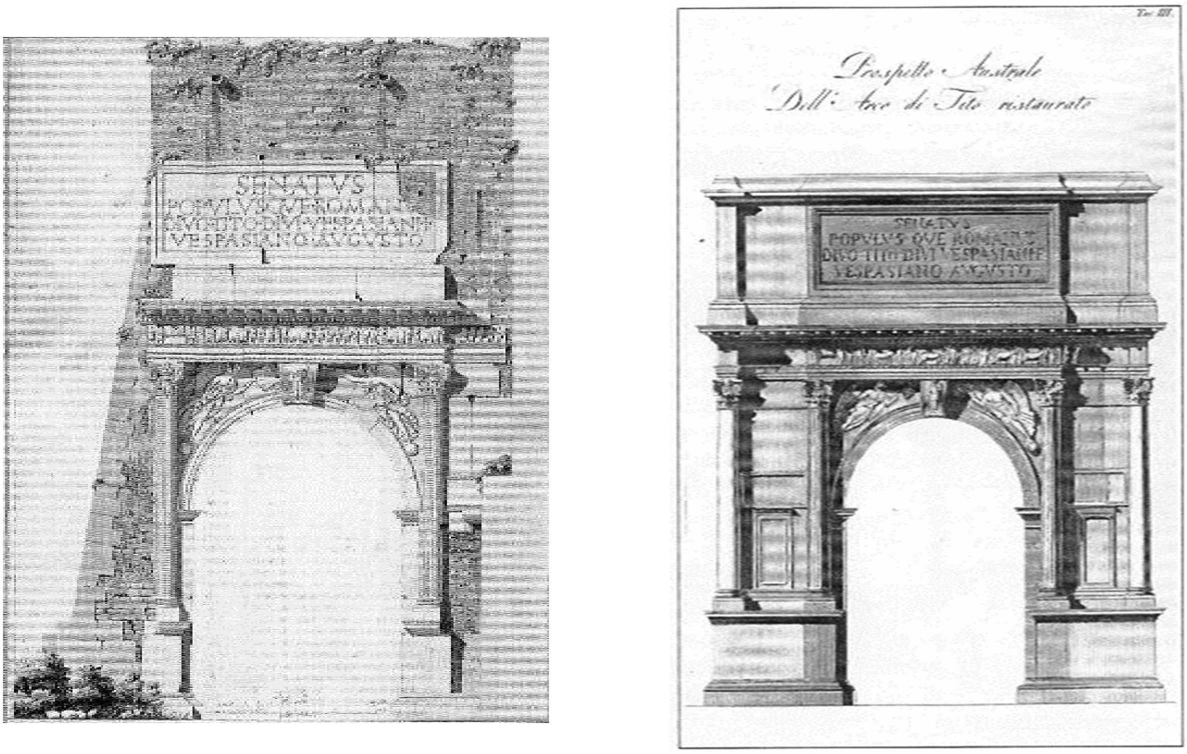

b)

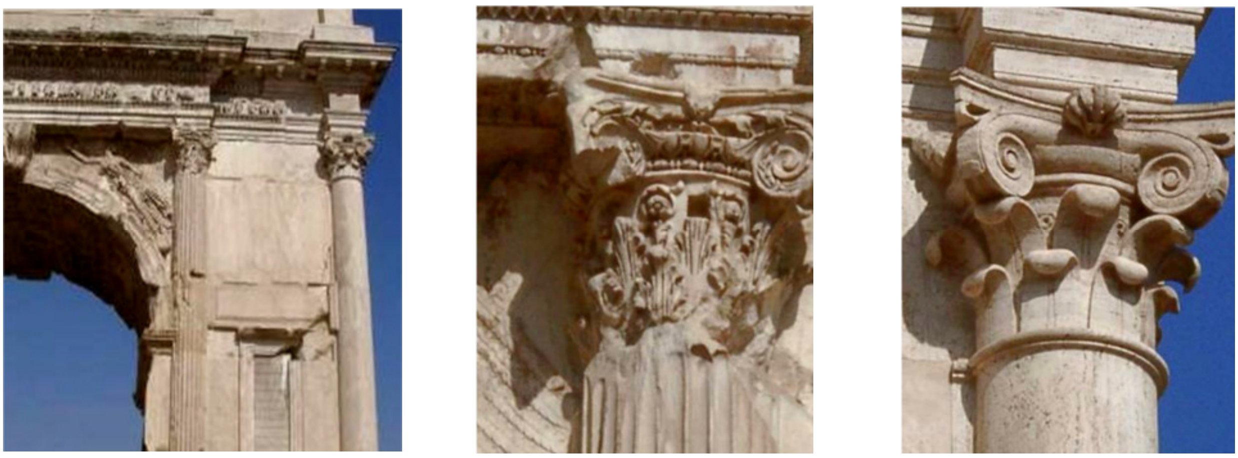
Figure 1.4: Church of Santa Croce in 1857, a) before completing the unfinished façade and b) the church after the building of the new façade in neo-gothic style. (from G. Carbonara, "Avvicinamento al restauro", 2002, p. 105).

Nevertheless, at the beginning of the XX century, Valadier offered an interesting alternative. He designed the intervention for the Tito's Arch in Rome (Figure 1.5a) and his proposal was extremely unusual for that time: he proposed to reconstitute the missing geometry of the monuments (Figure 1.5b), but using a simplified language for the new additions (like the decorations), in order to distinguish the original remains of the arch from the rebuilt parts (Figure 1.6).



a) b)

Figure 1.5: a) A.J.M. Guenepin's survey of Tito's Arch (1809) and b) G. Valadier's drawing for the restoration design (1822) for Tito's Arch (from G. Carbonara, "Avvicinamento al restauro", 2002, p. 84).



a) b) c)

Figure 1.6: a) view of portion of Tito's arch and detailed views of a) the original capital and c) of the simplified capital (pictures of the author).

- In a period characterized by the recovery of the formal uniformity of the buildings of the past, where the design for restoration assumed the features of a compositive exercise (according to Viollet le Duc's praxis), the sensibility towards the contents of truth implicit in the original materials of the building represented a turning point for the theoretical approach to restoration. The further contributions to the definition of a theory of conservation are strictly connected to the diffusion of Alois Riegl's work[13], that revealed a modern approach to the problem, considering the values of the material culture preserved in the sign of the time (*antiquity value*), in the traces of past events (historical value) and in general in the evidence of the human activity coming naturally to the original materials of the architectural work.

- In Italy, Gustavo Giovannoni and Cesare Brandi gave important considerations to define the characteristics of Conservation and to contrast the praxis of imitation. Giovannoni played an important role for the preservation of important historical aggregates belonging to historical centres like Siena, from the modernization pressures of the middle class. Brandi, after the dictatorship period characterised by a cutting of the cultural relationships with the other European countries, updated the theory of Conservation with original contributes.

- Further definitions like Scientific/Philological Restoration, Analytical Restoration and Integrated Conservation are parts of the contemporary development of the debate that is still going on since its origin. These definitions, which will be treated in depth afterwards, represent an overcoming of the imitation as a solution for the protection of historical buildings, but they maintain several open questions. The above mentioned ambiguity of the term *restoration* survives and the choices imposed by the design process are still creating discussions around the results which sometimes show other risks for the protection of the architectural heritage.

The aim of this short description on the interpretation of the meaning of Restoration was developed in order to introduce the complexity that has always characterized this topic. Furthermore the current directions of the theory of conservation are a direct consequence of past experiences in the field of restoration.

[13] Due to hegemony of the neo-idealism in the Italian culture, during the first half of the XX century, the main work written by Riegl "The modern cult of Monuments: its character and its origin", contained in (Riegl, 2003), had not a large diffusion until the end of the Second World War.

1.1.2 The respect for the patrimony: preservation of ancient buildings and historical centres

All the different positions concerning the restoration practice have a common purpose: the research of the historical truth. The concept of restoration itself was systematized during the Enlightenment period, when the human history started to be organized in different categories (history of the wars; history of the religions; history of the arts, etc.) and the documents of the past times attracted the attention of the emerging intellectuals. Buildings, mainly important monuments such as castles, cathedrals and palaces, were seen as documents and pieces of the human history in that period. Their preservation was necessary to protect a source of information for the interpretation of the past and their restoration was requested to support the readability of the monument/document.

As mentioned by Amedeo Bellini[14], the idea of the monuments as a source of historical information produced two different attitudes: according to an archaeological sensibility, one line privileged the conservation of the integrity of the building (with its stratifications and its materials), whilst the second line believed in the recovery of the lost "passages" of the text of the monument/document. Generally speaking, the possibility to recover the lost parts of the text represented by a monument was a direct consequence of the Illuminist thinking: from the mediaeval age to the modern one (since the Renaissance) the concept of time gradually moved from a predetermined idea to a linear principle of cause-effect. The history was considered to be a progression of interconnected facts. For this reason the use of the logic was considered able to determine the correct interpretation of an incomplete document. According to this opinion, a monument with its complexity of layered traces left by the history could be revealed by the restoration. The linearity of the process cause-effect of the historical process allowed the research of the truth embodied in the incomplete documents. The restoration of those documents (monuments included) became a sort of mission, for the research of the historical truth.

As remarked by A. Bellini, problems of historiographical nature appeared. The interpretation of the historical events is usually influenced by the hegemony of the people holding the power: history is written by the winners and not by the losers. The main examples of building restorations

[14] Amedeo Bellini, edited by, *Tecniche della conservazione*, Milano, 1983. (Bellini, 1983)

seem to respect this principle and the alteration of ancient building became a diffused practice in name of a reliability addressed by the historiography.

A useful example of the path determined by the restoration procedures is offered by the case of the Laucoonte's statuary group (Figure 1.7). Laocoonte is an original Hellenistic- Greek sculpture, owned by Roman Emperor Tito and discovered in Rome in 1506. In 1532 Montorsoli restored the Laocoonte's main arm, following the idea to reinforce the comprehension of the sculptural work by the addition of an invented part[15]. In 1727 Cornacchini restored the children's arms using original pieces of other Hellenistic rests, in order to give a complete image to the group (he erased the lacks of the document). In 1906 Johann Pollak discovered casually the original arm of the statue and in 1960 the sculpture was de-restored by F. Magi. According's to Magi's idea, the fake elements added to the original group were considered a wrong interpretation of the work of art and their removal was an act of respect to the historical truth.

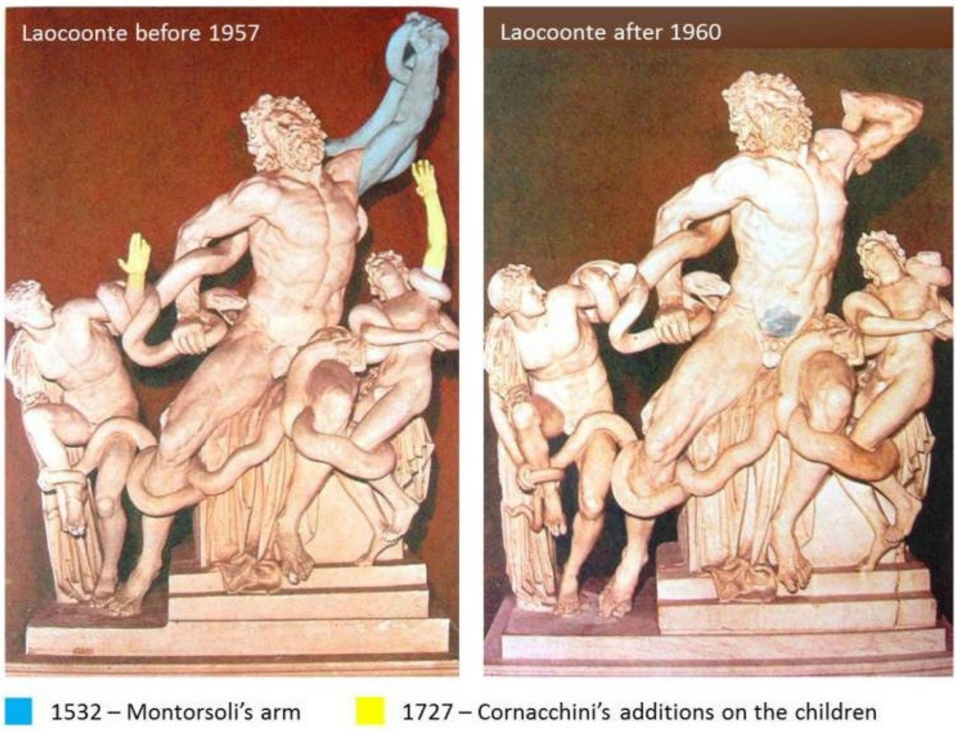


Figure 1.7: Comparison between the restored and the de-restored Laocoonte's statuary group (pictures from G. Carbonara, "Avvicinamento al restauro", 2002, p.231 and modified by the author).

[15] S. Settis, Laocoonte, Donzelli editore, Roma, 2006. (Settis, 2006)

The path followed by the Laocoonte's sequence is comparable to the one occurred to important buildings which were restore for more than one time under the influence of different strategies that reached different results.

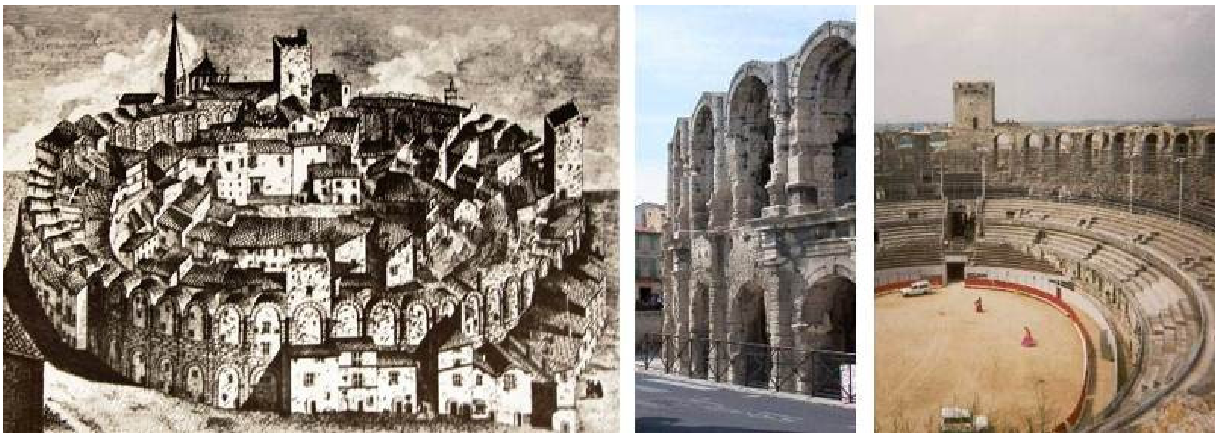
The defensive walls of Carcassonne, a medieval town in south France (Figure 1.8), represent another example of the complexity of the problems generated by a restoration design based on wrong interpretations. Viollet le Duc realized a detailed reintegration of the lost roofs for the towers of the walls and the town acquired a new image in the XIX century. Nowadays the researchers established that the slanting roofs in south France were not characterized by marked slopes and for this reason Viollet le Duc's work is under dismantlement. Also in this case the historical truth that the monument should present was betrayed by the results of the first restoration and the monument is under work to correct its meaning.

Figure 1.8: Two views of Carcassonne. On the left the defensive walls present the conic roofing design by Viollet le Duc. On the right the conic roofing has been dismantled (pictures free available from the Carcassonne City hall website).

The loss of the meaning of the document, due to an alteration that changes the historical information contained in the past heritage, was the main fault of the restorers, according to Ruskin's opinion. The restores, following the idea of a reconstitution of a unitary image, showed the attitude to modify deeply the characteristics of the ancient buildings: eliminating the supposed stratifications (superfetation), hiding the signs of the time and consequently the original content that the historical fortunes left on the materials of the building.

An interesting example showing the high cost paid for the research of the historical truth is the arena in Arles. The excavation of the remains of the roman arena was realized destroying one of the few rare examples of mediaeval village grown inside a misused monumental building (Figure

1.9). Nowadays the roman arena presents original remains in the external ring, whilst the interior was fairly totally destroyed, in order to re-use the building for social events through the realization of new steps.



a) b) c)

Figure 1.9: The transformation of Arles: a) a representation of the mediaeval village built inside the remains of the roman arena; b) view of some spans of the external ring of the arena and c) a view of the reconstructed interior of the arena (illustration from L. Benevolo, "Storia della città. La città medievale", 1993, p. 147 (Benevolo L. , 1993) and pictures available from Arles Town hall website).

In Italy, in Bra, a town near Turin, the peculiarity of a village grew up into a roman amphitheater is still existing (Figure 1.10a/b). The simple two storey houses are displaced along the walls of the arena and they remind its geometry. In this case the path to reach the truth was pursued by a conservation of the data left by history: the village was saved and the archeologists' work emphasized the traces of the ancient structures, preserving the buildings and the social identity of this quarter (Figure 1.10c).

a) b) c)

Figure 1.10: Bra (Cuneo), Coliseum quarter. a) sky view of the Coliseum quarter; b) Hypothetical reconstruction of the roman arena of Pollentia (from the explanatory panel edited by the superintendency of archaeological heritage of Piedont and modified by the author); c) view of the typical elliptical street of the village with a detail of a masonry texture (author's pictures).

The last two cases show the consequences that the restoration design can produce in terms of negation or respect of some historical phase. The case of the excavation of the Arena of Arles presents the main problems connected to the critical selection of the elements layered in the monument that the restorers decided to save and the ones that must be eliminated for the reliability of the building. A similar situation is visible in Split, a town in Croatia that was built in mediaeval time inside the perimeter of the Constantine's palace (Figure 1.11 and Figure 1.12).

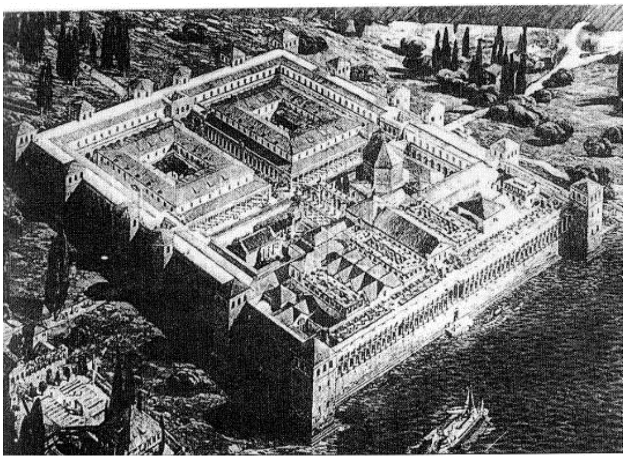


Figure 1.11: An hypothetical representation of the Constantine's Palace by E. Hebrard (from C. Blasi and I. Carabellese, "Lacune urbane e recupero del centro storico di Spalato", in "Memoria e Restauro dell'architettura", Milano, 2005, p.55).

Figure 1.12: Sky view of Split (picture from L. Benevolo, "Storia della città. La città medievale",1993, p. 148). (Benevolo L. , 1993)

The case of the historical center of Split was recently described in depth by Carlo Blasi and Ignazio Carabellese[16]. Here the entity of the problem spans both the scale of the monument (the remains of the representative rooms of the palace and the mausoleum/cathedral) and the scale of the whole historical center. Since the VII century people from Salona began to live inside the Constantine's Palace. The mediaeval buildings were designed on the main interior walls of the remains of the previous buildings, occupying the old streets, but conserving their directions. At the beginning of the XX century, archaeological excavations took place around the cathedral (the old mausoleum) and the south-east quadrant of the center (Figure 1.13). The aim of the demolition of

[16] C. Blasi and L. Carabellese, *Lacune urbane e recupero del centro storico di Spalato*, in "Memoria e Restauro dell'architettura" a cura di M. della Costa e G. Carbonara, Francoangeli, Milano, 2005. (Blasi, 2005)

a so large part of the city was the research of the rests of the ancient throne room of the palace (Figure 1.14).

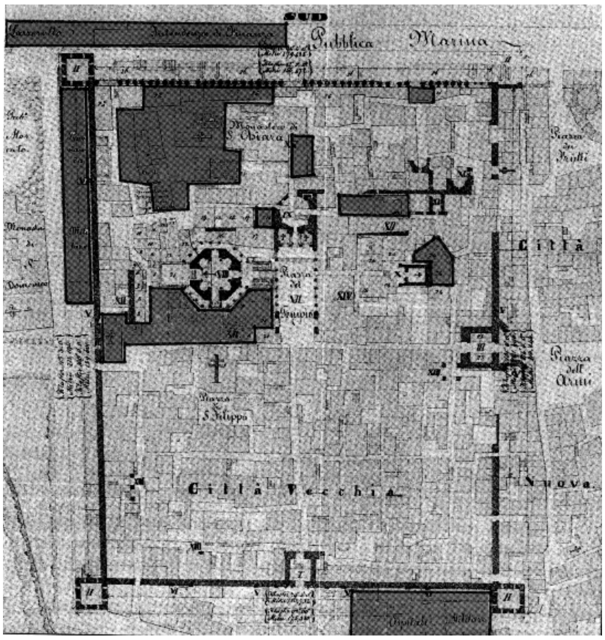


Figure 1.13: Plan of the historical centre of Split with the archaeological excavations indicated in dark grey (from C. Blasi. I. Carabellese, "Lacune urbane e recupero del centro storico di Spalato", in "Memoria e Restauro dell'architettura", Milano, 2005, p.58).

Figure 1.14: View of south-east area of the centre with the main demolitions caused by the archaeological excavation (from C. Blasi. I. Carabellese, "Lacune urbane e recupero del centro storico di Spalato", in "Memoria e Restauro dell'architettura", Milano, 2005, p.67).

In 1997 the administration of Split decided to stop the archaeologists work. After almost 100 years of researches, the sensibility changed and the contradictions presented by the restoration design were dramatically clear: an entire sector of the centre had been irremediably damaged, emptied of its unitary contents shared with the rest of the town and transformed into a wasteland. Since the end of the last century, the idea of a partial reconstruction of the Constantine's palace was substituted with a new organic plan for the whole historical centre. The idea of a recovery of a palace that does not exist anymore by the removal of parts of the old city centre became useless.

The short descriptions of the mentioned cases allow drawing some considerations:

- The cult of antiquities determined the development of a philosophy of the recovery and the restoration discipline became the expression of a new feeling devoted to the historical beauties;

- The restoration discipline showed many trends. Different positions were defined to give a solution to problematic questions: decay, stratifications, interpretations, etc.
- Reliability, reinforcement, integration are an example of the different categories of intervention set for the main problems concerning the restoration discipline, but each decision showed often criticisable effects.
- Conservation appeared as the best chance to preserve the authenticity of the cultural heritage and the diffusion of Riegl's writings contributed to the success of this approach.
- The affirmation of the conservative approach was confirmed by international recommendations: from the Athens Charter (1931) to the Venice Charter (1964) and the Declaration of Amsterdam (1975), the idea of the stylistic restoration is rejected.
- At the same time, international recommendations introduced the attention for the context: the aim is to extend the preservation to the so called minor architectures, ancient buildings without monumental characteristics.
- Afterwards the protection of historical centres became a new priority and the subject of the restoration included cases at the scale of the single building and at the scale of the city.

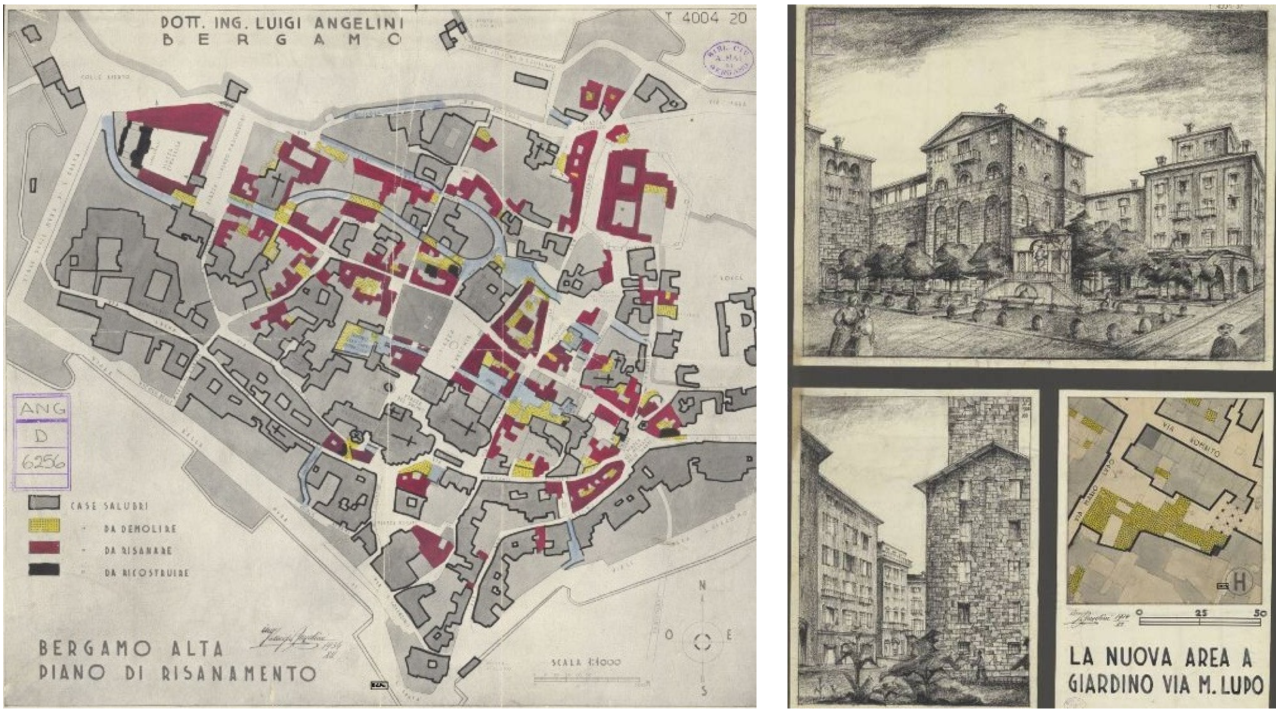
In Italy, Gustavo Giovannoni's work[17], before, and the following effects of Brandi's theoretical treatises[18], developed the conservation design for historical buildings. Giovannoni identify a strategy to allow the urban renewal (for hygienic and healthy reasons): by prudent urban regenerations and the introduction of neutral elements, he suggested the way to avoid a direct conflict between modern and historical buildings. His lesson was an example for the plan of the centre of Bergamo, designed by L. Angelini in 1934, who proposed Giovannoni's prudent renewals to adapt the existing buildings to modern standards and a new road system to improve the connections between the opposite sides of the centre by a sort of ringway. The plan contained

[17] See Gustavo Giovannoni, *Questioni di architettura*, Roma, 1929 (Giovannoni, 1929), and voce *Restauro (Restauro dei monumenti)* in Enciclopedia Italiana, vol. XXIX, Roma, 1936, , pp. 127-130. (Giovannoni, Restauro (Restauro dei monumenti), 1936)

[18] See Giuseppe Basile, Teoria e pratica del restauro in Cesare Brandi. Prima definizione dei termini *(Theory and practice of conservation-restoration according to Cesare Brandi. Preliminary definition of terms)*, Il Prato, 2007. (Basile, 2007)

also detailed indications for the preservation of the main features of the architectonic language of the town (doors, frames, mouldings, etc.).

Leaving apart the peculiar situation produced by the effects of the war devastations after the Second War World, in Italy the philological restoration was assumed as the correct position between the extreme theories represented by Ruskin and Viollet le Duc. New efforts for the development of the theory of conservation were introduced by Cesare Brandi, the promoter of the central institute for restoration. Brandi was firmly convinced that the materials forming the work of art should be preserved: the restoration can act only on the material and its preservation assures the perception of the work of art.



a) b)

Figure 1.15: Urban renewal plan for the historical centre of Bergamo, designed by L. Angelini in 1934: a) plan with the detailed indications of prudent local regenerations and b) detailed plate of the renewal results in a central area (from Biblioteca Civica Angelo Mai, Bergamo. Archivio storico fondo '900, available on Archivio ARUP – www.arup.it).

G. Carbonara, one of the main expert of the history of the theory of conservation-restoration, outlined the merits achieved by Giovannoni and Brandi's works in the definition of the Italian scientific conservation[19]. Through the respect for the information contained in the material data, the conservation praxis became the field of interest for different experts: the conservation design emerged as a combination of contributions from historians, architects, engineers, physics, chemists, etc.

Two examples can show the results pursued through the scientific conservation. In Rome, the problem of the sedimentation of various historical layers in the Marcello's theatre was faced with the rigorous respect for the documentary content of the building (Figure 1.16): trough the identification of the parts of the palimpsest, the historical/aesthetical truth of the building was revealed. In the same way, the research of the documentary traces of the palimpsest were shown even in restyled buildings, in order to memorise their transformations along the time, like in the archbishopric palace in Milan (Figure 1.17). Here, the unitary image coming from the Barocco renewal of the palace was eliminated in order to show the history of its transformations.

The idea of desplaying the palimpsest of the traces left by historical events in the building was strictly connected to the content of the Venice Charter: in the article 9, concerning the aim of restoration, the sentence "Its aim is to preserve and reveal the aesthetic and historic value of the monument" indicates the purpose of revealing the values hidden in the building and this operation requires its critical interpretation. Until the success of Giovannoni's theories, the aim of the theoreticians was the definition of operative methodologies. In this way the identification of different application fields suggested the possibility of using different categories for each specific case (restoration for liberation, recomposition, .innovation, etc.). The assumption of critical restoration is different. As mentioned by G. Carbonara, due to the complexity that characterized ancient building, the categories are not always able to give the right solution for each case. Critical restoration identify the right approach case by case, after a specific exam of the problems through historical sensibility and technical competence[20]. In this sense, the rescue of the bombed ancient hospital of Milan (Figure 1.18) represents a masterpiece for the contemporary debate about

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[19] Giovanni Carbonara, *Avvicinamento al restauro. Teoria, storia monumenti*, Liguori Editore, Napoli, 1997 and G. Carbonara (edited by), *Trattato di restauro architettonico*, vol. 1, UTET, Torino, 2007.

[20] The description of the debate between scientific restoration and critic restoration is mentioned in G. Carbonara, *Avvicinamento al restauro*, Liguori Editore, 1997, Napoli and in R. Pane, *Architettura e arti figurative*, Venezia 1948. (Pane, 1948)

conservation. Here, G. Annoni and L. Grassi applied, case by case, specific solutions in order to respect the original structures of the building and its evolution, with the aim of updating the building for the introduction of new functions. From anastilosys to the integration of the destroyed volumes through a modern architectural language (Figure 1.19), each problem was faced with original solutions.

Figure 1.16: View of the Marcello's Theatre in Rome (author's picture).

Figure 1.17: Facade of the archbishopric palace in Milan (author's picture).

Figure 1.18: View of the main cloister of the Ospedale Maggiore, after 1944 (from L. Grassi, Lo Spidale di Poveri. Del Filarete. Storia e Restauro. Ed. Università degli studi di Milano, Milano, 1972. Fig. 30). (Grassi, 1972)

Figure 1.19: View of a minor cloister from the addition of a modern part in the Major Hospital of Milan, degined by L. Grassi for the restoration of the complex (author's picture).

1.2 Conservation between compatibility and reversibility

According to the indications contained in the Venice Charter, the use of innovative technology is promoted as correct solution to repair or reinforce the historical buildings. Since the end of the

Second World War and the development of new technologies for the building industry, different innovative applications were tested in conservation field.

The use of reinforced concrete was mainly adopted to strengthen damaged structures showing problems of instability. Concrete itself was supposed to be a very strong materials. For this reason also cement based mortars replaced lime and hydraulic mortars for pointing and sealing.

Research in the field of silicone epoxy (etc.) mixtures developed new chemical protective solutions for the preservation of plasters and stones grouts were studied to improve the injection techniques for strengthening damaged structures.

P. Sanpaolesi tested the introduction of new building technologies in different experiences[21]. A. Spinosa, in a recent study[22], described Sanpaolesi's proposals for the application of reinforced concrete to strengthen masonry structures and rebuilding roofing systems. Furthermore, Sanpaolesi tested the use of chemical mixes for the strengthening of masonry structures.

Many buildings seriously damaged during the war were restored using modern technologies. Reinforced concrete was proposed for the reconstruction of the roofing of. S. Chiara in Naples by one of the most influent theoreticians of architecture in Italy, Roberto Pane. For the reconstruction of Santa Trinita bridge in Florence, destroyed during the German's retreat, the use of a concrete structure further hidden by the laying of natural stones was supported by Pane and Sanpaolesi.

After years of diffused use of new technologies in the field of restoration, the negative effects produced by several applications appeared. The interaction of chemical treatments produced secondary effects on the original materials: alterations and in many cases an acceleration of the decay process of the materials. The introduction of reinforced concrete structures produced a changing in the distribution of stresses in the original structure and other mechanical and physical

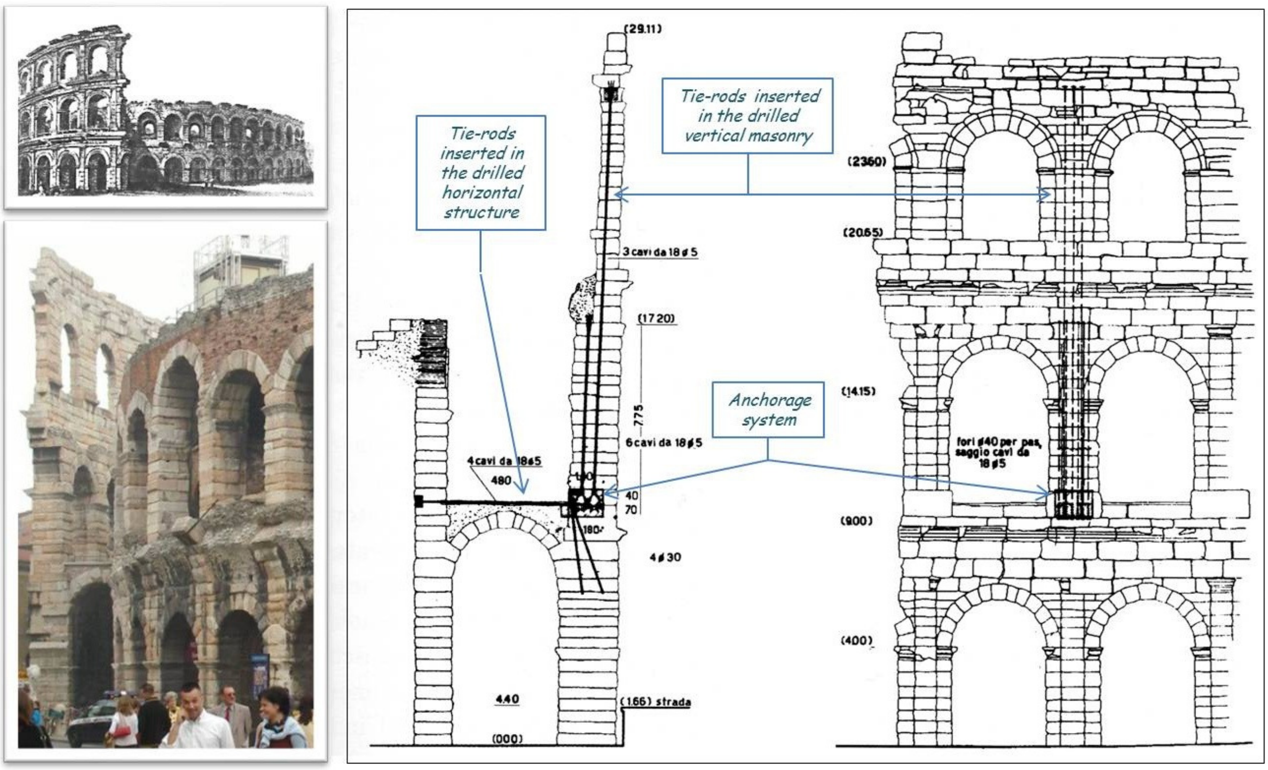
[21] P. Sanpaolesi, *Discorso sulla metodologia generale del restauro dei monumenti*, Edam, 1973, Firenze. (Sanpaolesi, 1973). P. Sanpaolesi, *Il restauro, dai principi alle tecniche*, in IV assemblea generale ICOMOS, Firenze, 1981. (Sanpaolesi, Il restauro, dai principi alle tecniche, 1981)

[22] A. Spinosa, *Ingegneria e restauro nella ricostruzione postbellica. Gli studi di Piero Sanpaolesi per la copertura del Camposanto Monumentale di Pisa*, in "Storia dell'Ingegneria. Atti del secondo convegno Nazionale", Napoli, pp. 1487-1499. (Spinosa, 2008)

problems. The recent collapse of the “Fauno House” in Pompei showed the adverse effects of the partial reconstruction in reinforced concrete of the roofing of the original roman masonry.

The problem of the compatibility between different materials and structures became a new priority and the experts introduced the request of reversibility for the conservation design to ensure the possibility of retrieve to the wrong applications of modern technologies in ancient buildings.

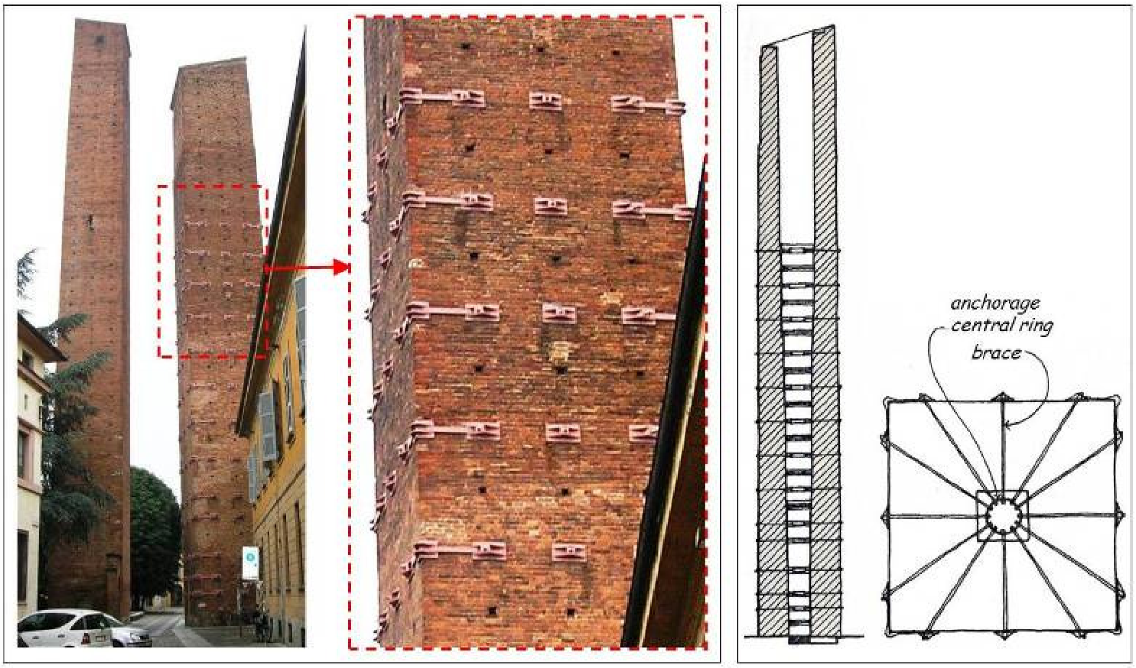
The development of innovative strategies for the repair and strengthening of existing (historical) buildings introduced new technical solutions for reinforcements, and problems linked to out of plane actions, instability and settlements. In 1955, Morandi and Forlati designed an original solution to assure a pre-stressed state to the remains of the external ring of the arena of Verona (Figure 1.20a). Few spans of the external ring of the arena, three levels high, showed problems of instability due to the missing arches which provided a balancing action. Tie rods were inserted vertically in the structure of the last 2 levels and anchored to horizontal bars introduced in the extrados of the first level (Figure 1.20b).



a) b)

Figure 1.20: Strengthening design of the external ring of the Arena of Verona: a) engraving of the arena in 1830 (from S. Maffei, “Arena di Verona venti secoli di storia”, 1973) and detailed picture of the external ring (R. Carta’s picture modified by the author); b) transversal section and partial frontal view of the strengthening design (from G. Carbonara, “Trattato di restauro architettonico”, vol I, UTET, 2007, p. 51 and modified by the author)

In Pavia, after the dramatic collapse of the Civic Tower (1992), several mediaeval towers of the historic center were controlled in depth. For the Fraccaro Tower, a building presenting a diffuse crack pattern, G. Ballio proposed an original idea for the strengthening design. Ballio used pre-stressed radial bars acting from the interior of the tower to contain the thrusts which were affecting the vertical walls: bulging of the walls towards the outside (Figure 1.21) was in fact observed.



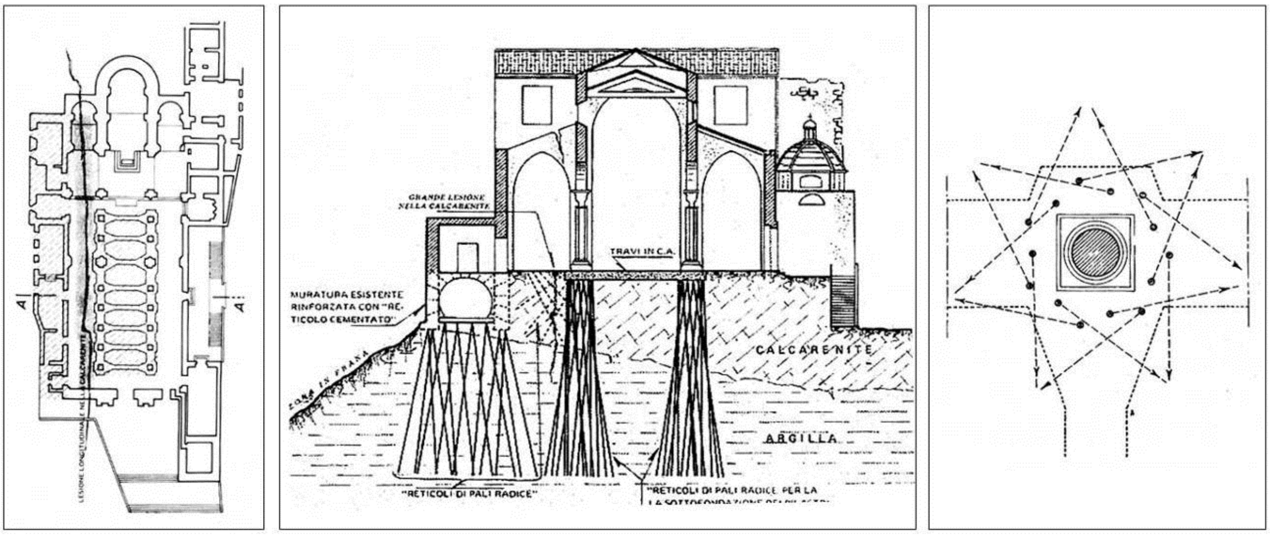
a) b)

Figure 1.21: Strengthening design for the Fraccaro Tower in Pavia: a) general and detailed view of the tower and the anchors of the bars (author's pictures); b) layout of the design (from M. Levy and M. Salvadori, "Why buildings fell down. How structures fail", W. W Norton, 1992, p. 227). (Salvadori, 1992)

The last two examples describe technical solutions that resolved structural problems in ancient buildings trough the addition of new elements able to correct or change the mechanical behaviour of the building. In both cases the reversibility of the intervention is purely theoretic.

Moving from the strengthening of the vertical walls to the actions against the effects of settlements, technical literature reports three main methods to face the problem: a) masonry substructions; b) concrete piles; c) micro-piles. These elements should support the existing foundations through a new connection to the deeper and more compact layers of the soil. Concrete piles maintain the old foundations operative and complete its action increasing the resistance. An example of this specific application can be seen in the strengthening design for the

Agrigento Cathedral. Here the settlement along the profile of the hill produced deep damages to the building that was reinforced through the subsidence of the hillside and the realization of concrete piles under the bearing structures of the cathedral (Figure 1.22). Micro-piles were widely used to reinforce the foundations and soils of the building placed on hills or areas characterized by settlements phenomena for their capacity to compact clayey soils. Nevertheless this technology is based on an invasive connection to the existing foundations and the reversibility principle is here totally ignored.



a) b) c)

Figure 1.22: Strengthening design of the foundations of Agrigento cathedral. a) Plan of the chathedral with the linear crack along the aisle; b) section of the building with the design of the concrete piles; c) layout of the grid design for the concrete piles around a pillar (pictures reassembled by the author from G. Carbonara, "Trattato di restauro architettonico", vol III, UTET, 2007, p. 669 (Carbonara G. , 2007)).

As for the foundations, the resistance increasing was widely pursued even for other vertical and horizontal structures, in order to adapt the ancient buildings to the modern standards. Concrete elements were added in the historical buildings to substitute traditional timber structures (like floors and roofs). In many cases, concrete elements substituted the entire traditional diaphragms, changing in depth the mechanical behaviour of the building. Concrete columns and beams were supposed to be an efficient solution for damaged masonry walls. Concrete floors were indicated as fire-resistant elements which should replace the flammable timber structures. Cement mixtures were proposed as strengthening injections for damaged walls and pillars. Even in these cases the principles of compatibility and reversibility were totally not respected.

The invasive interventions outlined a diffused trend for the restoration practice: historical buildings were considered the result of a weak technology, not able to provide an efficient mechanical response. Since the success of concrete in the building industry, the study and the knowledge of traditional buildings techniques were gradually dismissed from the educational system. For this reason the respect for the historical structures became always lower and the conservation of the technological elements of the ancient building was not considered a priority. Detailed roles and recommendations for the conservation of the surfaces of the ancient buildings were set by important administrative offices (Central Institute for Restoration, Ministry of Culture, CNR-University laboratories, etc.), whilst the structures supporting the surfaces were not taken into account as elements forming the material integrity of the structures.

The problems connected to a firm renewal of traditional bearing structures with new reinforced concrete elements showed dangerous consequences after a short period from their application. The incompatibility between the stiffness of the reinforced concrete structures and the one of masonry structures caused serious static problems. The durability of the new structures was another problem that was not take into account, having the idea that cement and concrete could be a sort of eternal support for ancient buildings.

In Italy, the worst effects, were observed after the seismic events. The mechanical response between mixed structures, containing more deformable elements (like brick-works or stone-works and timber structures) and stiff elements, was often the cause of the collapse of the building (see Figure 1.23).

Figure 1.23: Three views of a building stroke by the 1998 Umbria earthquake. The overturning of the façade is connected to the presence of stiff floors made by hollow bricks and reinforced concrete (courtesy of Arch. Antonella Saisi).

Despite a tradition including several experts which performed fundamental studies concerning the traditional building techniques, the Italian culture was not able to provide a correct regulation to control the indiscriminate abuse of incompatible modern technologies, applied to ancient buildings.

The frequent reference to the use of new technology to improve the resistance and the durability of ancient structures, contained in the before mentioned charters, showed a blind faith in the modern materials. At the same time it revealed a diffused ignorance about the mechanical behaviour of ancient structures and their components.

1.3 Conservation: thematic limited to the superficial image or theme extended to the third dimension of the architecture?

The influence of the contents of the Venice Charter and the further Declaration of Amsterdam is testified by several examples in Europe and in general in the Western culture. Recently, E. Limbouri described the development of the preservation activities in Cyprus, from the British colonization until 1960) to the period of independence, taking into account the Turkish invasion[23]. In different periods, the monuments of the island were cared according to the main trends in the field of restoration: from the anti-restoration (privileging maintenance efforts according to Ruskin's view) applied by the British, to the philological restoration proposed by William Douglas Caroe (a theorist clearly close to Boito's positions) and the further influence of the indications coming from the Venice Charter (supported by the English administration and P. Gazzola, who worked in Cyprus as UNESCO consultant).

The example of Cyprus demonstrates the success and the diffusion of the main theories in preservation field. In Italy, a decisive effort to this discipline arrived in the sixties of the last century, when C. Brandi published his *Teoria del Restauro*[24] (Theory of Restoration), a text that

[23] E. Limbouri, *The restorations of ancient monuments of Cyprus from the establishment of the Department of Antiquities of Cyprus in 1935 until 2005*, in *Structural Studies, Repairs and Maintenance of Heritage Architecture XII*, edited by C. Brebbia, WITTpress, 2011, pp. 45-59. (Limbouri, 2011)

[24] The first edition of C. Brandi's "Teoria del Restauro" was in 1963 and the second edition was printed in 1977.

updated the debate around the practice of restoration and had a deep impact in the further education addressed to the experts of this sector.

As mention before, the differentiation between categories was considered a solution for the application of the correct methodology in the preservation field. In Brandi's theory, different categories for specific problems are present. In his opinion the identification of the work of art determines the further attitude towards the respect for the materials supplying the image of the architectural work. Influenced by the diffused practice of the removal of pictorial layers from their support, Brandi introduced the distinction between *aspect* and *material-image*. The direct consequence of this separation was the idea of a static restoration[25]: a series of actions with the aim of the reinforcement or the strengthening of the structure supporting the exterior finishing of the work of art (painting, sculpture, fresco, or building).

1.3.1 An open question: material as epiphany of the image

For practical reasons, according to Brandi's theory, the aspect of the work can be distinguished into *aspect* and *structure* of the material. As G. Basile remarked:

The image is coextensive to the material, even though it is not the same, yet cannot exist without it: hence the concession, in the presence of a grave danger and with no valid alternatives, of sacrificing that which supports, "is beneath" the material image, i.e., the structure, to save that which constitutes the image, i.e., its appearance (the most common example is the removal of mural painting from its wall if the letter is no longer capable of adequately carrying out its function)[26].

[25] The idea of the static restoration was introduced by R. Bonelli at the voice *Restauro (il Restauro architettonico)*, in *Enciclopedia Universale dell'Arte*, vol. XI, Venezia-Roma 1963, coll. 344-351. (Bonelli, 1963)

[26] *(Theory and practice of conservation-restoration according to Cesare Brandi)*, in G. Basile, *Teoria e pratica del restauro in Cesare Brandi,* Il Prato, 2007, p.62.

The misunderstanding, that put into practice the modification of the original structural systems in the ancient buildings, hides behind this Brandi's proposition. As Brandi underlined, this eventuality should be taken into account only for exceptional reasons[27].

As a result, thanks to the further introduction of the category "static restoration" proposed by R. Bonelli, the object of the conservation was limited to the superficial aspect of the building surfaces, whilst the support was interpreted as an element that could be deeply modified. By distinguishing the problem in two different categories, the experts were addressed to their specific field of competence and the interaction between them became limited.

The division between architectonic and engineering expertise promoted the application of rules and codes developed in different disciplinary fields. One procedure is devoted to the elements providing the aspect of the architectonic work, whilst one method is set just for the hidden layers of the building. In both cases the support offered by diagnostic techniques for the determination of the state of conservation of the material elements composing the building should be shared. The use of non-destructive techniques was particularly appreciated in relation to the assumption that each study or analysis of the building had to respect as much as possible the integrity of the materials. Minor destructive techniques offered a tolerable compromise compared to the waste of original materials caused by the application of destructive tests.

The efforts provided by Brandi for the respect of the integrity of the original materials were original and had a wide success. He introduced the use of neutral colored paintings to reconfigure the aspect of the buildings effected by lack of materials (*dampening of visual tonality*). For the missing parts of the paintings, he invented the "tratteggio" (hatching) technique, to compose a mental image of the work by parallel lines with specific chromatic tones, close to the original colors.

At the same time Brandi introduced the concept of "patina":

[27] G. Basile, *Teoria e pratica del restauro in Cesare Brandi*, Il Prato, 2007; Giovanni Carbonara, *Avvicinamento al Restauro*, Liguori Editore, 2002

This is a kind of anomalous addition due to natural ageing (and Brandi adds, "adjustment") of the artifact's constituent materials, the effect of which on the appearance of the opera was, nonetheless, often foreseen (and planned for) by the artist. It should always be conserved due to its function as an "imperceptible damper on the material", which facilitates the perception of the image with respect to the material and which is valuable also from the operational point of view, as it delineates the point beyond which one should not go (e.g., in cleaning the work)[28].

The attention towards the problems of the material decay and the respect for the patina produced a sequence of very detailed operations for the preservation of the ancient surfaces of the buildings, their rendering materials and their decorations. This set of actions is considered the conservation design that is briefly summed up in the following paragraph.

1.3.2 Short description of the conservation practice

The following definition of conservative intervention was conceived in the perspective of the planned preservation, taking into account alteration and decay phenomena of the materials, limited to the first layer of the elements covering the historical buildings. Considering only the operations set to contrast decay processes limited to the superficial materials of a building, the following procedures are particularly indicated for those buildings which receive a constant care for keeping in efficient conditions its different parts. These procedures are not able to provide all the solutions for the frequent cases of buildings in serious state of neglect: misused buildings or deprived of regular maintenance. In these cases, the different types of decay assume dangerous extensions, reaching the structural elements of the building and, more in general, reducing the mechanical properties of the materials. In this way, another order of problems is achieved: the safety for the entire structural organism of the building.

In the case of safeguarded buildings, where the execution of urgent works on the structures is not necessary, the conservative practise recommends specific operations limited to the

[28] *Theory and practice of conservation-restoration according to Cesare Brandi*, in G. Basile, *Teoria e pratica del restauro in Cesare Brandi,* Il Prato, 2007, p.64.

architectural surfaces. According to this perspective, the procedures set to contrast alteration and decay pathologies observed on the materials of the building are the following:

a) pre-consolidation phase;
b) cleaning phase;
c) re-pointing phase;
d) consolidation phase;
e) protection phase.

Some of these phases are considered always necessary: cleaning, sealing and pointing and protection.

a) <u>The cleaning phase</u>

Considering the state of the material to which it has to be applied, the cleaning phase could request a pre-consolidation in order to make the damaged materials more resistant, able to face stresses (mostly of mechanical order) determined by different cleaning methods.

The cleaning methods are chosen according to four fundamental conditions, which should be respected to guarantee the preservation of the materials in the site. Cleaning should be:

- Controllable by the operator, selective, gradable;
- not corrosive;
- able to limit the formation of discontinuities
- able to avoid the formation of damaging products for the correct conservation of the materials.

The aim of the cleaning phase is the removal of what is injurious for the material: soluble salts, not very soluble incrustations, stratifications of various materials, intentionally applied or not suitable, in general no more adequate, weed vegetation, animal faeces.

According to the theory of conservation and the indications from the material culture, the cleaning procedures should not be invasive in order to preserve the traces of polychromy and the signs of the utensils used to work out the materials.

Considering Brandi's definition of "patina", the cleaning procedures should maintain a layer composed by a film formed as a result of the interaction between the material and the atmosphere, proof of the time, that can be hidden under other layers of damaging materials.

Paribeni defined the "patina" as the interaction between the surface of the material and the air: the product of the natural oxidation should not be removed, whilst efforts should be made on the deposits of the dirt.

Decay type	Cleaning procedure (indicated for sculptured surfaces)
Soluble salts and atmospheric particle	Sprayed water
insoluble dirt and fatty substances (oil, grease, etc.)	Wet pack with absorbent material: phyllosilicates (attapulgite, sepiolite or cellulose pulp) absorbent materials, covered by polyethylene papers. The solvent evaporates, whilst the dirt remains in the sorbent material. Organic solvents are indicated for oxidation products (treeline and chloride composts). Butilamine, triethanolamine and rather basic solvents are used for oils and fatties. Benzene and aromatic solvents are suited for bituminous substances. These wet packs are able to remove the dirt that was not eliminated by spayed water.
Crust phenomena	Water solutions or suspensions with solvent or complex action. Chemical solutions present a Ph comprises between 6.5 and 8.5. A typical example is the AB57 solution, composed by: distillate water (the solvent), ammonium bicarbonate (that transforms the gypsum into soluble bicarbonate); E.D.T:A. (a bisodium salt that remove the crust); Desogen (acts as a biocide); carbossilmetilcellulose (the wet pack).
Encrustations and compact deposits	Ions exchanging resins: polymeric substances that must be applied on the material surface.
Insoluble dirt and compact deposits	Mechanical methods: bistoury or knife are allowed in those positions not easily reachable by the water.
Black crusts and compact deposits	Laser: suitable for black crusts, encrustations and stains. It should be avoided on light surfaces due to colour alteration effects.

Table 1.1: Material decay typology and relative cleaning procedure for sculptured surfaces.

In Italy, specific research team, since the 80s of the last century, produced several operative indications to carry on the cleaning phase. The NorMAL commission (*Normativa Materiali Lapidei -*

Regulations for Stony Materials) of the CNR (National Research Centre) distinguished two types of cleaning procedures:

1) Cleaning procedure suited for sculptured surfaces (decorated);
2) Cleaning procedures suited for worthless surfaces (without decorations and aesthetical values).

Specific manuals about the cleaning of ancient stony surfaces indicate the use of water solutions to respect the sculptured surfaces. The different remedies should be applied according to the observed decay acting on the material (Table 1.1).

Moving to the building elements without aesthetical values, cleaning procedures are based on the mechanical actions of the of the solvents. Four main methodologies are indicated in Table 1.2.

Decay type	Cleaning procedure (indicated for surfaces without aesthetical values)
Soluble salts and atmospheric particle	Rain water supplied by waterworks pressure: water supplied by tube and apposite rain nozzle
Compact deposits	Spray water supplied by waterworks low pressure (2.5 – 3 atm): water supplied by tube and apposite pray nozzle (in order to increase the contact angle)
Crust phenomena	Spray water supplied by low pressure followed by saturated vapour blast: the use of vapour is indicated when organic substances are present
Black crusts and insoluble dirt	Low pressure hydro-sandblasting or sandblasting: mechanical cleaning through water jets (at controlled pressure) or using abrasive minerals (like quartz).

Table 1.2: Material decay typology and relative cleaning procedure for surfaces without aesthetic values.

b) <u>The phases of re-pointing: injecting and pointing</u>

In order to guarantee an appropriate defence from the main decay sources, the materials must be repaired through injecting and pointing: these procedures block the penetration of the meteoric water in the depth and ensure a correct adhesion between the materials. Re-pointing techniques are able to reconstitute the adhesion between detached or sliced fragments.

Injecting is obtained by adhesive components with the following characteristics: i) good adhesion; ii) durability; iii) low shrinkage; iv) elasticity; v) mechanical characteristics similar to that of the stony material in which is applied. This operation is obtained using epoxy resins and polyester resins (these only for light proof positions). For the detachments of large portions of the material, stainless steel hinges can be inserted to re-join the separated parts.

Pointing operation consists in filling all the thin superficial discontinuities with dry or hydraulic mortar. Large fractures are repaired by mortar with large granulometry. Fluid mortars are suitable for thin cracks. In the case of thinner cracks, the repointing can be obtained through pen-pipes injections (the acrylic resin Primal AC33, made by lime and an organic binder, is a typical example).

c) Consolidation phase and water-proof treatments

According to the conservation applied to stony surfaces, the term consolidation is used to describe procedures suitable to protect materials presenting mechanical problems. Consolidation is considered necessary for incoherent materials. The procedure consists in the application of mixtures which ensure a deep penetration from the decayed external layer of the material to its interior sane part, in order to reconnect them.

Considering the water as the main vehicle for decay processes, water-proof products are considered useful to protect the stony surfaces. Recent studies, on the other hand, showed very injurious results due to the application of chemical treatments and this critic must be taken into account for the final design.

Consolidation products must have the following characteristics: i) any development of secondary damaging products must be avoided; ii) the product must reach the entire decayed stony element, in order to be uniformly absorbed to guarantee a connection to the healthy part of the material; iii) the thermal dilation coefficient must be similar to the one of the material; iv) protective treatments are allowed but the surface must be permeable to the vapour; v) the external aspect of the stony element must be preserved (no alterations are allowed).

Also in this case, the consolidation products are suitable for specific problems and materials, as reported in Table 1.3.

The main characteristic of the consolidation products is that they don't react with the original materials on which they are applied. These products realize their action through polar and electrostatic bonds.

These products can be applied by brush: they don't penetrate in depth and constitute a waterproof barrier. For smooth surfaces the products are applied by percolating: by this technique the mixture should have the time to penetrate uniformly in the material. Wet packs are indicated for the application of products on sculptured materials: the pack is placed on the material and the mixture is introduced trough several tubes inserted in it, for a uniform imbibition. The application takes from 42 to 72 hours. During this period, the product penetrates by capillarity rise.

Decay and material type	Consolidation procedure
Superficial decay and damaged frescos	Acrylic resins: organic products with a limited penetration in the first layers of the material.
Silicate materials and damaged sandstones	Organic esters and ethyl-silicate: these are organic products based on silicon and have a good penetration. The ethyl-silicate develops amorphous silica that does not react with the material.
Presence of water	Alchilalcossisilane (Si+CH3.): contains an hydrophobic group that make the mixture a waterproof solution.
Carbonate and calcareous surfaces	Silicone resins. These are organic synthesis products.

Table 1.3: Main consolidation products and relative field of application

d) <u>The protection phase</u>

After cleaning and repointing, the stony surfaces should be preserved from the aggressive agents present in the atmosphere. This is the aim of the treatments, fluid mixtures that form a sort of protective film on the surface and for the first layers of the materials.

The application of protective products is recommended to slow down the deterioration process of the material and consists in the application of water-repellent mixtures. The idea is that the water is the main vehicle for different forms of decay (chemical, physical and mechanical), and after repairing and curing the material, through the application of a water-repellent treatment, the water coming from the atmosphere is not able to enter the material. However, the treated material remains permeable to the vapour, because the protective treatments must allow the exchange of humidity with the environment.

The introduction of treatments that do not allow the passage of the vapour can cause deep damages to the material and its durability (considering its natural interactions with the environment) decreases seriously. To ovoid this risk, protective treatments must respect the following characteristics: i) chemical inertia; ii) absence of damaging products; iii) chemical stability respect to the pollutants and the oxygen; iv) stability respect to U. V. radiations; v) low permeability to the liquid water (water-repellent); vi) good permeability to the vapour; vii) minimal influence on the optical-chromatic properties of the surface of the material; viii) good solubility in organic solvents, even after ageing, in order to allow the removing of the product (reversibility) during further planned maintenances.

When the presence of salt solutions in the material is observed, consolidation solutions and protective treatments cannot be applied. This indication is based on the fact that the crypto-efflorescence phenomena were identified by the crystallization of salts dissolved in the water, along the water-repellent barrier that takes origin in depth into the material, at the level of the mixtures penetration.

The application of the treatments is carried out by brush or spray method. The whole surface must be covered by the application, in order to avoid alterations depending from a not homogenous capability to contrast the water penetration in the material.

The action of the protective treatment is generally certified for five years, after which the product should be applied in the view of a regular maintenance of the building.

1.3.3 Conservation praxis and safety of the traditional buildings

The previous detailed description, of the procedures contained in Italian recommendations and manuals, for the conservation of the surfaces of the ancient buildings, shows a clear address of the conservative design: the main purpose is the protection of the integrity of the original materials, considered as parts of the original document coming from the past, with the traces left by people and historical events. The same evidence of the past can be found even in the hidden structural elements of the building: a static conception or peculiar technical solutions are part of the human being's evolution and for this reason should be carefully preserved.

The mechanical behaviour of the ancient structures is hardly predictable. The heterogeneity of the materials and the inhomogeneity of the building structures do not allow a clear interpretation of their performance. Nowadays, structural aspects are studied through the support of manuals set for the use of modern structures. Manuals and codes, developed since XIX century, when the behaviour of the building techniques, based on the use of concrete structures, became predictable through analytical models. The deep changing produced by the success of the modern building techniques caused a progressive separation from the traditional techniques. Masonry structures, being not easily interpretable, were considered not reliable. They were not suitable for the national and international standards which introduced the safety criteria for the buildings. As a result, the diffusion of a serious lack of knowledge, concerning the traditional structures, is the reason for wrong choices for strengthening and repairing design on structural elements. Since the appearance of the Athens Charter, the use of modern technology (the reference to reinforced concrete is very clear) is supported due to the will of a general increasing of the resistance of the structures. This idea was also introduced in national rules, such as the code 457/1978[29] and above all in the anti-seismic code[30].

The problems created through the introduction of reinforced concrete structures in ancient building will be presented in the further chapter, but a the relevant relationship between engineering approach and rehabilitation must be briefly outlined.

An important evaluation of the properties of the traditional building structures was supported by Antonino Giuffrè. Through his studies and his collaboration to the publication of operative manuals[31] for the interpretation of the mechanical behaviour of ancient building and the renewal of ancient centres[32], Giuffrè retrieved the knowledge and the mastery that went lost, since the success of the new building techniques. His research focused on the interpretation of the “box-like behaviour” that characterized the ancient buildings[33]

Giuffrè’s work belongs to an important tradition of research related to the masonry and timber structures that was outlined by the experts working in the superintendence offices or in other public corporations. These experts (usually engineers and architects) were responsible for the

[29] Legge 457, 1978, *Norme generali per il recupero del patrimonio edilizio*. The article 31 introduces the following definitions: ordinary maintenance, extraordinary maintenance, conservative renewal, rehabilitation. (Legge-457, 1978)

[30] Decreto Ministro dei Lavori Pubblici 24 gennaio 1986 (G. U. 12/05/1986, n. 108), Norme tecniche relative alle costruzioni antisismiche. (D.M.LL.PP.24-01-1986)

[31] Antonino Giuffrè, Caterina Carocci, *Codice di pratica per la sicurezza e la conservazione del centro storico di Palermo*, Laterza, 1999. (Giuffrè, 1999)

[32] A.A.V.V., , *Manuale del recupero del Comune di Città di Castello*, DEI 1993 (Castello, 1993); A.A.V.V., *Manuale del recupero del Comune di Roma*, DEI, 1997. (Giovanetti, 1997)

[33] Antonino Giuffrè, *Letture sulla meccanica delle murature storiche*, Editore Kappa, 1999, Milano (Giuffrè A. , Letture sulla meccanica delle murature storiche, 1990)

definition of the solutions required for the safety of the historical buildings. In this sense, Giovanni Poleni with his studies on the catenary, was a forerunner of the modern construction science[34], whilst Camillo Guerra[35] and Sanpaolesi[36], with their works for the superintendence offices, showed a great attention for the compatibility between ancient and modern structures.

A different approach, alternative to the theory of conservation, is proposed by Paolo Marconi. Through the study of the ancient structures, the identification of the characteristics of the building techniques, Marconi participated to the publication of several manuals containing a detailed description of the traditional building techniques, in specific geographical areas[37]. Marconi is convinced that reproduction (and not the imitation) of the traditional technique offers the best solution for the repairing and rehabilitation of the ancient structures. Marconi focused on the problem of the comprehension of the architectural work and the respect of the building lexicon.

Before the diffusion of the manuals for the rehabilitation of the historical centres of Rome, Palermo and Città di Castello, Giuffrè concentrated the attention on the technical Code[38] characterizing the historical buildings. This code is the result of a secular refinement, where the technical abilities developed during the time, forming a set of rules indicated by the definition of "getting down to a fine art". His purpose is to combine the safety requirements with the conservation rules: the respect of the fine art execution becomes the parameter that addresses the development of the design for the existing buildings. This approach has been turned into practise through important cases, as the plan for the rehabilitation of Ortigia, the ancient centre of Syracuse in Sicily. Thanks to this approach the protection of the traditional structures received an important support. The recent diffusion of the interpretation of the collapse mechanisms of the

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[34] Silvia Pennisi, Raffaella Riva Sanseverino, *Ingegneria e beni culturali: interdisciplinarietà in una collaborazione recente e in continua evoluzione*, atti del convegno "Storia dell'Ingegneria", Vol. 1, Napoli, 7-9 aprile 2008, pp. 309-320 (Pennisi, 2008)

[35] Renata Picone, *Camillo Guerra e gli aspetti strutturali del restauro architettonico*, atti del convegno "Storia dell'Ingegneria", Tomo 1, Napoli, 7-9 aprile 2008, pp. 1413-1428 (Picone, 2008)

[36] Bianca Gioia Marino, *Note sulla diagnosi dei dissesti strutturali tra XVIII e XIX secolo*, atti del convegno "Storia dell'Ingegneria", Tomo 1, Napoli, 7-9 aprile 2008, pp. 509-520. (Marino, 2008)

[37] P. Marconi, *Sicurezza e conservazione del patrimonio architettonico: il ruolo delle tecniche tradizionali*, Workshop *Memoria e restauro dell'architettura. Saggi in onore di Salvatore Boscarino*, 2005, Milano, pp. 182-185 (Marconi, 2005)

[38] A. Giuffrè, *Codice di pratica per il centro storico di Palermo*, 1999. (Giuffrè A. C., 1999)

macro-elements, in which the structures of a building can be divided, is a direct consequence of Giuffre's study of the seismic vulnerability for the historical buildings, proposed in his codes. Giuffrè remarked a deep critic towards the invasive transformation of the mechanical behaviour of the ancient structures and used the rule of the fine art execution to point out the resources offered by those structures.

1.4 The craftsman approach to the material culture

Referring to a thematic developed by Richard Sennett[39], the empirical experience can be a source of knowledge and an opportunity for valorizing the material data. The American sociologist proposes the image of an *homo artifex* able to formulate the best answer to a problem through the empirical experience.

In the same way, Giovanni Carbonara remarked the rule played complementary from the theoretical and the practical experience: the architectural restoration gets its auto-consciousness from the theory and its renovation from the practical experience[40]. Carbonara refers to the ideological conflict between different praxis of restoration and notices that the quality of the intervention is deeply influenced by the critic to the experiences (and many of them are negative) matured in the sphere of the architectural restoration. This evaluation of the operative praxis for carrying out the restoration process turns out in the application of technologies based on safeguarding criteria and the comprehension of different characteristics: from the construction rules of the building, to the details of the alteration and decay processes affecting their structures.

Even if some assumptions of his research are not shared from the theoreticians of conservation, A. Giuffrè provided an important contribution in the debate, moving the attention to the cultural values embodied in the structure of the ancient building. More in general, his work was useless to remark the importance of the mechanical behaviour that controls the architectural work. In his opinion, the identification of a constructive language respondent to a correct realization known as "fine art execution" [41], is the result of a review of the traditional building

[39] Richard Sennett, sociologo, autore del saggio *L'uomo Artigiano*, Feltrinelli, Milano, 2009
[40] Giovanni Carbonara, *Trattato di restauro architettonico*, vol. I, p. 4, UTET, Torino, 2007
[41] Antonino Giuffrè, *Letture sulla meccanica delle murature storiche*, Kappa ed., 1999.

techniques. According to Giuffrè, these realizations are the consequence of an evolution; the result of progressive changing in the technical field, imposed by the contingency and the empirical experience. He refers above all to the correction for some building praxis in problematic areas, characterized in the past by destructive events, like earthquake. The "fine art execution" as a sort of not formalized technical code, reached by a secular refinement in which the ancient builders identified the proper procedures for the realization of structures able to face the stresses produced by seismic events.

The identification of the agreement to the fine art execution of an historical building is based on researches and analysis on the state of conservation of its structures: the procedures developed to reach this knowledge are the results of what Sennett calls "craft-mastery"

1.5 Review of the substantial aspects of the material culture

According to the previous descriptions concerning the conservation design, the procedures set for the preservation of architectural surfaces are widely considered as the main issue of the conservation theory. As a consequence, this attitude did not promote an attention to the problematic of the maintenance of the building structures. Elevations are not bidimensional entity; their finishing is a surface layer connected to load-bearing walls, linked to horizontal (i.e. beams, wooden floors) or spatial (i.e. vaults, domes) structures. The structural system of historical buildings is often an invisible entity and its preservation has always been subordinated to the protection of the outer visible layers of the buildings. The definition of "structural restoration" given by Bonelli gave rise to some deep modification of the original structures of ancient buildings. Changings and substitutions of entire portions of the historical structure were recommended in the following cases:

- to adequate the existing building to the safety standards set for new constructions;
- to avoid the risk of fire, substituting the traditional wooden floors, roofs and beams with new fire resistant materials, such as reinforced concrete.
- to allow a new reuse of the existing buildings, introducing new functions sometimes not suitable to the original characteristics of the buildings.

Finally, after tragic seismic events, the introduction of new rules for the strengthening of old buildings has produced invasive procedure set to transform radically the traditional structural system in order to follow the ideal of an infinite stiff behaviour of the structure.

In this way, theoretical contributions related to the protections of the structural components of ancient buildings were not able to provide better technical solutions to contrast the methodology of deep renewals.

As a paradox an effort arrived by the field of structural engineering, which critic reviews of the negative effects due to new techniques and materials after years of continuous alterations of the original structure started to be remarked. In this sense the work of Antonino Giuffrè pointed out the problematic effects of invasive modern techniques inserted in ancient buildings.

Chapter 2. Rescue and protection of historic buildings: the operative tools available for the experts in the conservation field

2.1 Introduction to new complexities: from "Cecchi's Code" to the experience of the Seismic Risk Commission

By the definition of two theoretical positions (conservation and building rehabilitation), described in the previous chapter, concerning the protection of the historical architectural heritage, a common link can be observed: the technical knowledge is at the base of the design strategy for the conservation of ancient buildings.

The key role of the cognitive process was confirmed during the preparation and the application of the so called Merloni ter.[42] (DPR 21/12/1999 n. 554, new guidelines for the public works), that introduced the requested programmatic report related to the investigation on the building. This report is developed for diagnostic sectors and operation methods. The applied diagnostic tests will later support the feasibility study and will provide the basic knowledge for the judgment about the conditions of the investigated buildings. The choices for the conservative operations, in terms of types and methods, should be developed in a second time, during the phase of the detailed design. The aim of this regulation, issued by the Ministry of Public Work, is to subdivide the design process in three levels of elaboration: i) preparatory; ii) ultimate; iii) executive. This set of rules represents an important indication for experts (architects and engineers) and its field of application includes also low-restricted ancient buildings.

The Ministry of Cultural Heritage, thanks to the work of Roberto Cecchi, provided in 2004 the Code of Cultural Heritage and Landscape (DL 22 gennaio 2004, n. 42)[43]. The so called Cecchi's Code is a fundamental guide to interpret the philosophy of the conservation design and introduces for the first time the preservation of the landscape according to the European Convention of the Landscape (stipulated in 2000). This code refers to buildings subjected to low-restrictions and provides very generic specifications concerning the aim of the conservation design. It must be remarked that the code takes into account the problem of conservation of historical buildings in seismic area: article 29, paragraph 4, points out that works of structural improvement are allowed

[42] D. P. R. 21/12/1999, n. 554 (Merloni ter.), *Regolamento di attuazione della L. 11 febbraio 1994, n. 109 legge quadro in Materia di Lavori Pubblici*. (Merloni, 1999)

[43] Decreto Legislativo 22 gennaio 2004, v. 42, Codice dei beni culturali e del paesaggio, ai sensi dell'articolo 10 della legge 6 luglio 2002, n. 137, G. U. 24 febbraio 2004, n. 45, S. O. n. 28 (DL42, 2004).

in seismic areas. No specifications are given about technical information concerning the structural improvement.

Technical information is available in guidelines elaborated by experimental applications carried on by different commissions. Important efforts for the drafting of technical regulations have been matured in the last 20 years of the XX century thank to the research developed by the Research National Group for Defence against Earthquake (GNDT – Gruppo Nazionale Difesa dai Terremoti)[44]. The work of the group was useful for saving the knowledge about traditional building techniques: masonry above all. The results of the Group work were the Guidelines proposed in 1986 to the experts. He studies were followed by a cluster of university laboratories aimed to set the new code "Technical roles for buildings in seismic areas" in 2003.

The previous Seismic Risk committee was substituted by a network of university laboratories called ReLUIS[45] that will have an important role in the preparation of the new "Guide-lines for the application of the technical standards to the Cultural Heritage", elaborated after recent seismic events (i. e. L'Aquila). The new regulation is based on a complete definition of the typological characteristics of the historical buildings and for the first time a new category is introduced: the so called "aggregate". This building category is much diffused in Italy and is characterized by the union and overlay of buildings realized in different times in a unique complex volume. The interpretation of the mechanical behaviour for the connections of such complicated structures is the point for setting an appropriate conservation design.

2.2 Codes, ordinance and guide lines: compromises between conservative requests and safety requirements

The aim of this research is to discuss on the indications for the preservation of the cultural heritage, collected in regulations and recommendations.

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[44] Information about the G.N.D.T. project and the materials published by different subjects involved in this research are available at the following link: http://gndt.ingv.it/Menutree/Home.htm. (GNDT, 2008)

[45] ReLUIS is a network of university laboratories. Information about ReLUIS project are available at the following link: http://www.reluis.it/. (ReLUIS)

Thanks to the Italian approach to antiquities, also the architectural heritage is considered as a complex of material objects, able to generate religious, social and political values: its protection does not represent only the defence of an historical memory, but the immanence of an aesthetical value that reached shape and consistency through the architectural expressivity.

Weltanshaung of various periods, evidence of the intellectual achievements, historic buildings preserved a multiplicity of values which justify their conservation. The conservation practise is based on a debate continued for centuries which showed periodically some difficulties for the solution of peculiar problems: from the loss of the built heritage (the problems connected to the war devastations or the collapses due to natural events) to the problem of its transformations, the conservation practise have always been facing an intricate reality. The complex nature of the problems concerning building structures is a limit for the codification of a specific intervention methodology for each issue.

a) b)

Figure 2.1: Milan, Palazzo della Ragione: a) facade on via Dante and b) detail of the preserved overlap of the surface of the facade (pictures from G. Carbonara, "Trattato di restauro architettonico", p. 609).

A first unsolved question is connected to the origin of the conservative approach: the protection of monuments. Conservative methodologies developed for the defence of monumental buildings, as described in the first chapter, are based on innovative results provided by experts operating in research centres and not completely adopted by the common building market. For this reason the conservation techniques are not integrally applied to the so-called diffused historical patrimony. For instance, the conservation design adopted for the preservation of the stratigraphic overlap of the plasters in the *Palazzo della Ragione* of Milan (Figure 2.1) is the result of the procedures described in paragraph 1.3.2. This peculiar attention to the consistency of the material data and of the signs left by the time on the surfaces of the facades is not present for the typical renewal of an old building without monumental characteristics. In this cases the signs of the time on the external surfaces are totally erased and so the historical aspect of these buildings is substituted by the standardization of the surfaces (Figure 2.2). The same approach is adopted for the hidden building structures, which are more respected in the monumental buildings than in the diffused one.

Figure 2.2: Views of the facade of a building in an historical centre before and after the renovation of the surfaces (author's picture).

This topic becomes relevant if compared with the today's debate on the measures for the defence of the historical centres damaged by catastrophic events, like earthquake or wars (Figure

2.3). In these cases, the regulations and the solutions are developed in an extraordinary condition of urgency. This is the case of the suspension of the 1931 Charter's principles proposed by G. Giovannoni and G. De Angelis D'Ossat[46] on the morrow of the Second World War. Considering the extension of the damages, the destruction of several monumental buildings, De Angelis D'Ossat published the guidelines for the intervention on the existing buildings. As remarked by A. Spinosa[47], these recommendations were set to rebuild the lost shapes for deeply damaged buildings where the traces of the original architecture were still recognisable. For these buildings completely destroyed, the recommendations were oriented to the reconstruction by new formal configurations. This set of rules was based on a deep feeling of the destroyed monument and on the will of erasing the destructive event. The same condition of emergency is represented by devastations caused by seismic events. Since Italy is a seismic territory, regulations containing indications for the post-seismic reconstruction are present even in the pre-unitary states of the peninsula.


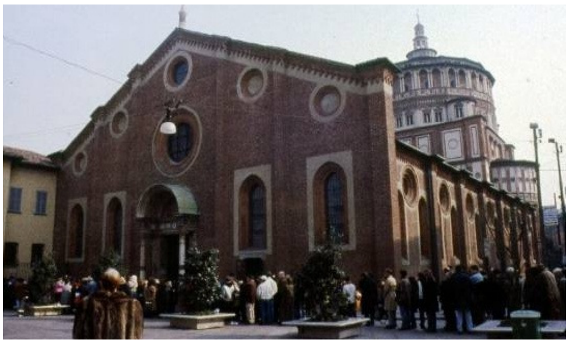

Figure 2.3: Milano, Santa Maria delle Grazie: a) view of the church after 1944 bombing and b) a recent view of the church, repaired fallowing the D'Ossat's recommendations.

The recent anti-seismic regulations of the Italian Republic was developed since the 70s of the last century. The characteristic of the main acts referred to earthquakes is a strict distinction between the competition between the Ministry of Public Works and the Ministry of Cultural

[46] Guglielmo De Angelis D'Ossat was the director of the Office for Antiquity and the Fine Arts after the Second War World and published, in 1948, the paper *Danni di Guerra e restauro dei monumenti*. (De Angelis D'ossat, 1977)

[47] Arianna Spinosa, *Ingegneria sismica e restauro nella ricostruzione postbellica. Gli studi di Piero Sanpaolesi per la copertura del Camposanto Monumentale di Pisa*, in "*Storia dell'ingegneria*", Atti del 2° Convegno Nazionale, April 7-9, 2008, Napoli, pp. 1487-1500.

Heritage. The first provides the operative regulations for the buildings (even the historical ones) which are not classified as monuments, whilst the second provides the recommendations for the monuments. For this reason the praxis of the interventions on buildings damaged by seismic events are different for diffused buildings and monuments. As a result, legislative instruments for the preservation of ancient buildings could present discordant procedures. According to the legislation set for the buildings under preservation, the conservative approach provides the indications for the conservation of the integrity of the historical traces, both for formal and material aspects. On the other side, the legislation set for the non-protected existing buildings promotes the defence of formal and aesthetical aspects, ignoring the material consistency of these works.

The discrepancy between these methodologies acting on the architectural heritage compromised the defence of the historical buildings, usually for the diffused buildings. This is the case of the buildings subjected to anti-seismic adaptation, a strengthening conception that privileged the introduction of modern structures providing strength increasing on the existing one. This idea was introduced with the first version of the Italian code for the anti-seismic measures[48] in the 70s of the last century. This kind of disposition did not take into account the resources of the ancient structures, ignoring their original mechanical properties. This trend was unfortunately present in the several recommendations appeared after recent earthquakes. This means that the strategies indicated by the experts to guarantee the safety of the buildings were based on the prospective of a strengthening of the structures and not on their deformability[49].

On one side, historical buildings were transformed in depth without taking into account their real mechanical characteristics, whilst on the other the organisms arranged for their defense ignored important questions. The main paradox came from the criteria contained in the conservation theory: the first principle indicates the necessity of maintaining the historical

[48] Legge 2 febbraio 1974, n. 64, *Provvedimenti per le costruzioni con particolari prescrizioni per le zone sismiche*, Gazzetta Ufficiale21 Marzo 1974, n. 76. (Legge n. 64, 1974)

[49] A synthesis of the main approaches concerning the strengthening and the repairing techniques is contained in D. Liberatore, G. Spera, G. Perillo, *La riabilitazione strutturale di aggregati edilizi murari con solai flessibili in zona sismica*, in L. Binda (coordinator), *Sicurezza e conservazione degli edifici storici in funzione delle tipologie edilizie, della concezione costruttiva e dei materiali*, Workshop, Milano, 2004. (Liberatore, 2004)

building assuring its life-time; the second remarks the request for maintaining the signs of the time; the third referred to the design as synthesis of the previous questions. P. Torsello[50] pointed out that each principle is formulated in a contradictory way. He uses the term “aporia” to describe the main questions:

- *Aporia* 1: maintenance should be assured applying all the strategies matching this purpose but not conflicting with the preservation of the sign and the defects produced by the time. Unfortunately the common methodologies used to extend the life-time of the ancient buildings are usually fairly invasive, especially with the superficial signs of the time.
- *Aporia* 2: permanence of the signs left by the time must be preserved without compromising the duration of the building in the time. Also in this case the common solutions applied for the conservation of the alterations of the materials are a limit for more invasive techniques used to reinforce and repair the structures of the ancient buildings.
- *Aporia* 3: the questions imposed through the previous points request the formulation of a design that is able to match the complexities and the contradictions contained in the conservation principles. Torsello suggests the adoption of a responsible ethics: the architect (or more in general the designer) is the responsible for the final choice and must be able to evaluate the consequences of the proposed technical strategies, in order to avoid the mechanical application of methodologies codified for very specific problems and not applicable to each similar case.

As many other experts, Torsello was critical to the idea that the codes and the recommendations for the conservation field contain the answer for each questions. In his opinion the complexity of the reality does not allow a categorization into problems and of the corresponding solutions. He invites to tour the enclosures of the knowledge, in order to open the designer’s mind to strategic solutions able to overpass the *aporia*. In this way the restrictions imposed by each theoretical assumption can be smoothed and adapted for the different circumstances. The conservation practice, for example, has been limited in many cases to the

[50] The main publications from M. Torsello, one of the main exponents of the Restoration School of Genoa are: P. B. Torsello, *Figure di pietra. L'architettura e il restauro*, Marsilio, 2006 (Torsello, 2006), and P. B. Torsello, *La materia del restauro. Tecniche e teorie analitiche*, Marsilio, 1988. (Torsello, 1988)

documental values of the ancient buildings. This approach can be applied to the work of arts (i.e. portraits), but the architectural field presents more complexities: it cannot be reduced to an aesthetical problem, but architecture cannot exist without taking into account even its function (*utilitas*).

The main problems connected to the diffusion of technical regulations are the limited views of the problems: historical buildings present a heterogeneity of characteristics which do not allow a standardization of the procedures for their conservation. The three dimensions of the architecture, *venustas*, *firmitas* and *utilitas*, impose strategic solutions which should be evaluated time by time for each case. According to this view, codes, manuals and regulations are able to give an important effort for the research of strategic technical solutions (*firmitas*), but the other fundamental components for the architectonic design must be achieved from other fields of knowledge (*venustas* and *utilitas*).

The risk is that the conservation practice, focusing on the respect of the surfaces and on their decay processes, could be influenced by aesthetical purposes. According to this attitude, the historical structures, like masonry walls, vaults, timber roofs or floors and all the elements supporting the surfaces, are ignored, being hidden parts of the building without aesthetic values. Privileging the *venustas*, the *firmitas* (intended as use of the building techniques) is assigned to those experts which nowadays lost the knowledge of the traditional techniques, being educated to the new principles of standardization and following the utopia of the indestructible material, the concrete.

Another issue that was skipped by the theoreticians of conservation is the problem of the historical buildings in seismic area. The removal (or at least the reduction) of the pathologies afflicting the surfaces, limited to the external layers of the buildings, is not sufficient to insure the structural safety in seismic area. The method of study proposed by Brandi, based on the elaboration of a material-pathological survey, cannot provide detailed information for the hidden layers of the structures: textures, materials, connections, etc. According to this problem, another *aporia* takes origin: the conservation theory and its assumption of limiting the visual inspections on the structures in order to preserve the integrity of the historical buildings and the need of knowledge concerning hidden structures.

Recently in Italy, as a consequence of tragic events, new indications were set by the legislator, providing new solutions for the existing buildings. After the Umbria and Marche earthquake, in order to overpass the gaps present in the idea of the adaptation, the concept of improvement (mentioned in the D.M. 24/01/1985 but never applied) was supported through new efforts. The main one came from the retrieval of the knowledge concerning the properties of the traditional building techniques. At the same time, the importance of taking this issue further, in order to interpret the properties of the historical structures, was promoted by other international organisms. Institutions like UNESCO or ICOMOS supported the debate on conservation design, introducing the exchange of knowledge between experts. In these stimulating confrontations between different local experiences, the role played by the diagnostics in the definition of the final design increased.

In this context, the outcome obtained by recent Italian regulations outlined a new trend. Since 2003, after a tragic earthquake that hit Campobasso and Molise region in 2002, the publication of the *Technical rules for buildings in seismic areas* (Ordinance 2003)[51], followed by the *Guide-lines for the application of the technical standards to the Cultural Heritage*[52] (edited in 2004) arriving to the recent *Guide-lines for strengthening design on complex buildings*[53] (edited in 2010), showed a synergy between the Ministry for Cultural Heritage and the Ministry of Public Works. These regulations mention the necessity of a detailed knowledge of all the components forming the building system. Being so much variable, only generic regulations can be provided for the building typologies.

2.3 The practice of conservation in seismic area

Although the directive contained in the Ordinance 3724/2003 of the Prime Ministership[54] and in the further Technical regulations for the buildings edited in 2010 by the Ministry of Public

[51] Ordinanza n. 3274 del 20 marzo 2003, *Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica.* (OPDCM n. 2374, 2003)

[52] Ministero delle attività Culturali, *Linee Guida per l'applicazione al patrimonio culturale della normativa tecnica di cui all'Ordinanza della Presidenza del Consiglio dei Ministri 20 marzo 2003, n. 3274. Edited in 2004.* (Ministero per le Attività Culturali, 2004)

[53] Ministry for the public works, *Linee guida per il rilievo, l'analisi ed il progetto di interventi di riparazione e rafforzamento/miglioramento di edifici in aggregato*, maggio 2010 (Ministero dei Lavori Pubblici, 2010)

[54] See reference n. 51. (OPDCM n. 2374, 2003)

Works[55] constitute a serious tentative to make order in the Italian legislative panorama, they are partially taking into account the requirements connected to the complexity of the conservation. In order to provide indications for ancient buildings under protection, in 2005 the Ministry for Cultural Heritage published the Guide-lines for the application of the technical standards to the Cultural Heritage[56].

Other efforts came from the research units participating in the ReLUIS project[57]. Respect to the lack of clarity that characterises the 2005 guide-lines, some research, promoted in ReLUIS contracts[58], developed the applications of diagnostic techniques useful for the evaluation of the mechanical properties of historical buildings.

The long path, starting with the first measures to contrast the effects of earthquake in the pre-unitary states of the Italian peninsula and concluded with the above mentioned regulations, produced a series of acts briefly summarized in Table 2.1.

Since the first studies for the micro-zoning carried on in Friuli Region in 1972, the project for the micro-zoning of the entire national territory had a new stimulus after the 2009 L'Aquila earthquake. Nowadays the preparation of the guidelines for the definition of geotechnical and dynamic properties of the ground are under construction[59]. Some Italian Regions, as Lombardy, have already adopted the new criteria contained in the guidelines, providing short typological profiles to support the expert's activity.

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[55] DM 14 gennaio 2008, Ministero delle infrastrutture e dei trasporti, *Norme tecniche per le costruzioni*, supplemento ordinario n. 30 alla Gazzetta Ufficiale del 29/3/2005 (DM 14 gennaio)

[56] Dipartimento della Protezione Civile, Dipartimento per i Beni Culturali e Paesaggistici - Direzione Generale per i Beni Architettonici e Paesaggistici del Ministero per i Beni e le Attività Culturali, attuazione del Decreto Interministeriale 23 maggio 2005, finalizzato all'elaborazione delle *Linee Guida per l'applicazione al patrimonio culturale della normativa tecnica di cui all'Ordinanza della Presidenza del Consiglio dei Ministri 20 marzo 2003, n. 3274* (D. Interministeriale 23 maggio 2005, 2005)

[57] The network of the university laboratory of seismic engineering (ReLUIS), was created in 2003, April 17. It is a inter-university group with the aim of coordinating the activities of the seismic engineering laboratories, providing scientific, organizing, technical and financial supports of the associated universities.

[58] Dipartimento della Protezione Civile, ReLUIS, *Linee guida per il rilievo, l'analisi ed il progetto di interventi di riparazione e rafforzamento/miglioramento di edifici in aggregato*, maggio 2010, Available at: http://www.reluis.it/

[59] *Indirizzi e criteri per la micro-zonazione sismica* (*Guidelines and Criteria for the seismic microzoning*) (Protezione Civile, 2011). These guidelines contains more detailed procedures for the determination of the acceleration spectra characterising specific administrative areas and represent an alternative respect the *Norme tecniche per le costruzioni* (NTC, 2008 – *Technical Regulations for the Buildings*).

Seismic event	**Period**	**Regulations**
Reggio Calabria	1894	
Messina	1908	Regio Decreto 193 – 1909 *portante norme tecniche ed igieniche obbligatorie per le riparazioni ricostruzioni e nuove costruzioni degli edifici pubblici e privati nei luoghi colpiti dal terremoto del 28 dicembre 1908 e da altri precedenti elencati nel R. D. 15 aprile 1909 e ne designa i comuni.*
Marsica	1915	Decreto Legge 1516 - 1919
Belice and Western Sicily	1968	
	1971	Legge 1086 – 1971. *Norme per la disciplina delle opere di conglomerato cementizio armato, normale e precompresso ed a struttura metallica.*
	1974	Legge 64 -1974 *Provvedimenti per le costruzioni con particolari prescrizioni per le zone sismiche.*
Friuli Region	1976	Legge Regionale n. 30 - 20 Giugno 1977. *Nuove procedure per il recupero statico e funzionale degli edifici colpiti dagli eventi tellurici* (Giuseppe Zamberletti Commission)
Irpinia Area	1980	Decreto Ministeriale del 2 Luglio 1981 (G.U. 21-7-1981, n. 198 supplemento). *Normativa per le riparazioni ed il raffor-zamento degli edifici danneggiati dal sisma nelle regioni Basilicata, Campania e Puglia.*
	1986	Decreto Ministro dei Lavori Pubblici 24 gennaio 1986 (G.U. 12/05/1986 n. 108). *Norme tecniche relative alle costruzioni antisismiche.*
	1996	Decreto Ministeriale 16 gennaio 1996 (G. U. 5/2/1996 – N. 29). *Norme tecniche per le costruzioni in zone sismiche.*
Umbria and Marche Regions	1997	Delibera Regionale 24 marzo 1998. *Primi interventi di riparazione dei danni e di miglioramento sismico delle unità immobiliari destinate ad abitazione principale danneggiate dagli eventi sismici iniziati il 26 settembre 1997*.
	1998	D.G.R. n. 2153 SI/LPU del 14/09/1998 recante : *Modalità e procedure per la concessione dei contributi previsti dall'art. 4 della L. n. 61/1998.*
Molise Region	2002	OPCM del 30 Marzo 2003. *ORDINANZA del Presidente del Consiglio dei ministri 20 marzo 2003, n. 3274. Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica*
	2004	Decreto Legislativo 22 gennaio 2004, n. 42. (G. U. 24 febbraio 2004, n. 45 - Supplemento Ordinario n. 28) *Codice dei beni culturali e del paesaggio, ai sensi dell'articolo 10 della legge 6 luglio 2002, n. 137.*
	2008	Decreto Ministeriale 14 Gennaio 2008. *Nuove Norme Tecniche per le Costruzioni.*
	2009	Circolare esplicativa n. 617 del 2/2/2009. *Testo unico sulle costruzioni.*
L'Aquila and Abruzzi Region	2009	Linee Guida della Protezione civile. *Linee guida per il rilievo, l'analisi ed il progetto di interventi di riparazione e rafforzamento/miglioramento di edifici in aggregato.*

Table 2.1: Sequence of the measures in anti-seismic field in relation with the main seismic events occurred in Italy.

Actually, in Italy, a wide reorganization of the regulations concerning the buildings in seismic areas (for new projects and existing buildings) is going on. The change began in 2003 through the editing of the Ordinance n. 3274, containing a set of rules for the seismic classification of the territory and for the design in seismic areas. The ordinance is not a complete law, but a transitory measure that introduces important innovations: the national territory is divided into 4 levels (1 is the most dangerous area) and for the first time all those areas which were not classified by the previous regulation (Legge 64, 1974 – *Act 64, 1974*) were inserted in the fourth level (the less dangerous). For specific building typologies (like bridges, houses, foundations), the ordinance introduced the principles contained in the Eurocode 8.

The Ordinance 3274/2003 had to be turned into law in 2004, but its promulgation was suspended: since 2004 this measure has been periodically postponed. A reason for this delay is the contemporary promulgation, in 2005/09/23, of the *Comprehensive text of Technical Regulations for the Buildings* ("Testo Unico delle Norme Tecniche per le Costruzioni" - NTC), by the Ministry of Infrastructures. This text collects all the regulations of the Italian code concerning building design. The new technical regulations were edited as ministerial order 2008, January 14[60], but the complexity of the about 400 pages of the text and the difficulties in the homogenization of the Italian rules with the new Eurocodes determined a delay in its conversion into law. Since 2008 the technical regulations for the building have been regularly postponed.

The comprehensive text for the technical regulations contains criteria for:

- designing, realization and testing of new buildings;
- the definition of the required performances in terms of stability and mechanical resistance;
- the identification of the mentioned performances in case of fire;
- the estimated durability of materials and structures;
- the definition of the actions (stresses) which the design have to adopt;
- the characteristics of the materials used for the buildings;

These criteria deal with the safety of the building structures, from its design to its execution. It is clear that this measure was specifically set for new planning activities and in this enormous legislative corpus the existing buildings are not considered.

This gap was corrected by the President of the Council in January 2008, through the promulgation of the *Guidelines for evaluation and mitigation of seismic risk to cultural heritage*, according to the indications contained in the Technical Regulations for the Buildings (NTC). The new recommendations were later on completed by the officers and the consultants of the

[60] DM 14 gennaio 2008: *Norme Tecniche per le Costruzioni*, in Gazzetta Ufficiale 4 febbraio 2008

Ministry for the Cultural Heritage and Activities. As explained in the premise by R. Cecchi, these guidelines are in compliance with the Ordinance of the President of the Council no. 3274/2003 "First elements on the topic of general criteria for seismic classification on a territorial scale and standards for construction in seismic zones" which was prepared and improved by the Task Group for The Great Risks Committee coordinated by the Civil Protection Department and in collaboration with the Ministry for Cultural Heritage and Activities. According to Appendix no. 2 of the Ordinance, "Technical rules for the design, evaluation and seismic assessment of buildings", and considering the 11th chapter, a fruitful collaboration between the General Direction of Architectural Heritage and Landscape of the Ministry for Cultural Heritage and Activities and the Department of Civil Protection was engaged. Mentioning Cecchi and Calvi's words:

"The aim was that this document would be able to reconcile the fundamental need to reach higher levels of safety with protective measures. Furthermore, the document would translate into an operational plan orientated towards research on minimum intervention techniques so as to favour systems which relates different aspects of knowledge rather than the indiscriminating overlapping of regulations."[61]

The aim of the guidelines is to work out the final evaluation of the safety ensured by mathematical modelling and design, applied to masonry buildings. At the same time the guidelines promote the control on the conservation of the original material characteristics of the existing buildings.

The conservation of the architectural heritage and the respect of the safety conditions is supported through different levels of evaluation: the vulnerability is studied at the level of the territory (urban scale) and the evaluation of the safety is controlled at the level of the building.

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[61] Text taken from L. Moro, *Guidelines for evaluation and mitigation of seismic risk to cultural heritage*, Gangemi Editore, Rome, 2007, p. 5. (Moro, 2007)

2.3.1 Introduction to the mechanical interpretation of masonry structures

The work group that developed the guidelines outlined that the safeguarding of the architectural heritage can be obtained through measures of prevention, rather than strengthening interventions. The long experience of poor projects, formulated through superficial studies of the characteristics of the existing buildings, showed the inadequacy of that approach. The reference to new construction criteria, not in harmony with the existing building properties, produced disastrous results, compromising the conservation of considerable parts of the Italian cultural heritage.

The main damages reported in recent seismic events take origin from an incomplete comprehension of the mechanical behaviour of ancient masonry and timber structures. Monumental buildings present complex spatial structures, such as domes and vaults, and the interaction between them and two-dimensional elements (like walls or floors) is not easy to interpret. Usually these kind of structures were realized following very high standards of efficiency, but their response under the effects of an earthquake can have unexpected results. This is the case of the collapse of the vaults of the first two spans in Assisi Cathedral (Figure 2.4).

Figure 2.4: Two frames of the video recorded in the superior Basilica of Assisi during the collapse of the vaults of the first two spans of the nave (pictures available in the web at the following link:)

In other cases the buildings techniques used for large structures were not correctly designed or not properly realized, as the collapse of the Cathedral of Noto demonstrated (Figure 2.5a). Here the pilasters of the nave presented a diffused crack pattern along vertical paths, index of a progressively loss of effectiveness of the masonry structures under the compressive stresses, but this clear indication was unfortunately ignored. The missed recognition of a dangerous state of conservation of the structures drove to the failure of the pillars of the south side of the nave, which produced the collapse of the roof of the main nave, the south aisle and the dome[62]. During the reconstruction works the survived pillars were investigate in depth: the dismantling of these pilasters could be performed (during the investigation phase) by hands, due to the bad conditions of the stones (Figure 2.5b). Moreover, after the removal of the plaster, several cracks were observed on the masonry structure (Figure 2.5c).


a)


b)

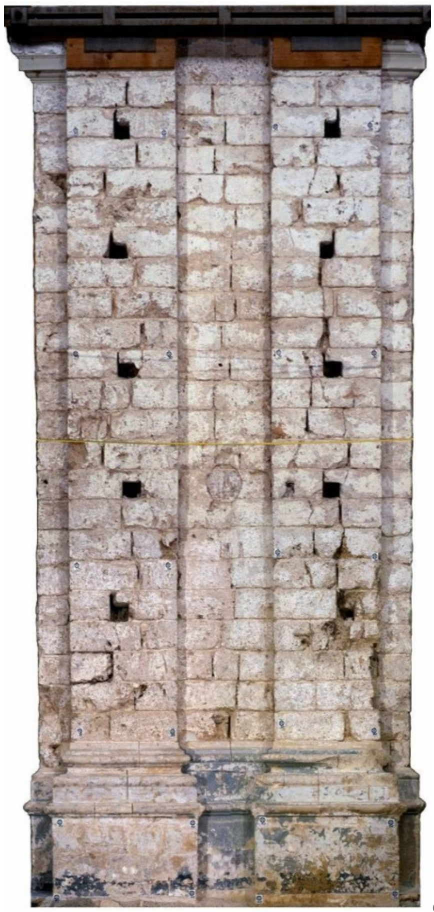
c)

Figure 2.5: Pictures from the collaped Noto Cathedral: a) view of the interior of the cathedral after the collapse (picture taken from R. De Benedictis e S. Tringali "La ricostruzione della Cattedrale di Noto", LCT Edizioni,2000, p. 20 (De Benedictis, 2000)) ; b) view of a stone during the dismantling of a pilaster (courtesy of prof. L. Binda); c) digital photo-straightening of one side of a pillar of the nave after the removal of the plaster (courtesy of A. Saisi).

[62] Information concerning the causes which drove to the collapse of the Noto Cathdral are contained in *Construction and Building Materials – Special issue on reconstruction of Noto and Dresden Cathedrals*, no. 8, Volume 17, December 2003, Elsevier, 2003 (L. Binda, 2003). Other detailed information are available in Binda L., Saisi A., *The collapse and reconstruction of the Noto Cathedral: importance of investigation for the design choice*, published in "Restoration of Buildings and Monuments", Vol. 9(4), pp. 415-433, 2003. (Binda, 2003)

As mentioned before, many damages on historical buildings are the consequence of wrong projects. The idea of changing the mechanical properties of ancient structures, following the short-sighted conviction that masonry structures are inadequate, showed several problems. The effects of the adaptation to safety coefficients of new structures are largely recognised: absence of connections between the existing structures and new stiff reinforcing elements (such as modern floors, r.c. curbs, etc.) and a general increasing of the stresses acting on the existing walls. After the earthquake that stroke L'Aquila, many adequated historical buildings collapsed totally or partially (Figure 2.6). This was also the destiny of many other historic buildings which were not improved by prevention measures (Figure 2.7). They presented structural faults (mainly due to bad connections between the different structural elements), but those existing buildings respecting the principles outlined in Giuffre's studies showed a good response to the earthquake (Figure 2.8).

Figure 2.6: Onna (L'Aquila). View of a collapsed building, damaged by the wrong design of the new adapted r.c. roofing system, placed on the existing masonry structures (author's picture).

Figure 2.7: Onna (L'Aquila). View of the devastation of an urban quarter in the centre of the village. (author's picture)

a) b)

Figure 2.8: Bazzano (L'Aquila). Comparison between two historical buildings stroke by the 2009 earthquake: a) view of an existing building (an aggregate) that was able to face properly to the earthquake; b) view of a collapsed existing building, placed in the nearest of the previous one, that was not able to contrast the seismic actions (author's pictures).

a) b)

Figure 2.9: Bazzano (L'Aquila). Detailed views of the buildings presented in figure 2.8: a) the texture of the walls reveals an edge built with larger shaped well connected stones and the floors are even connected to the vertical masonry walls through tie rods as shown by the head of the rod visible on the façade; b) the collapse of the building is due to an insufficient connection between the components of the building (author's pictures).

The interpretation of the mechanical behaviour of historical buildings received a considerable support from the experts working in the structural engineering field. A useful synthesis of the evolution of the main techniques designed for the conservation of the historical buildings is presented by A. Aveta[63]. According to Aveta's opinion, since the appearance of the legislative measures for the implementation of the technical codes of the so-called Merloni-ter[64] (the reform concerning the public works), the restoration methodologies were reformed following these steps:

[63] A. Aveta, *Le tecniche tradizionali per la conservazione dell'architettura: applicabilità e limiti*, in A. Aveta, S. Castello, F. La Regina, Renata Picone, *Restauro e consolidamento*, Mancosu Editore, 2005, pp. 27-36. (Aveta, 2005)

[64] Legge 18 novembre 1998, n. 415 G.U. n. 284 del 4 dicembre 1998 – Supplemento all' ordinanza, Legge 11 febbraio 1994, n. 109 coordinata con la legge 18 novembre 1998, n. 415 recante *"Modifiche alla legge 11 febbraio 1994, n. 109 e ulteriori disposizioni in materia di lavori pubblici".*

a) Preparatory design: it is composed by a programmatic report of the knowledge concerning the building, developed through investigation sectors and intervention methodologies. Investigation techniques are used to produce a feasibility study on the project.
b) Final design: it represents a deepening for the definition of the choices concerning the solutions requested through the previous feasibility study.
c) Executive design: it contains the detailed indications for the application of the interventions prepared in the final design.

The preparatory design represent the basis for the development of the further design levels. The code contains some indications for the definition of the test typologies:

- Historical-critical research;
- Building materials and techniques;
- Survey of the fabrics;
- On-site diagnostic tests, at the building level and at territory scale;
- Evaluation of the structural behaviour of the building and identification of material decay and failures;
- Other contribution from other research fields.

These indications are useful, but they provide slight requirements and represent a simplification of the knowledge process. New contributions to the definition of a complete anti-seismic strategy came from the re-actualization of past studies. Due to delays for the definitive promulgation of the anti-seismic roles, experts and researchers rediscovered the studies of important masters. S. Mastrodicasa can be an important example. His book, published in 1943, "*Dissesti statici delle strutture edilizie"* (*Static faults of building structures*) is a basilar work for the interpretation of the mechanical behaviour of existing buildings (Figure 2.10) and had a great influence on further developments of this discipline[65]. This publication contains schematic illustrations describing the main stress distributions according to building structures. The collapse mechanisms are explained by referring to real cases and considering static models (Figure 2.10 b and c).

[65] S. Mastrodicasa, "*Dissesti statici delle strutture edilizie*", nona edizione, Hoepli, 1993. (Mastrodicasa, 1993)

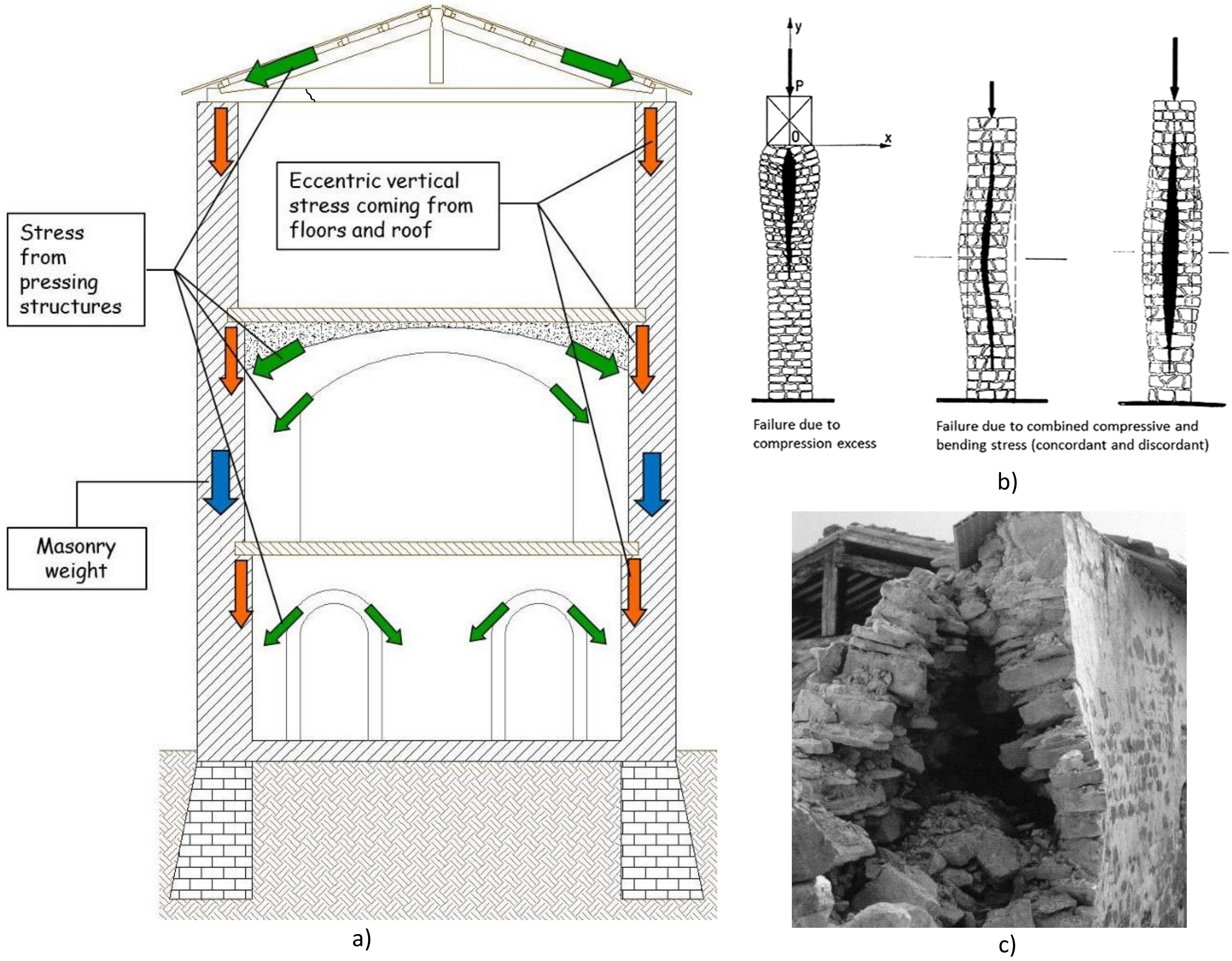

Figure 2.10; Example of mechanical behaviour interpretation for an historical building according to the Mastrodicasa's layout: a) stress distribution in an ancient buildings composed by masonry structures, wooden floors, wooden roof and pressing structures like arches and vaults (author's draft); failure mechanisms for masonry walls (drafts from Mastrodicasa, "Dissesti statici delle strutture edilizie", 1943, elaborated by the author); c) example of vertical division between masonry layers due to lack of connections (picture taken from F. Doglioni and P. Mazzotti, "Codice di Pratica per gli interventi di miglioramento sismico nel restauro del patrimonio architettonico", Regione Marche, 2007, p. 109. (Doglioni F. M., 2007)

Even tragic circumstances favoured the development of innovative means, especially in the information technology. In this sense, after the Friuli Region earthquake, the POR method[66] was introduced during the 70s of the last century to support the structural design. This software

[66] The POR method in officially introduced in Circolare 21745 del 30/07/1981, Legge 14 Maggio 1981 n. 219 - art. 10 "Istruzioni relative alla normativa tecnica per la riparazione ed il rafforzamento degli edifici in muratura danneggiati dal sisma" (Legge n. 219, 1981) but was previously adopted in Regional recommendation DT2, *Raccomandazioni per la riparazione strutturale degli edifici in muratura,* Regione Autonoma Friuli Venezia-Giulia, Aprile 1978. (D.T.2, 1978)

allowed the modification of the structural layout of the building, in order to introduce different interpretations of the constraints between its parts. Nevertheless, it presented several limits in the interpretation of the collapse mechanisms of the load bearing walls and it was substituted by other methodologies, like the structural analysis in elastic field proposed, among many other experts, by G. Croci, who contributed to the diffusion of the finite element method. The introduction later on of the limit analysis allowed simplifying the structure into a series of stiff elements, connected by plastic zones, in which all the deformations were concentrated. Applying the limit analysis, the identification of the actions corresponding to the collapse of the structure was possible: the evaluation of the safety margins can be determined by mean of the definition of the working loads[67].

Once of the most important contribution was introduced by the dynamic analysis. It can evaluate the seismic effects through the use of layouts based on the progressive plasticization of the structures of the building. The utilization of equivalent static analysis provides a simplification of the problem allowing the determination of the vibration modes of the structure[68]. This mathematical layouts were implemented thanks to the study promoted by the GNDT research group: the definition of the so-called macro-elements was particularly supported by the information collected by the research unit *"Definizione qualitative dei danni attesi e casistica di interventi preventivi per la loro riduzione in edifici ecclesiastici e complessi monumentali"* chaired by prof. F. Doglioni. The macro-elements are the constitutive parts of the building (see) and can be divided into two-dimensional elements (walls, floors, arches, etc.) and three-dimensional elements (vaults, domes, etc.). The connections between these parts guarantee the structural effectiveness of the building and its response during seismic events. This research[69] introduced the parallelism between the crack pattern layout characterising the macro-elements (Figure 2.11) and

[67] A: Giuffrè, C. Carocci, *Codice di pratica per la sicurezza e la conservazione del centro storico di Palermo*, Laterza, 1999.

[68] Benson H. Tongue, Principles of Vibration, Oxford University Press, 2001 (Tongue, 2001)

[69] The study was edited in F. Doglioni, A Moretti, V. Petrini, Le chiese e il terremoto. Dalla vulnerabilità constatata nel terremoto del Friuli al miglioramento antisismico nel restauro, verso una politica di prevenzione, Ediziioni LINT, Trieste, 1994. (Doglioni F. M., 1994)

the corresponding collapse mechanisms (Figure 2.12). This idea met a large agreement and was later systematize in a new specific guidelines by the Department of Civil Protection[70].

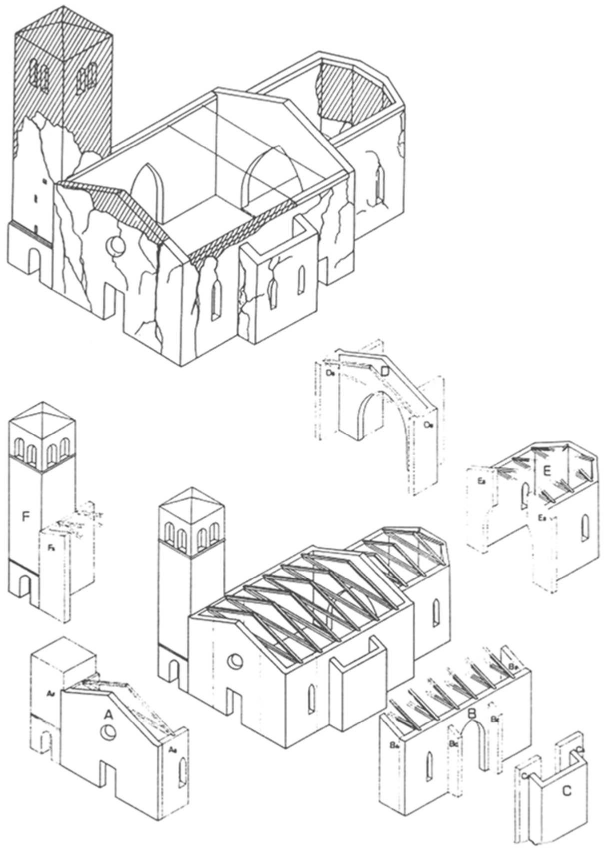

Figure 2.11: Example of macro-elements subdivision for an ancient church (draft taken from F. Doglioni, A Moretti, V. Petrini, "Le chiese e il terremoto", Ediziioni LINT, Trieste, 1994p.72).

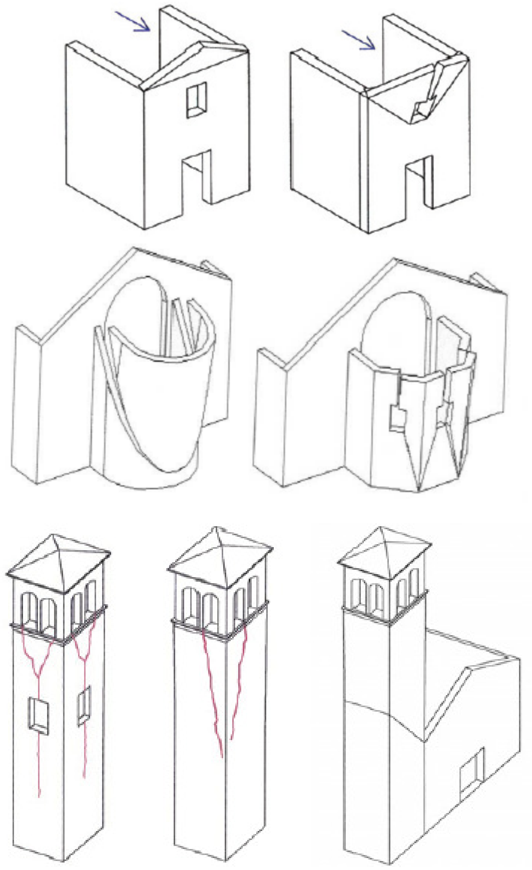

Figure 2.12: Collapse mechanisms corresponding to the macro elements facade, apse and bell-tower (from the annex to the Ordinance no. 3274/2003).

As mentioned before, one of the most important critic to the short-sighted use of the modern invasive techniques for the protection of ancient buildings came from A. Giuffrè. In 1999 he presented his "Codice di pratica per il centro storico di Palermo", a study that tried to combine the

[70] The forms for the identifications of the collapse mechanisms od churches and palaces are available in: G.LA.BE.C. 2006a: Gruppo di Lavoro per la Salvaguardia e la Prevenzione dei Beni Culturali dai Rischi Naturali, *"Scheda per il rilievo del danno ai beni culturali – Chiese"*, http://www.protezionecivile.it/cms/attach/adc.pdf, 2006 (G.LA.BE.C., 2006); and in G.LA.BE.C. 2006b: Gruppo di Lavoro per la Salvaguardia e la Prevenzione dei Beni Culturali dai Rischi Naturali, *"Scheda per il rilievo del danno ai beni culturali – Palazzi"*, http://www.protezionecivile.it/cms/attach/bdp.pdf, 2006 (G.LA.BE.C., 2006).

safety requirements with the conservation demands. His strategy can be summarise in the following steps:

a) Study of the vulnerability of the building for the definition of the anti-seismic improvement;
b) Verification of the anti-seismic safety through the identification of the collapse mechanisms of the masonry macro-elements.

2.3.2 Short review of the "Guidelines for evaluation and mitigation of seismic risk to cultural heritage"

Taking into account Giuffre's lesson and the recent studies on the mechanical behaviour of ancient structures, the *Guidelines for evaluation and mitigation of seismic risk to cultural heritage* proposes an adequate methodology for supporting the designers in the difficult interpretation of the state of conservation of existing buildings.

The guidelines are organized in 6 chapters describing the general criteria inspiring the text and the specific actions for seismic risk mitigation.

The first chapter presents the relationship between the guidelines and other recent legislative measures: the *Technical Construction Regulations* (NTC/2005), the Ordinance 3274/2003 and the "*Cultural Heritage and Landscape Code*" (Law no. 42, 2004 January, 22). The guidelines appear as a part of a greater legislative system dedicated to different aspects connected to the seismic risk.

The second chapter describes the principles of the conservation according to the people's safeguard and to the preservation of the building functionality.

The third chapter is linked to the new Italian map of the seismic risk. These maps provide information concerning the levels of risk and are an important measure for the identifications of the historical buildings placed in dangerous areas. Special attention is expressed on the information that micro-zoning can reveal.

The fourth chapter introduces the path to the knowledge of the building. The study-methodology recalls the indications contained in the point no. 11.5 of the Ordinance 3274/2003. The guidelines contain also a detailed description of the results that a study in depth of the building must reach in annex A.

Chapter no. 5 presents different possibilities of structural modelling of historic masonry buildings. Three levels of complexity are introduced: LV1, referred to the evaluation of seismic safety; LV2, suitable for specific interventions on the existing buildings; LV3, indicated for strengthening designs and other interventions able to modify the previous structural model of the buildings.

Chapter no. 6 contains the description of the design strategies useful to reach the anti-seismic improvement: mitigation of the vulnerability of the building, studied following the indications obtained by the knowledge of the building and the results provided by the numerical models. The effectiveness of the proposed interventions is evaluated according to its impact on the conservation of the architectural work: non-invasiveness, reversibility and durability.

Going more in detail, the guidelines focuses on the prevention of the cultural heritage through the development of a database collecting the information concerning the vulnerability of historical buildings and works of art. In the second chapter the safety index is defined as the ratio between acceleration which brings the work to a limit state and the expected acceleration of the site that corresponds to a determined probability of exceeding the limit in 50 years. The reference limits for cultural heritage are identified by: SLU, last limit state evaluation referred to the residual resistance of the structure; SLD, limit state of damage, referred to frequent seismic events characterized by low intensity; SLA, limit state of damage for works of art, set for decorations and works of art hosted in buildings belonging to seismic zones. The methodologies for the identification of ground types, ground accelerations and response spectrums are briefly presented in the third chapter.

Chapter no. 4 is dedicated to the description of the "path to knowledge", according to these steps:

- The identification of the building, its location in relation to the seismic risk of the area.
- The geometric survey of the building in its actual state, intended as the complete stereo metric description of the structure, including eventual cracking and deforming phenomena.
- The identification of the evolution of the building: the sequence of the constructive transformations.
- The identification of the construction techniques and structural details such as connections and other elements increasing the resistance of the building.
- The identification of materials, their state of conservation and their mechanical properties.
- The knowledge of the foundation and eventually relative instability problems.

The study on the condition of the building is extended to the buildings in the surroundings and the identification of the structures is strongly remarked. The survey of the construction materials and their conservation state is useful for the evaluation of the quality of the structure, according to the following procedure:

- presence of transverse elements connecting different masonry layers and structures;
- the acknowledgement of the regular placement of courses;
- study of the regular staggering of the joints;
- study of the nature of the lime mortar and its state of preservation;

The determination of the structural functionality of the building requires the detailed description of its characteristics:

- Typology of walls (stones, bricks, pebbles, etc.), considering also the number of parameters (unique or more) and the properties of its texture (regular, irregular, with transverse joints, etc.)
- The quality of the connections (clamping in the corners, tie rods, etc.)
- The quality of the lateral joints (ceilings, arches and roof coverings) and walls.
- Elements of discontinuity (such as chimneys or other technological spaces.
- Typology of horizontal structures.
- The presence of structural elements designed to increase the performance of the buildings (trusses or other elements for thrusts control).

For the determination of the mechanical properties of the materials, according to the indications contained in paragraph 5.4 of the NTC (Technical Construction Regulations), the following diagnostic tests are recommended:

- Double flat jack tests, for the evaluation of the normal plastic model of the masonry wall, under compression.
- Diagonal compression tests on a square panel and compression and shear tests on a rectangular panel are tests of destructive nature, but able to determine the strength and the shear modulus for masonry walls.

Mechanical properties of different structures can be achieved by the institution of regional archives collecting abacus of masonry walls typologies, tables with reference values for mechanical properties.

The guidelines provide also indications for the characterization of soils and foundations, in order to define a geological model for the building foundation. Moreover, indications for the monitoring of the buildings are requested. Dynamic tests are particularly supported in order to control the variation of the properties of the structures in relatively short periods.

Once the building characteristics have been identified (through geometric survey, material and constructive surveys, mechanical research, etc.), the guidelines introduce a C*onfidence Factor* that must be assigned to the project. The Confidence Factor, ranging from 1 to 1.35, grades the reliability of the structural analysis model and the evaluation of the seismic safety index. The idea is that several Confidence Factors determined for the different aspects of the study are used to obtain the final Confidence Factor, representative of the level of knowledge achieved for the building (see Table 2.2).

Geometric Survey	Material and Construction Survey	Mechanical Properties of the Materials	Terrain and Foundations
The Geometric survey has been completed $F_{C1} = 0.05$	limited survey of materials and constructive elements $F_{C2} = 0.12$	mechanical parameters deduced from available data $F_{C3} = 0.12$	limited survey of terrain and foundations, in absence of Geological data or availability of information about the foundation $F_{C4} = 0.06$
The Geometric survey has been completed along with the graphic rendering of cracking and deformities	extensive survey of materials and constructive elements $F_{C2} = 0.06$	limited research of mechanical parameters of materials $F_{C3} = 0.06$	Geological data and information regarding the foundation structures is available; limited research on terrain and foundation $F_{C4} = 0.03$
$F_{C1} = 0$	exhaustive survey of materials and constructive elements $F_{C2} = 0$	extensive research of mechanical parameters of materials $F_{C3} = 0$	extensive or exhaustive research on the terrain and foundation $F_{C4} = 0$

Table 2.2: Definition of the levels of knowledge and relative Partial Confidence Factors (table taken from "Guidelines for evaluation and mitigation of seismic risk to cultural heritage, Gangemi Editore, Roma, 2007, p. 36).

As described in chapter five, the information concerning the structural characteristics of the building are used to implement the layout for the evaluation of the mathematical model. In this section the legislator emphasises the utility of provisional models, but at the same time underlines the difficulties for their applications to historical buildings, usually presenting complex conditions.

Chapter six is devoted to the seismic improvement criteria and strengthening interventions. Safety evaluation is the first step for the definition of the design. Interventions are categorised in these groups:

- Intervention to improve connections: metallic rings, tie rods, etc.;
- Interventions to reduce thrust of vaulted arches and their strengthening: tie rods, buttresses, masonry fillers, jacketing with light composite material strips, etc.;
- Interventions to reduce excessive flexibility of floors and their consolidation: addition of a second plank floor to the existing one, placing the elements in orthogonal directions, bracing made by metallic tie rods, light stiffening, etc.;
- Intervention for roof coverings: plates and metal bars to provide good connections to the junctions.
- Interventions for increasing the strength of masonry elements: local repairs to cracked or decayed parts, "rip and sew" injections, insertion of artificial diatones
- Interventions on non-structural elements: mouldings, parapets, chimneys, etc.;
- Intervention on foundation: jet grouting, deep mixing, widening interventions, etc.;

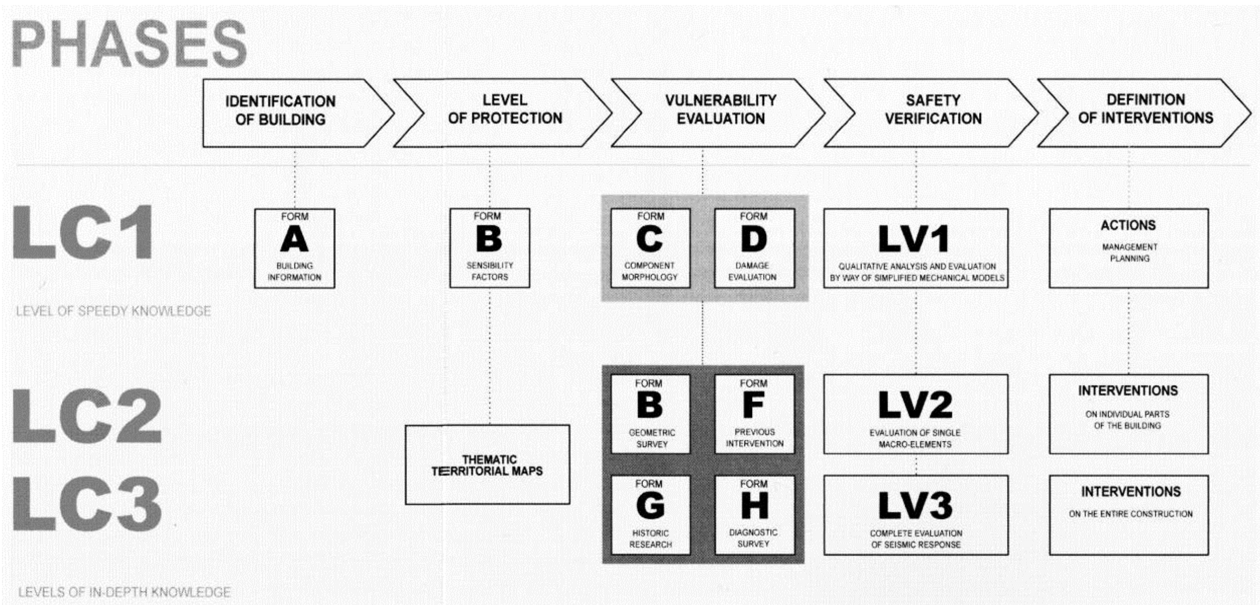

Figure 2.13: Relationship between the survey forms, level of knowledge and level of verification as defined in the Guidelines (taken from "Guidelines for evaluation and mitigation of seismic risk to cultural heritage, Gangemi Editore, Roma, 2007, p. 64).

To conclude, the procedure proposed by the guidelines is composed by five main phases of study: i) identification of building; ii) level of protection; iii) vulnerability evaluation; iv) safety verification; v) definition of interventions. They can provide a level of speedy knowledge (LC1), based on LV1 (level of complexity), and two levels of in-depth knowledge (LC2 and LC3), based on LV2 and LV3 (see Figure 2.13).

2.4 The work of the ISCARSAH Committee: critical awareness of the problematic connected to the protection of cultural heritage

Moving from the local scale to the international scenario, the experience of the ISCARSAH committee (part of ICOMOS organization), founded in 1996 under the chairmanship of Giorgio Croci, is now presented. The work of experts specialized in cultural heritage field was supported for long time by ICOMOS[71]. The ISCARSAH commission (*International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage*), founded in 1996, has been working for new guidelines[72], issued to uniform an intervention methodology related to the existent, addressed to the diffused historical buildings and not limited to monumental works.

Organized in different sub-working-groups, ISCARSAH commission developed a network addressed to experts working in the field of the architectonic heritage.

The work-group named ISO[73] is developing a regulation that could be internationally recognised concerning the definitions of the services for supporting the actions for the conservation of historical buildings. The incipit of the recommendation ISO 13822 edited in 2006 reports:

This annex is based on the premise that structure has cultural value in itself. Heritage structures should be preserved for their own sake and not merely as supports for the rest of the historic

[71] ICOMOS. *International Council on Monuments and Sites*. ICOMOS is a non-governmental organization involved in the conservation of ancient monuments and archaeological sites. It was founded in 1965, after the adoption of the Venice charter (Charter for the conservation and the restoration of monuments and sites) written in 1964.
[72] Carta ICOMOS: *Principi per l'analisi, la conservazione e il restauro strutturale del patrimonio architettonico* (2003), ratified during the XIV general assembly of ICOMOS in Victoria Falls, Zimbabwe, October 2003. (ISCARSAH, 2003)
[73] Information about the activity of the sub-working group ISO are available at the following link: http://iscarsah.icomos.org/index.php?option=com_content&view=article&id=51&Itemid=61

material. It follows that the integrity of the existing structure should be respected in any interventions[74].

This document, still in preparation, contains indications with generic valence, but indicates clearly that the prescriptions issued for modern structures are not suitable for ancient structures.

Even the passage in article 16 of their declaratory concerning the concept of *Structural Stability* is very significant:

The principles of assessment, diagnosis and treatment of historic structures are largely unaffected by climate change; decay and deterioration phenomenon arising from climate change are reasonably well understood. What will change is the vulnerability of particular structures (due to climate change) to different kinds of problems from the ones they were originally designed to cope with[75].

The importance of the knowledge phase for the technical aspects of the building, providing stability and resistance to the external agents, is taken into account also from the working-group studying the relationships between cultural heritage and climate changings (GCC)[76].

In this context, attention must be given also to the working-group of quality standards[77]: this research unit is focusing on the development of shared procedures for the conservation field. Experts, engineers, architects and contractors are the different subjects which have to interact

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[74] Draft 2 April 2008. Annex 1 – Informative: *Heritage Structures*. Available at the following link: :http://iscarsah.icomos.org/index.php?option=com_content&view=article&id=51&Itemid=61 (ISCARSAH, 2008)

[75] *Global Climate Change and its Impact on Structures of Cultural resources Concluding remarks and recommendations*. Available at the following link: http://iscarsah.icomos.org/index.php?option=com_content&view=article&id=50&Itemid=62 (ISCARSAH, 2009)

[76] Information on the activities of the sub-working group GCC are available at the following link: http://iscarsah.icomos.org/index.php?option=com_content&view=article&id=50&Itemid=62 (ISCARSAH, 2009)

[77] Information on the activities of the sub-working group Qualification Systems are available at the following link: http://iscarsah.icomos.org/index.php?option=com_content&view=article&id=52&Itemid=63 (ISCARSAH, 2009)

into a network of relationships based on clear and subscribed operative roles. As mentioned before, the complexity present in the conservation praxis is a limit for the success of this perspective. The Qualification System working-group matured the opinion that only the notable qualification level of the operators could be the solution to overpass this complexity. The working-group assumed that:

The greater methodological and technological complexity of heritage conservation compared to current construction requires greater qualification of the agents involved, both professionals and companies[78].

In 2005, ISCARSAH committee published the "*Recommendation for the analysis, conservation and structural restoration of architectural heritage*". The structure of the document recalls the logic used for the Guidelines described in paragraph 2.4.2. In the ISCARSAH recommendation the role of the mechanical behaviour investigation is highlighted. The documents provides general indications to drive the interpretation of the characteristics of the structure, its state of conservation, the stresses acting, in order to identify the causes of eventual decay and loss of efficiency.

The detailed description of the singular phases of this study-methodology ensures a shareable practise for experts in the cultural heritage field. These kinds of indications are now recognised as suitable procedures for the characterization of the complex questions presented in conservation field, but their recognition is a relatively recent result. Before the success of this new trend promoting the respect for the ancient fabric and its components, structures have been largely modified by innovative solutions which can produce even bad results in a long period. The introduction of reinforced concrete elements in masonry structures, during the beginning of the 20th century, represents the typical example of a supposed innovative and reversible technique that could save ancient buildings.

This problem is well exposed by S. Valtieri[79], taking into account the restoration designs for the Loggia Papale in Viterbo (Figure 2.14). During the "liberation restoration" (Figure 2.15), in the first

[78] V. Coias, *A qualification system for personnel and contractors working in heritage conservation: general outline*, "International Seminar On Seismic Risk And Rehabilitation of Stone Masonry Housing", Azores, 1998. (Coias, 1998)

decade of 20th century, a reinforced concrete beam was inserted behind the moulding, over the loggia, in order to unload the thin columns from the weight of the overhanging wall. This design was prepared by G. de Angelis who noticed the deterioration of the structures of the monument and decided to apply a new building technology. The idea that the columns of the loggia could not stand the compressive stress produced by the wall placed over the loggia was remarked by the compression tests performed on stones specimens made with the same material (*peperino* marble). The aim of the r. c. beam (Figure 2.16) was to reinforce the monument in order to increase the durability of the ancient structures.

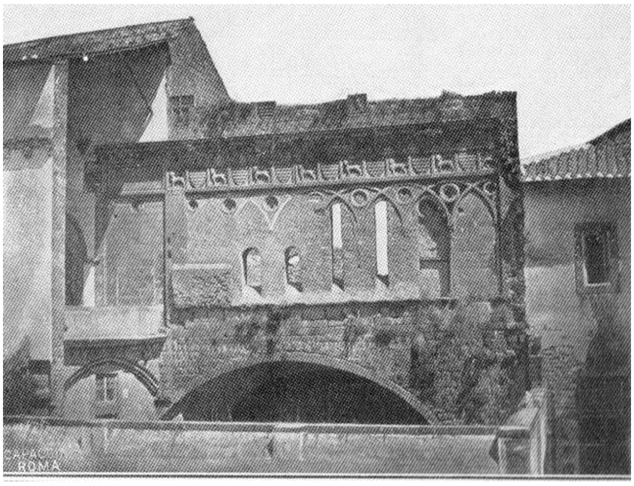


Figure 2.14: Viterbo. Loggia dei Papi. The state of the loggia before the "liberation restoration" in a picture of the end of 19th century (from S. Valtieri, "I restauri della loggia Papale di Viterbo", in M dalla Costa, G. Carbonara, "Memoria e restauro dell'architettura", Milano, 2005 and edited before in A. Scriattoli, "Viterbo e i suoi monumenti, Roma, 1915-20).

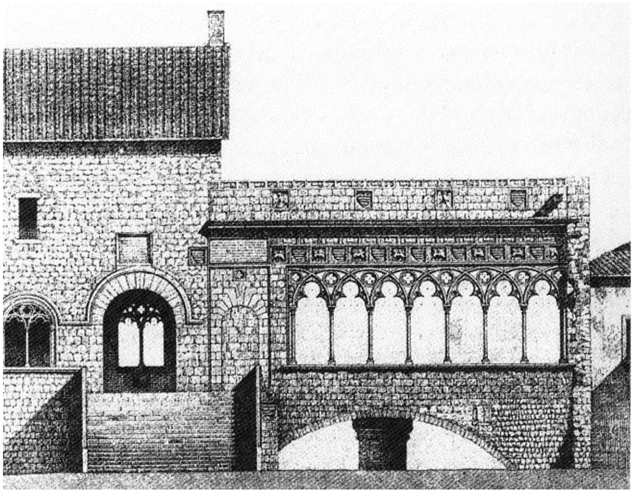


Figure 2.15: Viterbo. Restoration design of the Loggia dei Papi, edited by G. De Angelis in 1903 (from S. Valtieri, "I restauri della loggia Papale di Viterbo", in M dalla Costa, G. Carbonara, "Memoria e restauro dell'architettura", Milano, 2005

Since 1956 an important crack pattern was noticed on the columns of the loggia. The presence of a r.c beam behind the moulding is identified in 1983, after the application of gammagraphic tests. Since its introduction the beam increased the weight acting on the loggia and the columns showed the typical crack pattern associable to excess of compression. The effect of the combined

[79] S. Valtieri, *I restauri della loggia Papale di Viterbo*, in M dalla Costa, G. Carbonara, *Memoria e restauro dell'architettura*, Milano, 2005, pp. 281-290. (Valtieri, 2005)

compressive and bending stress is corrected by mean of a funicular polygon to which the beam is suspended. The masonry wall was reinforced through concrete injections (Figure 2.17). The original structural layout of the building is deeply changed. During the 80s historical buildings were neglected, not considered like past evidence, but they were identified as formal appearance. This approach caused the dissolution of the materiality of the architectural heritage.

The above described invasive restoration design shows that the consequences of invasive strengthening techniques were not sufficiently taken into account. The design of the 80s represents again an invasive transformation of the survived mechanical properties of the masonry structures. The sensibility for more compatible measures was theorized centuries before, but their application did not have a large success: this is due to a diffused ignorance concerning the mechanical behaviour of ancient structures. The work of the ISCARSAH committee can support a renewal in the knowledge of the existing structures and provide a significance contribution in the preservation of their integrity.

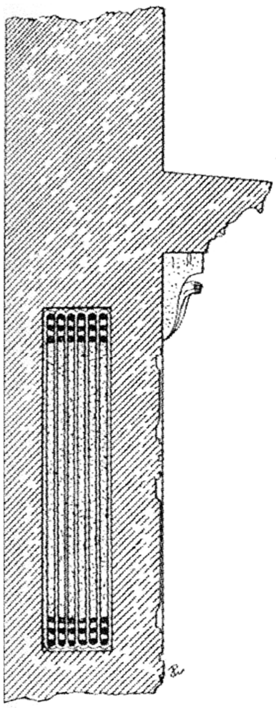


Figure 2.16: Detail of thereinforcement of the beam inseted in the trabeation of the Loggia dei Papi in Viterbo (from S. Valtiri, from S. Valtieri, cit., 2005)

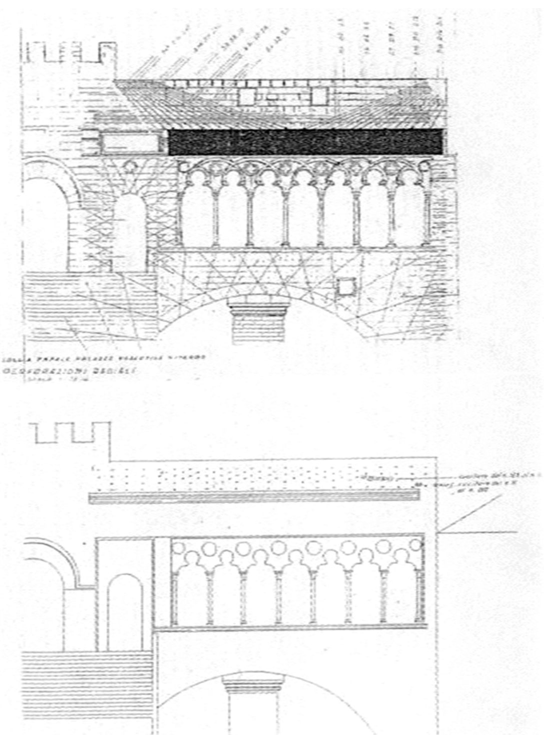


Figure 2.17: Design for the strengthening intervention on the Loggia dei Papi proposed in 1983. Layout of the radial drillings and top network for the funicolar polygon (from S. Valtiri, from S. Valtieri, cit., 2005)

2.5 Criteria for a methodology of intervention on historical buildings

Referring to chapter 8 of the *Technical Rules for buildings*, edited in 2008[80] by the Ministry of Public Works, the fact that several experiences matured in the field of the university research must be remarked. These experiences, at National, European and International levels, produced basic results for the definition of the strategies which are now accepted as useful to reach the structural effectiveness. One of the main experiences was the EU ONSITEFORMASONRY[81]: different subjects, European universities and institutional laboratories, tested on site a study-methodology developed for the ancient building structures. The results of this research were later assumed by national legislators and appeared in local guidelines.

RILEM Technical Committees are contributing to the diffusion of the results obtained by the ONSITEFORMASONRY programme. In the meantime some regulations were finally set into a new ISO standard[82] for the assessment of existing buildings. The ISO standard edited in 2008 introduces the issue of the structural reliability for historical buildings, taking into account even the seismic actions.

The above mentioned standards and recommendations demonstrate a wide interest for the study-methodology able to evaluate the bygone damages affecting the historical buildings. The identification of the main diffused diagnostic techniques is now considered a fundamental request for the elaboration of the design process and the next chapter will take into account the role of the diagnostic approach.

Intervention in heritage structures can be defined as a compromise between different needs, such as stabilization, repair or strengthening (seismic retrofitting). The choices for the definition of the design should be subjected to a series of requirements or criteria set to guarantee the efficiency of the solution together with its compliance with recognized conservation principles.

The intervention on historical buildings must focus on preserving the original features of the structure. When necessary, repair or strengthening works should cause the minimum alteration to

[80] Decreto Ministero delle Infrastrutture. Norme Tecniche per le Costruzioni, 2008 (DM 14 gennaio, 2008)
[81] ONSITEFORMASONRY Project: project EVK4-2001-00091 ONSITEFORMASONRY, coordinated by C. Maierhofer of BAM (Germany) and finalised to the calibration of on-site investigation techniques for the structural evaluation of historic masonry buildings
[82] ISO/CD 13822, 2008. Bases for design of structures – Assessment of existing structures. (ISO/CD 13822, 2008)

the existing structures. This is not only applicable to the geometry and materials: the authenticity of the mechanical and resisting principles governing the structural response (the nature of the structure and its resisting mechanisms) is also to be preserved to the possible extent.

Recently, an on-going EU project, named NIKER (New Integrated Knowledge-based approaches to the protection of cultural heritage from Earthquake-induced Risk), formed by a network of universities and private laboratories/experts, worked on the development and validation of innovative materials and technologies for improving the seismic behaviour of heritage buildings and other cultural heritage assets[83]. NIKER project focuses on the investigation techniques for buildings in seismic areas and on the improvement techniques suitable for historical structures. The research promoted by NIKER project represents an up-to-date state of the art concerning diagnostic techniques for preliminary investigations, control of the intervention and further monitoring in time of the conditions of the historical structures. Future evolution of the ISCARSAH standards are strictly connected to the NIKER project activities.

The main criteria that should lead the intervention on historical buildings, according to the ICOMOS/ISCARSAH standards, can be summarized in the following points.

Structural reliability requirements

A frequent reason for strengthening and seismic retrofitting is to achieve public safety, in order to protect human life and ensuring that the structure will not collapse on its occupants. Conventionally, it is required or accepted that structures of high cultural significance should be upgraded to remain unaffected (undamaged) by possible earthquakes. However, this requirement may often lead to invasive upgrading measures causing a significant loss in terms of cultural heritage. The extent of seismic upgrading in heritage constructions needs to be carefully

[83] The European funded project NIKER started officially on January 1st, 2010. (NIKER, 2011)The project covers development of an integrated methodology, including design methods, advanced monitoring and early warning techniques. To reach this goal, the project is structured into three main steps, over three-years:

- Creation of a database with new relational structure with the task of orienting and assisting the development of materials and techniques for intervention;
- Experimental testing, numerical simulation, parametric modelling and derivation of design methods for vertical and horizontal structural elements and connections and for the overall seismic behaviour of buildings;
- Development of knowledge-based assessment procedures and final validation of the entire methodology on real case-studies. Guidelines for end-users.

considered in every individual case based on a cost-benefit analysis which takes into account the cultural losses conveyed by the upgrading itself.

Minimal intervention

These measures are intended to produce only a reduced impact on the original structure. These kinds of interventions should in the meantime guarantee the required safety level. Among possible solutions, all of them providing the required level of safety, the one causing minimal alteration (the minimum intervention) should be preferred.

From an engineering point of view, the optimal solution is obtained after envisaging and analysing a series of alternative solutions. Each different solution should be evaluated regarding both its structural efficiency and compliance with conservation criteria (or, in other words, its cost in terms of loss of authenticity and cultural value). According to the ISO/FDIS 13822 final draft, the solution finally adopted should consists of a “minimal intervention”, defined as “an intervention that balances the safety requirements with the protection of character-defining elements, ensuring the least harm to heritage values”.

The possible impact of an intervention on a monument or building, in terms of loss or alteration of the original material and structural features, must always be investigated and quantified. As stated by the ICOMOS/ISCARSAH Recommendations, no action should be undertaken without ascertaining the likely benefit and harm to the architectural heritage. Comparing benefit and cost will permit the evaluation of the different solutions and the selection of the optimum one.

Compatibility

The ICOMOS/ISCARSAH Recommendations clearly state that “The characteristics of the materials used in restoration work (in particular new materials) and their compatibility with existing materials should be fully established (as for example to avoid risk of negative chemical reaction, etc...). In any case, it has to be clear that compatibility is a necessary condition but not sufficient to accept a product because its benefit has to be demonstrated. This must include long-term effects, so that undesirable side effects are avoided”. Figure 2.18 shows two examples where new materials were introduced to support existing structures: in the first case the use of a new steel structure to support the elements of a roof system guarantee a compatible solution between the different materials, whilst in the second case the effects of the thermal dilations of a tie-rod present no compatibility with the stone pillar in which it was inserted.

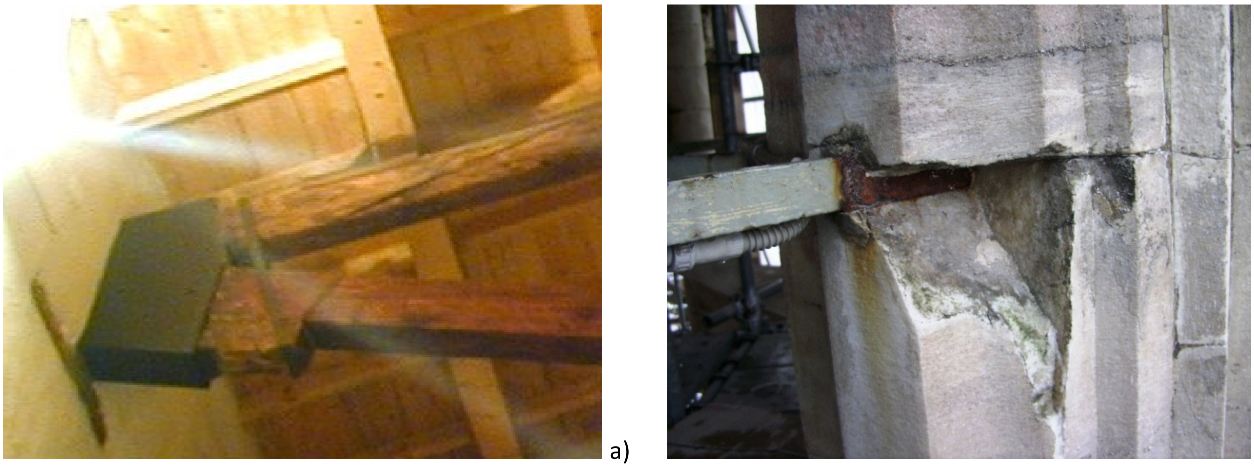

a) b)

Figure 2.18: Two examples of intervention on existing structures: a) reconstruction of the anchor of the timbers by a steel support ensuring compatibility with the existing structures and b) effects of the thermal dilation of a steel bar inserted into a stone pillar (pictures by the author).

The materials and the technical devices used for repair or strengthening must be compatible with the original ones, in the sense that no undesirable side-effect should result from their physical or mechanical combination. Compatibility problems may be related to the following causes:

- Chemical compatibility: ancient materials should not experience any form of chemical deterioration when in contact with the new materials or with substances delivered by them . For instance, Portland cements may free soluble salts which, after penetrating lime mortars or stone, may experience expansive crystallization and cause cracking, or concrete damaging chemical reactions if gypsum is contained in the original mortars on stones.
- Thermal compatibility: new materials or mechanical devices should not deform too differently from the original ones when subjected to environmental thermal variations. Thermal deformation of Portland Cement or concrete or embedded steel, may cause cracks to existing stone or brick masonry attached to it.
- Mechanical compatibility: repair materials or strengthening devices must have stiffness similar to that of the original material when embedded or externally attached to the latter, again to prevent cracking or other mechanical damage due to external loading. A mass of very stiff repair material inserted within the existing one may cause the latter to crack or crush due to the application of additional stones.

- Rheological compatibility: new materials should not experience any deformation or flow causing imposed deformation and hence damage to the original ones. The shrinkage of Portland cement or concrete may cause cracks to stone or brick masonry attached to it.

Durability

Conservation and restoration aim at significantly enlarge the life expectancy of heritage structures. Hence, the repair materials or strengthening mechanical devices used must be satisfactorily durable. Both the overall safety of the structure and the durability of the original parts can be compromised by the decay of new repair material. According to the ICOMOS/ISCARSAH Recommendations, no action should be undertaken without ascertaining the likely benefit or harm to the architectural heritage and long terms side effects.

Non-intrusiveness (non-invasivity)

Non-intrusive (or non-invasive) repair or strengthening techniques should be preferred to more invasive alternatives. They will, for obvious reasons, contribute to preserve the material integrity of the existing structures. Among possible alternatives, preference should be given to the least invasive one. As mentioned by the ICOMOS/ISCARSAH Recommendations, “the choice between “traditional” and “innovative” techniques should be determined on a case-by-case basis with preference given to those that are least invasive and most compatible with heritage values, consistent with the need for safety and durability”.

Non-obtrusiveness

Obtrusiveness refers to the quality of being undesirably noticeable. The Venice Charter for the Conservation and Restoration of Monuments and Sites (1964) states that “replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence. Additions cannot be allowed except in so far as they do not detract from the interesting parts of the building, its traditional setting, the balance of its composition and its relation with its surroundings”.

According to this understanding, any additional structural device included as part of a strengthening action must integrate harmoniously with the existing structure and should not cause a significant alteration of its initial aspect. It should, however, be distinguishable from the original parts or materials.

Removability

Where possible, any measures adopted should be reversible, or at least removable, so that they can be replaced with more suitable measures if new knowledge is acquired. In any case, interventions should not compromise possible later interventions.

In other words, it must be possible to dismantle any intervention without leaving any severe damage or producing any significant lasting alteration or deterioration to the original material and structure.

Nowadays, full reversibility (meaning that no any deterioration or impact, even if small, should be caused by the removal of the former intervention) is regarded as a too demanding and unrealistic requirement. Removability is considered at present as a more realistic and viable condition than full reversibility. Reversibility or removability leave open the possibility of eventually replacing the strengthening by another more adequate or effective one.

Possibility of monitoring and controll

Repairing or strengthening measures whose performance and effect on the building are impossible to control should not be allowed. In order to carry out such control, monitoring should be applied before, during and after the execution of the repair or strengthening. The intervention must be designed in such a way that monitoring can be implemented and successfully used during and after the execution. Any proposal for intervention must be accompanied by a programme of monitoring and control.

In the case of provisorional or emergency actions, the monitoring of the temporary strengthening is of large importance. It is used to know whether the strengthening (for instance, a propping system) is actually working and resisting some load, and thus partly or totally relieving the original structure, or whether the strengthening has not been in fact mobilized. This will lead to very different decisions regarding the new strengthening system and the way to implement it.

The listed criteria, matured above all in the field of the practice, represent a guide for the designers which have to face with historical buildings and archaeological remains. These principles lead the various design phases: at the scale of the single structure and at the scale of the whole building.

2.5.1.1 Requirements and solutions: a short review of some experiences

Solutions promoting the respect of the existing characteristic of the building and the requirements imposed by the introduction of new functions are usually a compromise between the principles of *minimal intervention*, *non-intrusiveness* and the *structural reliability* demands. This is, for example, the case of the realization of new visiting paths into ancient buildings: the pre-existent distribution of the building can be changed in order to support new linkages and the use of new materials can promote the safety of the structure and reveal the previous organization of the space. Crystal-glasses are typically used with this purpose: they guarantee structural safety and can show the underlying layers of the building on which are placed (Figure 2.19).

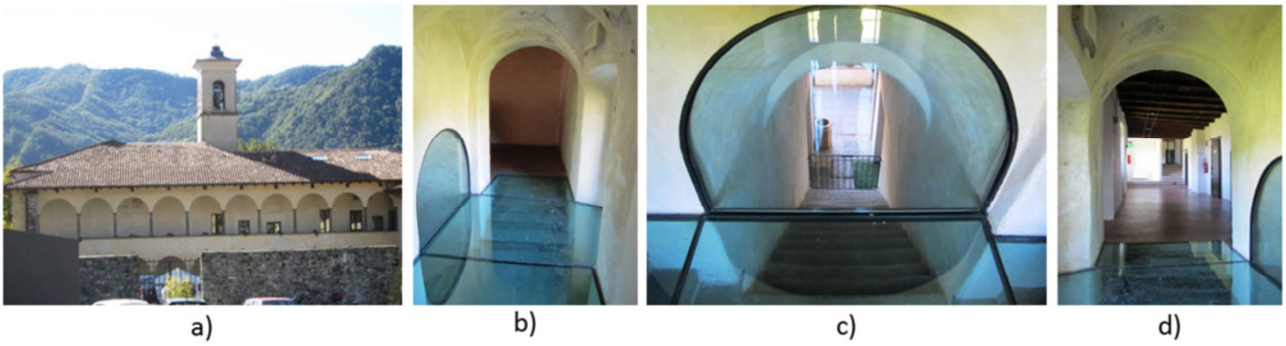


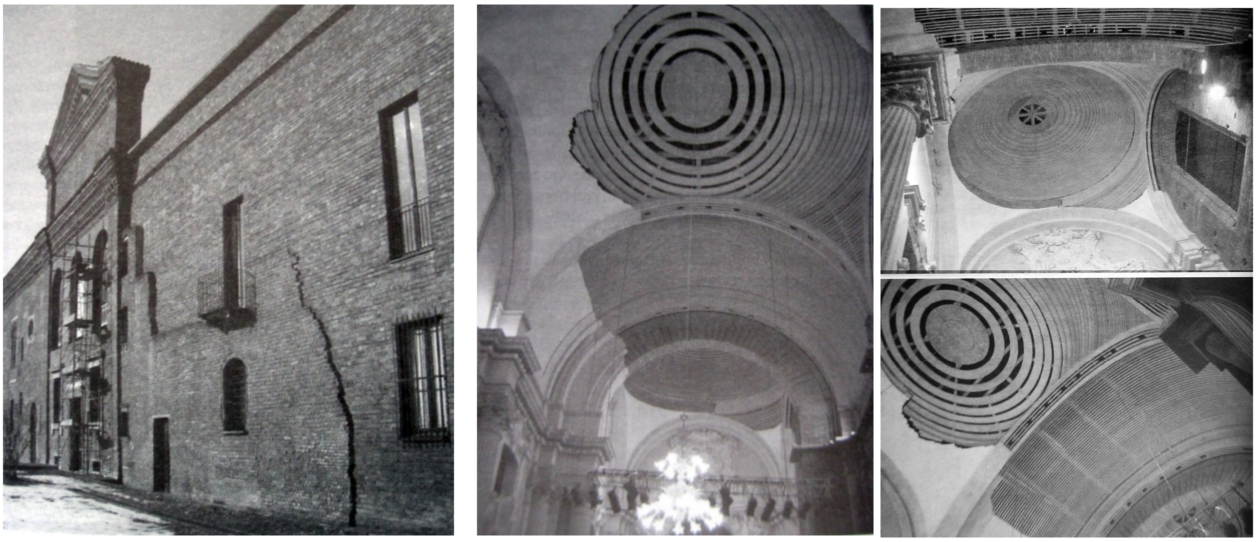
Figure 2.19: a) view of Lavello Abbey (in Calolziocorte - Lecco), where a new linkage in the expositions rooms was realized by b,c,d) crystal glasses which show the original distributive organization of the building (pictures by the author).

Figure 2.20: Reproduction of a collapsed vault in a room of Villa Borromeo-D'Adda in Arcore (Milan), a misused bulding under the protection of the FAI - Italian Fund for the Environment (pictures by the author).

Following the principles of *non-intrusiveness*, *non-obtrusiveness* and *removability*, designers tried also to provide didactical information, maintaining the memory of traumatic events occurred to damaged or misused buildings. This is the case of collapsed vaults or timbers structures, for instance. The intervention could consist in an integration of the image of the lost structures, by using new materials in different ways. The shape of a vault can be reproduced by a light wire-framed grid (Figure 2.20). In the same way the idea of the collapse mechanism of a timber can be represented by hanging the original damaged element to a steel beam (Figure 2.21).

Figure 2.21: Example of a didactical arrangement of a collapsed truss in a room of the Melegnano Castle (Milan), substituted by a steel beam (picture by the author).

These methods were used to solve very complicated situations in partially collapsed buildings (especially after the devastations following the Second World War). As said in the first chapter, architects and engineers had to respect the survived remains of the ancient buildings and guarantee their existence in the future through repairing interventions. L. Grassi for example, showed an uncommon sensibility in the reconstruction of some destroyed portion of the Ospedale Maggiore in Milan, maintaining the remains of the original brickwork masonry and realizing the new additions undercut (Figure 2.22a): this was a strategy to distinguish the original structure from the new one and to provide continuity (and compatibility) between the load bearing walls. At the same time, the memory of the tragic episode was preserved. In the same way, P. L. Cervellati proposed an original reconstruction of the missed vaults of the Oratory of St. Filippo Neri in Bologna. Here the memory of the devastations caused by the war are recognizable due to an integration of the collapsed vaults with concentric elements made by clearly different materials and a peculiar architectonic expressivity (Figure 2.22 b and c).



a) b) c)

Figure 2.22:a) Undercut realization of the rebuilt walls of the Ospedale Maggiore in Milan (picture from M. Boriani, Progettare per il costruito, 2008, p. 25 (Boriani, 2008)); b, c) views of the vault and the dome in the San Filippo Neri Oratory in Bologna (pictures from M. Boriani, cit., 2008, p.308 and 311).

The requirements of *compatibility* and *non-obtrusiveness* (including replacements of materials and distinguishing from the original one) seem to support the design for the reconstruction of the Frauenkirche in Dresden. Although the building was entirely destroyed by fire bombs in 1945, the new design was developed with the aim of preserving the unique apse that survived to the collapse of the dome. In addition the available original stone blocks conserving good mechanical properties were used for the new masonry structures. They maintain their typical dark colour (due to the fire) and are distinguishable from the new light stone blocks used for the reconstruction (Figure 2.23).

In the examples presented before, old and new materials were used with a special care: the compatibility was ensured trough the research of materials having very close mechanical properties (like the elastic deformability of wooden and iron elements), or adopting materials and building techniques equal to the existing one (like bricks or stone blocks). There are also cases where new technical solutions were introduced. For example, light shells composed by translucent glasses are nowadays frequently used to create covered public spaces (Figure 2.24).

a) b)

Figure 2.23: a) South front of the Fraenkirche in Dresden; b) detail of the integration of a moulding, maintaining the original material (pictures by the author).

a) b) c)

Figure 2.24: Dresden Castle was reconstructed to be a museum. The main courtyard was covered by a light transparent shell (pictures by the author).

These structures are the result of the technical innovations in building field. Their diffusion is strictly connected to their compatibility with the existing walls. In other cases, instead a clear exhibition of the new elements, modern structures composed by PVC or other plastic derivatives were hidden behind existing massive walls, in order to create the spaces requested by the project, avoiding any contraposition between new and old elements (Figure 2.25).

a) b)

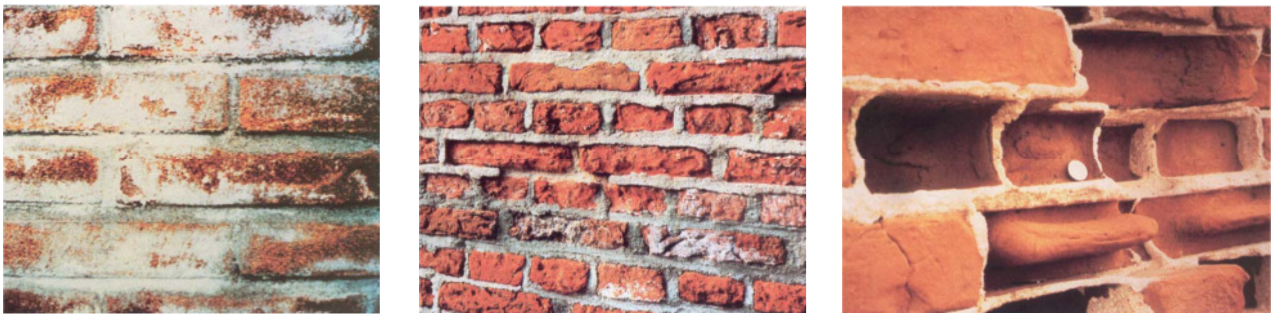
Figure 2.25: Mertula Caslte: the new volume hosting the museum was realized by wooden walls and covered with PVC panels, maintaining it under the skyline of the existing towers (pictures by the author).

The use of different materials is one of the most effective methods for distinguishing the original remains from new additions. In this way, the use of an adaptable product like cement or the strengthening provided by reinforced concrete structures appeared as a strategic solution to repair ancient buildings, in order to respect the *structural reliability* and *non-obtrusiveness* requirements (Figure 2.26).

a) b)

Figure 2.26: a) view of the Roman cistern in Istanbul; b) view of some rebuilt columns and pulvino realized by reinforced concrete (pictures of the author).

The time showed that this kind of structures can be subjected to fast decay forms, compared to the durability of other traditional materials. Based cement mortars, used for repointing in existing structures, gave several problems when applied on porous materials, as traditional fired bricks. In this case the adhesion between bricks and joints could present detachments phenomena. The salts contained in cement mixtures can be absorbed by porous materials and produce different negative effects on the structure: alteration of the surfaces or even deeper decays. Efflorescence is for example a typical alteration of the building surfaces caused by the migration of the salts from the cement joints to the masonry components, whilst crypto-efflorescence produces deeper damages inside the single materials (Figure 2.27).



a) b) c)

Figure 2.27: Three decay degrees caused by interaction between cement mortar and porous bricks: a) efflorescence; b) powdering; c) deep powdering due to crypto-efflorescence (pictures from L. Franke, I. Schumann, "Damage Atlas", 1998, pp. 95, 99, 109).

Moreover, the combination or conjunction of structures made with different constructive techniques such as masonry walls and modern reinforced concrete floors can be totally unsuccessful. In this sense recent episodes showed that the compatibility between massive multiple leaves masonry walls and reinforced concrete floors/coverings: this is the case of the Fauno House in Pompei (Figure 2.28), collapsed at November the 6th 2010.

Reinforced concrete is not the unique building technology presenting incompatibility for its application: negative long term effects can appear also using modern volumes made by synthetic materials, with the aim of covering and preserving archaeological ruins. The realization of the visiting paths for the Roman Villa del Casale in Piazza Armerina (Sicily) is an example of modern techniques (modern for the 70s of the last century) applied to existing remains. F. Menissi designed a re-composition of the image of the lost bodies of the villa (Figure 2.29). Through the use of scaffolding pipes and Plexiglas, he wanted to recall the monumental spatiality of the villa. This design represents the culture of that time, looking for a compromise between minimalism, new poor materials experimentation, compatibility and functionalism. Menissi's work became soon a masterpiece in architecture: his low cost solution guarantees still nowadays pedestrian paths for visitors, who can look to the roman mosaic works from an appropriate distance, and a general perception of the ancient spaces of the building. Even if the temperature increase during the summer creates a very unpleasant atmosphere inside.

Figure 2.28: Fauno Hause in Pompei: a) before the collapse; b) after November the 6th 2010 collapse (pictures from the "Sole 24 ore" website, at the following link: http://www.ilsole24ore.com/art/cultura/2010-11-06/scavi-pompei-crolla-domus-135046.shtml).

Figure 2.29: Villa del Casale in Paizza Armeria (Sicily): a) external view of the volumes of the villa reconstituted by metallic frames and plexiglass panels; b) internal view of a visitors path (pictures by the author).

During the first decade of the new century, the debate around Menissi's integrations became a current topic: the effects of the translucent bodies forming the geometry of the various parts of the villa gave rise to deep changings in the internal climate conditions and the conservation of the mosaics was compromised (Figure 2.30). Also in this case the lack of knowledge about long term effects of a sort of "glasshouse" placed on a pre-existing structure was the basilar cause of the failure of the design strategy. The decay of the "glasshouse" itself has nowadays become a problem: oxidation of the metallic frames and deformations of the Plexiglas elements are compromising the safety of the whole complex.

Figure 2.30: Views of the current state of conservation of the mosaics in Villa del Casale: a) general view of a corridor presenting biological growth; b) detailed view of the incrustations grew over the mosaics formed by lichens and algae (pictures downloaded from the official website of the Italian Ministry for Cultural Activities).

The effects of the long term behaviour of masonry buildings were developed also by L. Binda, G. Baronio, A. Anzani and A. Saisi. Their studies on collapsed buildings (such as the Civic Tower of Pavia) or partially collapsed monuments (like the Cathedral of Noto) provide useful interpretation of different constructive logic used in the past. During the research work on the remains of the Cathedral of Noto[84] [85] [86] [87] (Figure 2.31), their approach was based on the general comprehension of the mechanical behaviour of the existing structures. Their support to the reconstruction works

[84] L. Binda, G. Baronio, C. Gavarini, R. De Benedictis, S. Tringali, *Investigation on Materials and Structures for the Reconstruction of the Partially Collapsed Cathedral of Noto (Sicily)*, 6° Int. Conf. "Structural Studies, Repairs and Maintenance of Historical Buildings", STREMAH 99, Dresden, Germany, pp. 323-332, 1999. (Binda L. B., 1999)

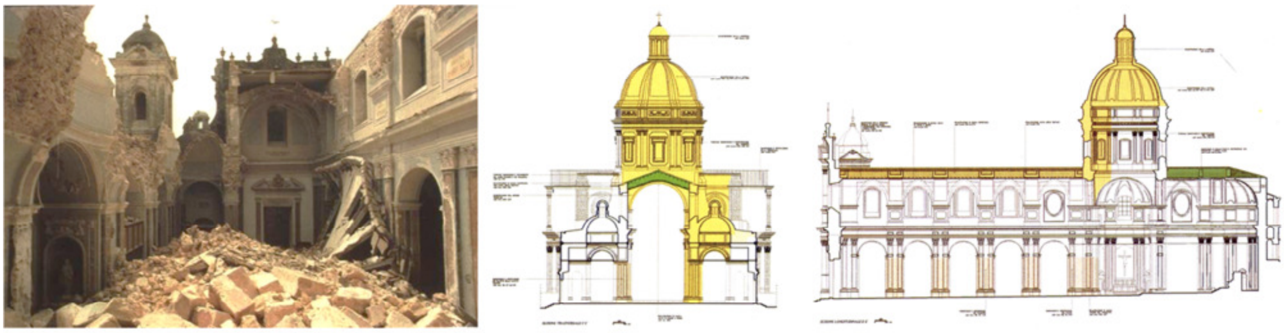
[85] L. Binda, A. Saisi, C. Tiraboschi, S. Valle, C. Colla, M. Forde, *Application of Sonic and Radar Tests on the Piers and Walls of the Cathedral of Noto*, in "Construction & Building Materials, 17(8), pp. 613-627, 2003. (Binda L. S., 2003)

[86] G. Baronio, L. Binda, G. Cardani, C. Tedeschi, *The Difficult Choice of Traditional Materials for the Reconstruction of a Partially Collapsed Historic Building: the Chathedral of Noto*, 9NAMC (9th Int. North American Masonry Conf.), 1-4/6/2003, Clemson, South Carolina, USA, CD-ROM, pp. 942-953, 2003. (Baronio, 2003)

[87] L. Binda, A. Anzani, A. Saisi, *Failure Due to Long Term Behaviour of Heavy Structures: the Pavia Civic Tower and the Noto Cathedral*, 8th Int. Conf. on STREMAH 2003, "Structural Studies Repairs and Maintenance of Heritage Architecture", 7-9/5/2003, Halkidiki (Greece), pp. 99-108, 2003. (Binda L. A., 2003)

for the collapsed parts of the Cathedral of Noto is widely known. It can be summarized into the following steps:

- Study of the vulnerability of the building
- Characterization of the existing materials used in the load bearing structures
- Study of the compatibility of the materials proposed for the reconstruction.



a) b) c)

Figure 2.31: a) view of the partially collapsed Cathedral of Noto; b) Layout of the transversal section of the Cathedral with the indication (yellow coloured) of the collapsed parts; c) Layout of the longitudinal section of the Cathedral showing the remains after the collapse of the roof and the dome (picture and layouts taken from R. De Benedictis, S. Tringali, "La Ricostruzione della Cattedrale di Noto", L.C.T., 2000, pp. 20, 22, 23).

These three main steps defined a diagnostic approach for the definition of the design process. Diagnostic tests were proposed and carried out to study the state of conservation and the efficiency degree of the survived structures of the cathedral[88]. The section of the masonry pillars was deeply investigated by visual inspections (Figure 2.32), on site and by laboratory tests, in order to verify if these structures could have any residual effectiveness, being the supports of the overhanging walls of the nave and the covering system.

The building technology used for the reconstruction of the collapsed pillars of the nave was defined looking at these parameters: a) compatibility with the masonry arches and walls; b) safety for a building placed in a seismic area; c) durability of the structural elements.

[88] L. Binda, A. Saisi, *Compatibility Between Safety and Authenticity: the Experience of Noto Cathedral,* in the "Restoration of Monuments, Journal WTA, "Wetenschappelijk- Technische Groep Voor Aanbevelingen, ISSN 0947-4498, Leuven (B), March 14th, pp. 1-11, Keynote Lecture, 2003. ; "International Journal for Restoration of Buildings and Monuments", ISBN: 0947-4498, Aedificatio Verlag GmbH, Freiburg, Vol. 9, n. 4, 2003, pp. 415-432

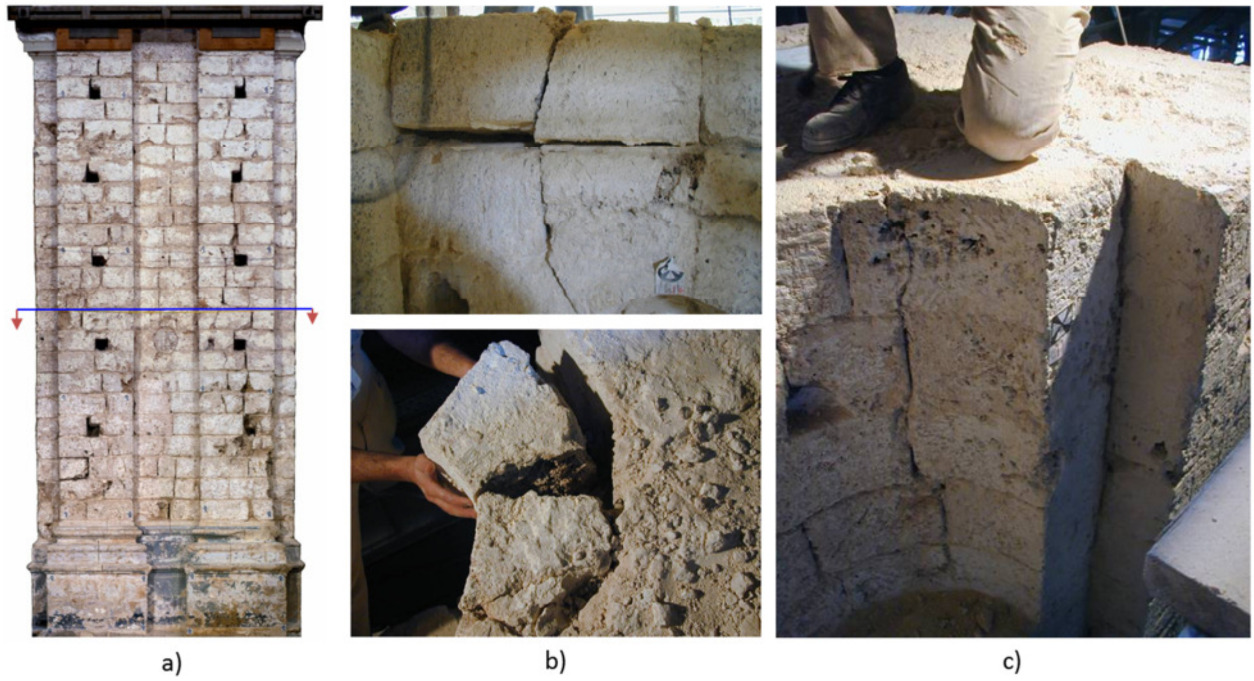


Figure 2.32: a) view of the diffused crack pattern on one side of a survived pillar of the navy of the Cathedral after the removal of the plaster; b) and c) inspection of the thickness of the cracks during the dismantling of the pillar (courtesy of prof. L. Binda and arch. A. Saisi and C. Tedeschi).

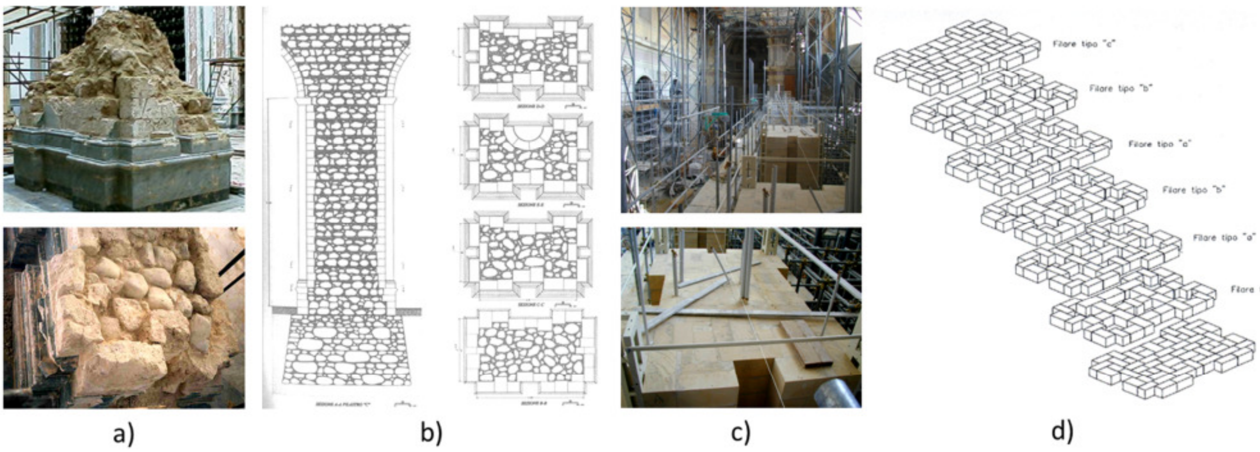


Figure 2.33: a) visual inspection of the remains of a collapsed pillar of the nave (courtesy of L. Binda); b) hypothetical reconstruction of the building technology of the pillars of the nave (from R. De Benedictis, S. Tringali, cit., 2000, p. 27); c) view of the pillars during their reconstruction (pictures by the author); d) 3D layout of the new texture used for the pillars (from R. De Benedictis, S. Tringali, cit., 2000, p. 63).

The use of the same type of stone for the reconstruction of the lost parts ensured a uniform mechanical behaviour between the remains and the new additions. The assemblage of the rebuilt structures was managed by applying different building techniques: multiple leaves structures where not proposed again, but a regular texture of shaped stone blocks was considered to be the right solution for the pillars after several characterizations on the materials (Figure 2.33). The materials of the building tradition of this area were assumed to be suitable for the reconstruction after specific tests, but the ancient building technique did not ensure the best mechanical response for the safety of the building, according to visual inspections, crack pattern survey, on-site and laboratory tests.

The rebuilt pillars of the nave became the new support for the still standing overhanging south wall of the central nave (see Figure 2.31c and Figure 2.34). The very complex demand for harmonizing safety and authenticity aspects was here solved through the ascertainment of the state of conservation of the structures and their components. The rule of the fine art execution was used as decisional parameter for the definition of conservative, strengthening and rebuilding solutions.

a) b)

Figure 2.34: a) view of two pillars rebuilt from the basement to the springer; b) view of the connection between a rebuilt pillar and the overhanging original wall of the central nave of the cathedral (pictures by the author).

This short (and incomplete) description had the aim to introduce a case study characterized by several difficulties for the arrangement of the final design. As remarked before, the ascertainment of the conservation state of the load bearing structures was the first step for the development of the project. The knowledge of the different aspects characterising collapsed and survived structures was achieved through the application of several diagnostic techniques that were not here described. This lack will be overcome in the next chapters, where the role of diagnostic techniques in the elaboration of the design will be examined in detailed.

Chapter 3. Methodology of study for the historical buildings

3.1 Experimental investigation on historical buildings

Considering the results obtained by the work of the ISCARSAH[89] commission, other important contributions for a complete definition of the state of the art can be mentioned: the so-called grey-literature, formed by conference proceedings, scientific manuscripts and more in general university studies, offers another source of information.

The diagnostics, referred to historical buildings structures, is an issue shared by several disciplinary fields: mainly architectural restoration and mechanics of the structures. The main publications are edited by international organizations like RILEM, IMS (International Masonry Society), North American Masonry Society, and many others.

Important studies on this issue are contained even in technical reports matured during the experimental activities for the calibration of non-destructive and minor destructive testing techniques. For this research some recent studies have been taken into account: testing campaigns promoted by ReLUIS projects before the earthquake in Abruzzi and, after it, other experimental applications were performed by research units from Politecnico di Milano and the University of Padua. The main results will be further presented.

One year before the 2009 earthquake, the research units from Milan and Padua were involved in a test campaign for the characterization of the historical buildings in the center of Sulmona, in Abruzzi. A similar experience was carried out before (in the 90s of the last century), during the first studies on the so-called “complex-aggregates”, promoted by the activities of the GNDT (Gruppo Nazionale Difesa Terremoti - *National Group of the Defense against Earthquake*). The GNDT organization involved many university laboratories in the research. The aim was focused on: the identification of the vulnerability of historical building in seismic areas. The research was organized following these steps:

a) Historical research on the centers chosen for the research (mainly located in Liguria and Umbria Region). This study is based on the consultation of different sources, from

[89] Carta ICOMOS: *Principi per l'analisi, la conservazione e il restauro strutturale del patrimonio architettonico*, Ratified during the XIV general assembly of ICOMOS in Victoria Falls, Zimbabwe, October 2003. (ISCARSAH, 2003)

national archives to local literature, and the aim is the reconstruction of the evolution of the building, with its changings and transformations.

b) Study of the geometrical, material and pathologic conditions of the buildings. This is a fundamental step of the study, that allows to document different aspects of the building: the modular-metrological proportions; the building techniques; statical problems showed by crack patterns; aesthetic peculiarities; the state of deterioration of materials and structures.
c) Knowledge of the mechanical properties of the building structure. The interpretation of the mechanical behaviour of the structures is necessary to assess the final goal of the research: the vulnerability of the building.

This study methodology was carried out in different situations, working on complex buildings, as a result of a progressive development of their structures and characterized by a deep interactions between them. According to the results presented in the final reports of these studies, the main innovative efforts at the research came from an extensive application of diagnostic testing techniques. The empirical activities on complex buildings allow to verify the applicability in real conditions of tests which are not always suitable for every building typology. As a consequence, non-destructive and minor destructive tests were calibrated on-site and their effectiveness was evaluated taking into account the complementary use of different testing techniques[90] [91].

The same approach was applied in Sulmona and in L'Aquila, in Abruzzi, for a study that was carried out for the qualification of the structural systems of the ancient buildings. In both cases, the theoretical approach promoted by A. Giuffrè was experimented through the empirical application of diagnostic tests. Furthermore, these experiences were also useful to observe the development of the work through the relationships between the subjects operating in the various

[90] E. N. Vintzileou, P. G. Touliatos, I. G. Konteas, V. A. Palieraki, The Katholikon of Osios Loucas *The Katholikon of Osios Loucas Monastery: in-situ investigations*, in "Proceedings of the First RILEM Symposium On Site Assessment of Concrete, Masonry and Timber Structures" (SACoMaTiS 2008), vol. I, pp. 539-548, 2008. (Vintzileou, 2008)

[91] P. Roca, J. Clapés, O. Caselles, M. Vendrell, P. Giraldez, S. Sanchez-Beitia, *Contribution of inspection techniques to the assessment of historical structures*, in "Proceedings of the First RILEM Symposium On Site Assessment of Concrete, Masonry and Timber Structures" (SACoMaTiS 2008), vol. II, pp. 621-632, 2008. (Roca, 2008)

activities: designers, customers, workers, experts, etc. The final design is intended here as a device for knowledge sharing, and not only as a set of rules and instructions. In L'Aquila, for example, the preservation of the architectonic heritage survived to the 2009 earthquake, is carried out through the study in depth of the historical building characteristics. This is a down-up approach: from the scale of the building to the urban scale. After the definition of the materials and structure mechanical properties, the design for the preservation of this peculiar urban model can be supported. L'Aquila was built during the mediaeval age, following the idea of connecting the organization of the new town with the organization of the surrounding territory. The plan followed a significant model[92]: the sequence of spaces forming the city is composed by squares, having in their center a fountain and the façade of a church closed at least one side of this area. Each church took the name from the village of origin of the population that was moved to the new town. The result was a set of quarters, organized around their main squares, hosting the people of a specific area of the territory. The protection of this singular urban organization passes through the comprehension of its single buildings, their material consistency and their technical properties.

3.2 Study of the masonry quality

The construction type, quality and state of preservation of masonry play a fundamental role in determining the capacity of a construction to sustain seismic actions[93]. Actually, the resistance of masonry to various actions (Figure 3.1) is not only governed by the mechanical properties of the constituent materials. This problem cannot be studied only in terms of stress and strain: a masonry which can resist and transfer the vertical and seismic forces without cracking should have geometric and physical characteristics that permit a monolithic behaviour[94]

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[92] More information concerning the origin and the historical development of L'Aquila are available in O. Antonini, C*hiese dell'Aquila. Architettura religiosa e struttura urbana*, Editore Carsa, 2004. (Antonini, 2004)

[93] P. Roca, F. Casarin, C. Modena, I. Rodríguez, A. Garay, *Damage monitoring of long-span historical structures*, in "Learning from failure. Long term behaviour of heavy masonry structures", WIT Press, Southampton, 2008. (Roca P. C., 2008)

[94] A. Borri, A. De Maria, *Eurocode 8 and Italian code. A comparison about safety levels and classification of interventions on masonry existing buildings*. In "Eurocode 8 Perspectives from the Italian Standpoint Workshop", 3 April, Naples, Italy, 2009 pp. 237-246. (Borri, 2009)

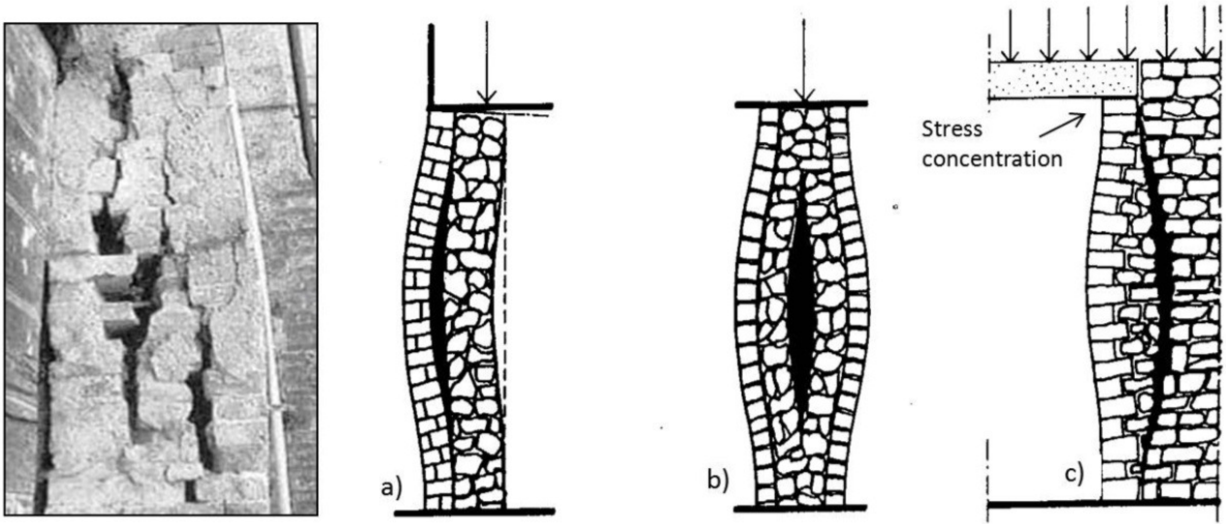


Figure 3.1: Examples of failure mechanisms due to compression stress in different masonry typologies (courtesy of Professor L. Binda).

Among the meaningful parameters to be examined in order to classify a masonry as being of "good quality" which are also introduced by the Italian Seismic Code (OPCM, 2003; LLPP, 2008 and 2009), the following characteristics should be taken into account:

- stones or brick laid in horizontal courses,
- vertical mortar joints not-aligned,
- use of almost square-shaped and stones of large size,
- limited volume of mortar as compared to the volume of bricks or stones,
- in case of multileaf masonry, leaves transversely connected and indeed sufficient mechanical properties of mortar and bricks or stones.

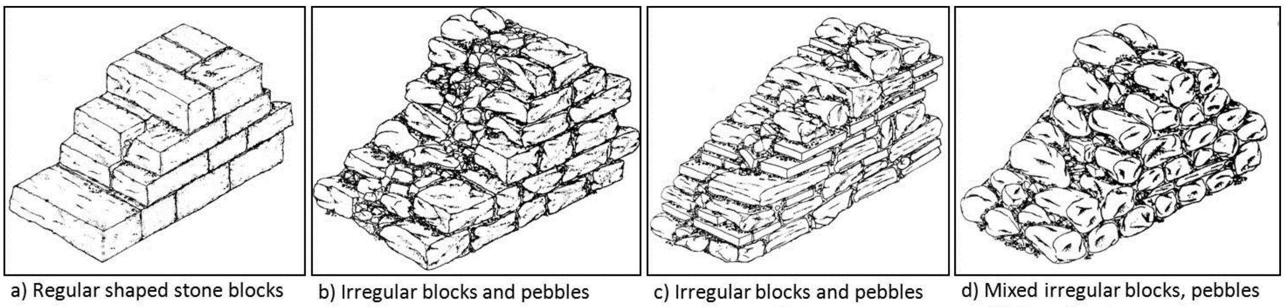
According to the regulations, the structural performance of masonry can be estimated considering the above mentioned parameters and providing the definition of the following factors[95]:

[95] L. Binda, *Caratterizzazione delle murature in pietra e mattoni ai fini dell'individuazione di opportune tecniche di riparazione*, CNR-Gruppo Nazionale per la Difesa dai Terremoti, Rome, Italy, 2000 pp. 181, http://gndt.ingv.it/Pubblicazioni/Binda_copertina_con_intestazione.htm. (Binda L. , 2000)

1. the geometry of the building and its structures,
2. the characteristics of the masonry texture (single or multiple leaf walls, connection between the leaves),
3. the physical, chemical and mechanical characteristics of the components (bricks, stones, mortar);
4. the characteristics of masonry as a composite material.

Double- or multi-leaf masonry is in numerous cases used in historic structures. In these cases the non-monolithic in-thickness behaviour becomes a governing parameter for the behaviour of masonry structures. Separation between adjacent leaves may be caused by decay of material in-time, combined with actions (vertical or horizontal) like the eccentric application of normal loads. For instance, floors or vaults can rest on one leaf of a multi-leaf masonry. Vaults, domes and arches are usually less thick than the masonry walls and piers by which they are supported. The situation is worsened by thrust forces acting through the thickness of masonry. Masonry with disconnected leaves is extremely vulnerable, especially against out-of-plane actions (like in the case of earthquakes).

Considering the large number of historic masonry typologies (with different cross-section layout), and the influence of the construction technique on its structural performance, a systematic study on the mechanical behaviour of existing masonry should begin from the survey of the various different geometry and building techniques (Figure 3.2), including the in-thickness characteristics (i.e. number of leaves and type of connection, if present, among them).



a) Regular shaped stone blocks | b) Irregular blocks and pebbles mixed type | c) Irregular blocks and pebbles mixed type with brick courses | d) Mixed irregular blocks, pebbles and flakes of rocks

Figure 3.2: Examples of different masonry typologies (from F. Doglioni, "Codice di pratica (linee guida) per la progettazione degli interventi di riparazione, miglioramento sismico e restauro dei beni architettonici danneggiati dal terremoto umbro-marchigiano del 1997", 1999, Bollettino Ufficiale Regione Marche). (Doglioni F. , 1999)

A large investigation on the morphology of masonry sections (Figure 3.3) on the Italian territory was started in the early nineties by L. Binda[96] [97], as it was considered as a prerequisite for drafting some guidelines for repair or strengthening by grout injection[98] [99] [100]. In this sense L. Binda and G. Baronio focused on the relationship between constructive typology, mortar quality and presence of voids (Figure 3.4) in order to determine the attitude of the masonry element to be injected. Their studies showed the difficulties connected to the execution of strengthening interventions and introduced new strategies for increasing the performance of damaged structures (as the application of deep repointing to reinforce masonry structures in seismic areas).

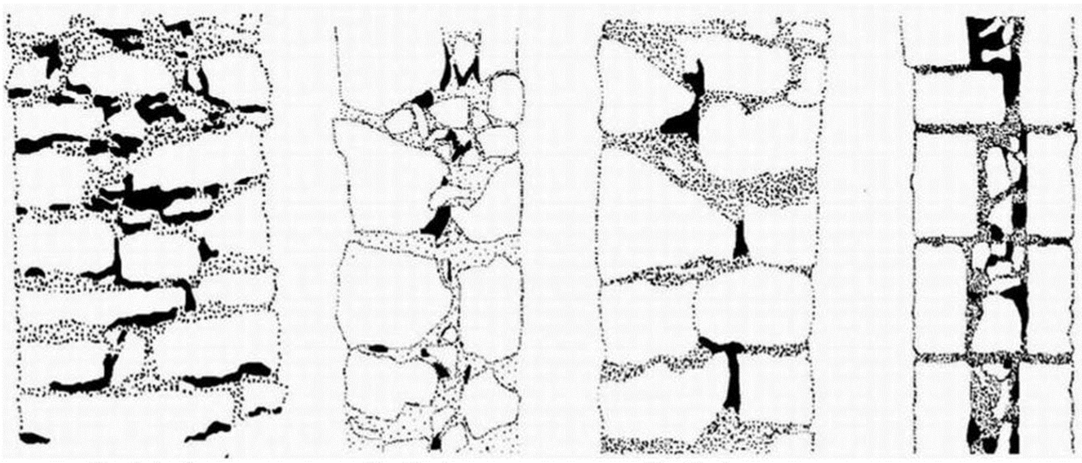


Figure 3.3: Examples of different masonry yipologies classification based on the characteristics of their sections (courtesy of Professor L. Binda and Arch. G. Cardani).

[96] S. Abbaneo, G. Baronio, L. Binda, C. Tiraboschi, *Murature in pietra: classificazione ed indagini preliminari per la scelta e la progettazione delle miscele per l'iniezione*. Convegno "Murature, Sicurezza, Recupero", Trento, Italy, 1993, pp. 185-222. (Abbaneo, 1993)

[97] See reference (Binda L. , 2000)

[98] G. Baronio, L. Binda, *Experimental approach to a procedure for the investigation of historic mortars*. In "IX International Brick and Block Masonry Conference", Berlin, Germany, 1991, pp. 1397-1464. (Baronio G. B., 1991)

[99] L. Binda, C. Modena, G. Baronio, *Strengthening of masonries by injection technique. VI North American Masonry Conference* - 6NAMC, Vol. 1, Philadelphia, U.S.A., 1993, pp. 1-14. (Binda L. M., 1993)

[100] M.R. Valluzzi, F. da Porto, C. Modena, *Behavior and modeling of strengthened three-leaf stone masonry walls*. RILEM Materials and Structures, MS 267, Vol. 37, April, 2004, pp. 184-192. (Valluzzi, 2004)

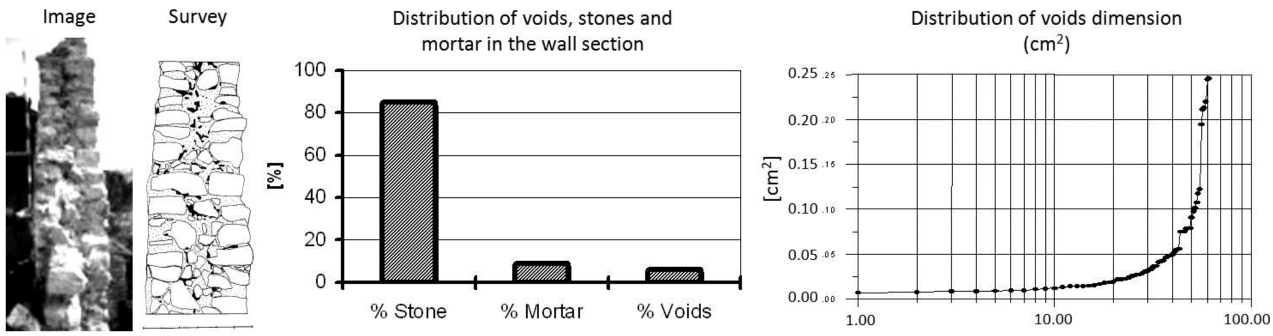


Figure 3.4: Phases of the study of a masonry section through the survey, the material analysis and the determination of the voids distribution (courtesy of Professor L. Binda and Arch. G. Cardani).

Contemporarily A. Giuffrè carried out in the early '90s[101] the first experimental and analytical studies about the mechanical behaviour of the stonework masonry typologies based on the recognition of "rule of art" characteristics after visual inspection, survey and typological classification. The studies were part of a more general analysis on the vulnerability of some historical centres like Ortigia[102], Città di Castello[103], Matera[104], Palermo[105]. These studies became a reference for the knowledge of the masonry quality. The masonry element was here carefully surveyed in order to identify the texture and the materials characteristics (dimensions, nature, etc.). Where possible (especially when partially collapsed structures of damaged or misused buildings were present), a detailed survey of the masonry section was acquired. These parameters were then reported in an abacus, showing the different characteristic of each typology. Following a A. Giuffre's opinion, the connection elements, defined as *headers*, can be a discriminating parameter for the evaluation of the wall mechanical behaviour, (Figure 2.20).

[101] A. Giuffrè, *Letture sulla meccanica delle murature storiche*. Rome, Kappa, 1990. (Giuffrè A. , 1990)

[102] A. Giuffrè, *Sicurezza e conservazione dei centri storici in area sismica, il caso Ortigia*, Laterza, Bari, 1993. (Giuffrè A. , 1993)

[103] A. Borri, E. Speranzini, G. Venturini, *Rischio sismico dei centri storici e protezione del patrimonio culturale. Il caso di Città di Castello*. "VII Convegno Nazionale di Ingegneria Sismica", Siena, Italy, 25-28 September, Vol. 2, 1995, pp. 1025-1034. (Borri A. S., 1995)

[104] A. Giuffrè, C. Carocci, *Codice di Pratica per la sicurezza e la conservazione dei Sassi di Matera,* La Bautta, Matera, 1997. (Giuffrè A. C., Codice di Pratica per la sicurezza e la conservazione dei Sassi di Matera, 1997)

[105] A. Giuffrè, C. Carocci, *Codice di Pratica per la sicurezza e la conservazione del centro storico di Palermo,* Laterza, Bari, 1999. (Giuffrè A. , 1999)

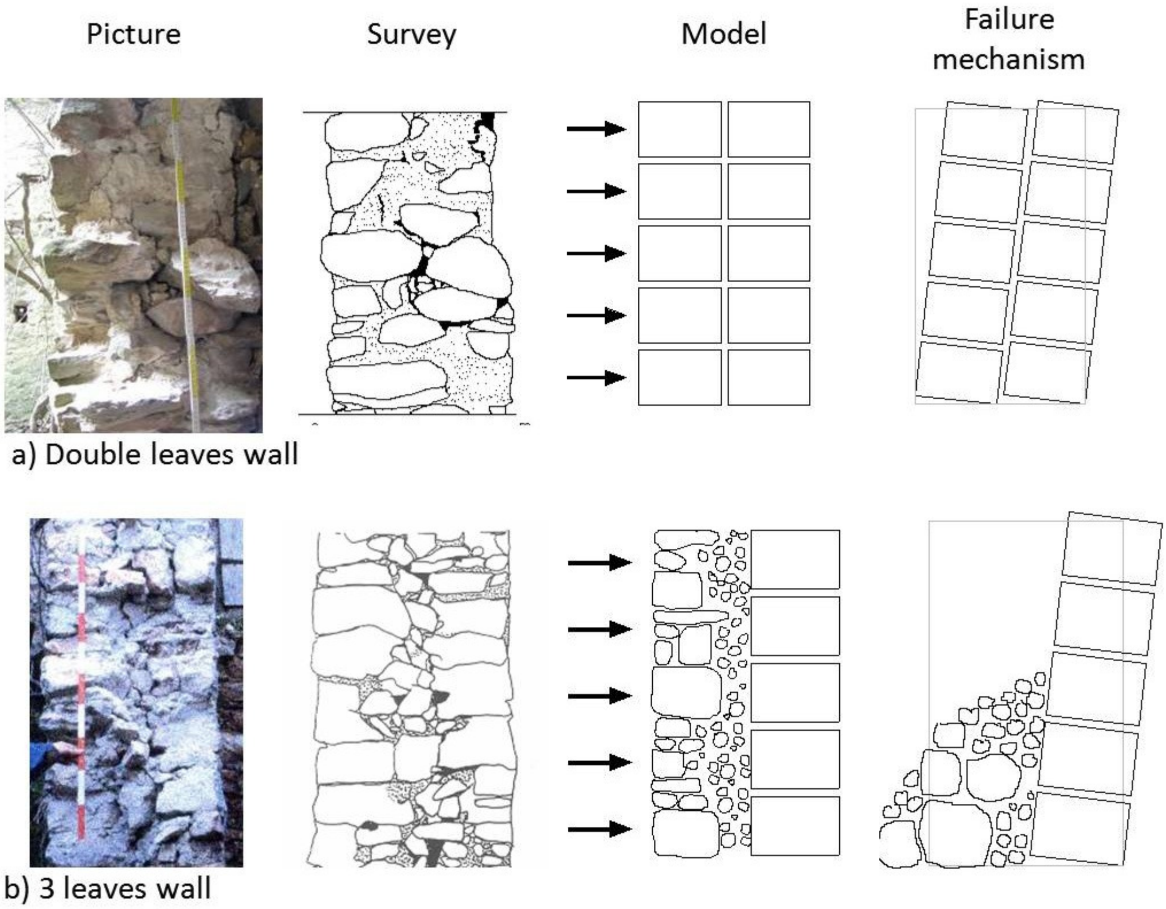


Figure 3.5: Classification of masonry typologies and relative failure mechanisms (courtesy of Professor L. Binda and Arch. G. Cardani).

Other parameters can be: dimension of the elements composing the masonry (bricks, stone, ashlar, etc.), shape and cutting of the stones, masonry texture, mortar quality, mortar quantity, presence of wedges, presence of non-horizontal courses, presence of leaves connections and headers[106], characteristic of the masonry section, homogeneity of the materials.

Giuffrè proposed a classification based on a parameter which indicates the ratio between the distance *d* of two subsequent headers and the thickness of the masonry wall[107]. The parameter is representative of the bending resistance of the wall.

[106] See reference (Giuffrè A. , Letture sulla meccanica delle murature storiche, 1990).
[107] See reference (Giuffrè A. , Sicurezza e conservazione dei centri storici in area sismica, il caso Ortigia, 1993)

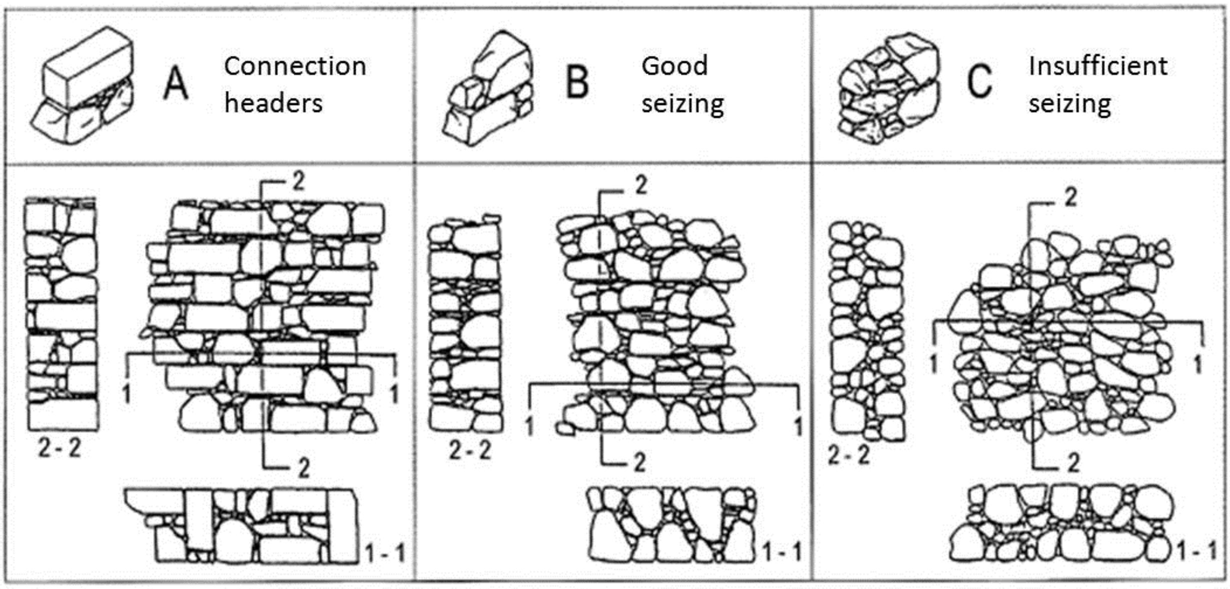


Figure 3.6: Study of the masonry characteristics through the identification of connectors: a) good connections; b) sufficient connections; c) insufficient connections (layout from A. Giuffrè, cit., 1993 and modified by the author).

The reference to these experiences matured during the 90s of the last century is useful for showing the connection between the university research and the development of the regulations concerning building safety and conservation. The comprehension of the masonry characteristic is now clearly requested in the Italian Seismic Code (OPCM, 2003; LLPP, 2008) and the assessment to the mentioned parameters became a topic of large discussion. The methodology to study the existing buildings are based on two main procedures: non-destructive methods, able to respect the integrity of the building materials, and slightly invasive tests, which produce minor alteration of the structures on which they are applied. The progressive standardization of these techniques will provide defined procedures for the application of different tests, in order to have several supports for studying the quality of the masonry buildings.

3.3 Review of the main diagnostic technique for historical buildings

It is a fact that conservation science is a multidisciplinary subject, involving experts coming from different technical fields (architecture, engineer, chemistry, physics, etc.). Since some decades the need of knowledge for the interpretation of the historic buildings offered the opportunity of the diffusion of diagnostic methodology for their characterization.

The diagnostic tests are usually divided in two categories: qualitative and quantitative tests[108] Qualitative tests provide generic information and cannot be directly related to the physical parameters of the materials forming the structures. For this reason qualitative tests are usually minor destructive type. On the contrary, quantitative results are obtained by minor destructive or destructive diagnostic tests.

Detailed reviews of the most useful diagnostic tests are well described in publications set for the university (i.e. "Tecniche della conservazione", edited by A. Bellini or "Recupero e restauro degli edifice storici", by S. F. Musso). The development of experimental techniques to study buildings characteristics is followed by different universities and research centres and in 2004 a project supported by the European Commission (project no. EVK4-2001-00091 – ONSITEFORMASONRY) was devoted to the calibration of innovative experimental techniques. These techniques are presented in the following and have the aim to support the study of the structural characteristics of the buildings.

The diffusion of the diagnostic techniques is connected to the increasing importance given to the qualification of the building structures. As mentioned in the previous chapter, national codes and international organisms are promoting the study of the structural performance of the ancient buildings through a procedure based on the following steps:

- Identification of the building typology
- Determination of the quality of the structure
- Comparison of the diagnostic parameters with the parameters fixed by the regulations;
- Definition of the structural performance.

[108] L: Binda, A. Saisi, C. Tiraboschi, *Investigation procedures for the diagnosis of historic masonries*, in *Contruction and Building Materials*, Vol.4, pp. 199-233, 2000; *Structural Engineering Compendium I*, Elsevier Civil Engineering Compendium, pp. 321-355, 2002. (Binda L. S., 2002)

According to the regulations, the control of the parameters which determine the respect of the safety conditions is obtained by applying three main categories of diagnostic tests[109]: non-destructive, slightly destructive and destructive tests. The first tests can be carried out on site, whilst a third category of tests is referred to the characterization of the sampled materials on-site (near diagonal test) or in laboratory through mechanical, physical and chemical analysis.

3.3.1 Non Destructive Tests (NDT)

Non-destructive tests are able to detect specific aspects of a material or a structure, respecting its integrity, avoiding any negative consequence from the interaction between the testing devices and the original materials. These kind of tests are based on correlations between some physical parameters (like density and elastic waves propagation or electrical impedance).

NDTs can be used for several purposes: (i) detection of hidden structural elements, like floor structures, arches, piers, etc..., (ii) qualification of masonry and of its composing materials, mapping of non-homogeneity of the materials used in the walls, (ex: 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.

The main non-destructive techniques, mentioned in the regulations, are shortly described in the following.

Active thermography

Every material emits energy in form of electromagnetic waves. Electromagnetic waves have different behaviour according to their wavelength. The electromagnetic radiation corresponding to the transmission of the heat is due to vibratory and rotatory motions of the molecules. The

[109] See reference (Binda L. S., 2002)

thermal radiation is the part of the electromagnetic spectra comprised between 01 – 100 µm (Figure 3.7).

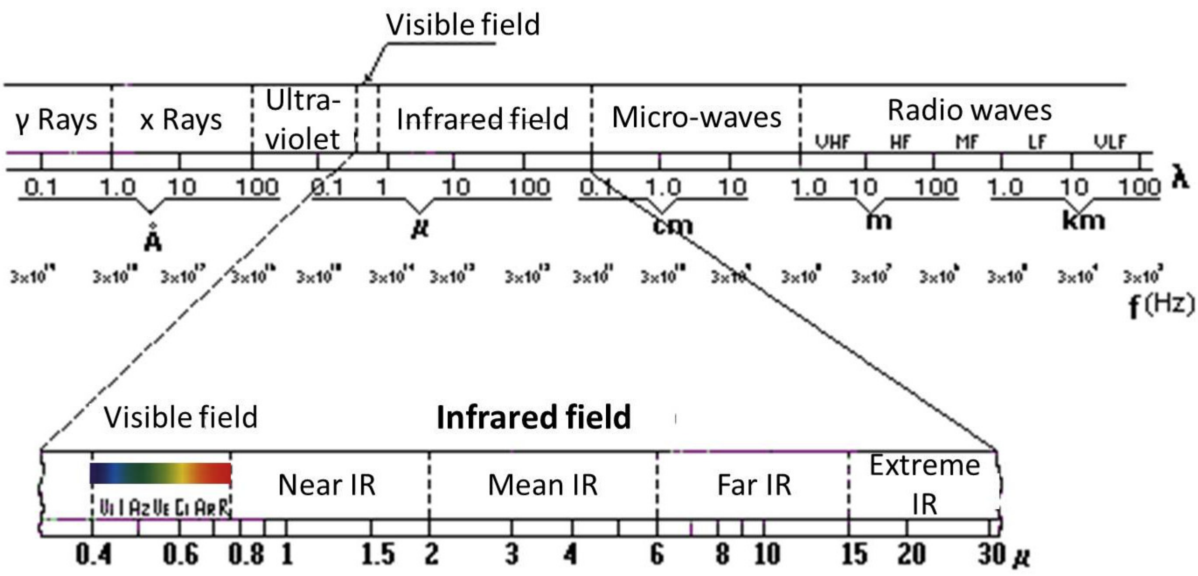


Figure 3.7: Electromagnetic spectra (layout by the author)

The principle of thermovision is based on the application of a thermal pulse to a surface, in order to cause a non-stationary heat flow. The propagation of the heat into the body depends on material properties like thermal conductivity, heat capacity and density of the inspected specimen. If there are inhomogeneities in the near surface region of the structural element this will result in measurable temperature differences in the local area of the surface.

This test is used for the following actions[110]:

- localisation of voids and other irregularities in the near surface region (up to 10 cm);
- Localisation of plaster delaminations;
- Investigation of the masonry structure behind plaster;
- Detection of moisture in the near surface region.

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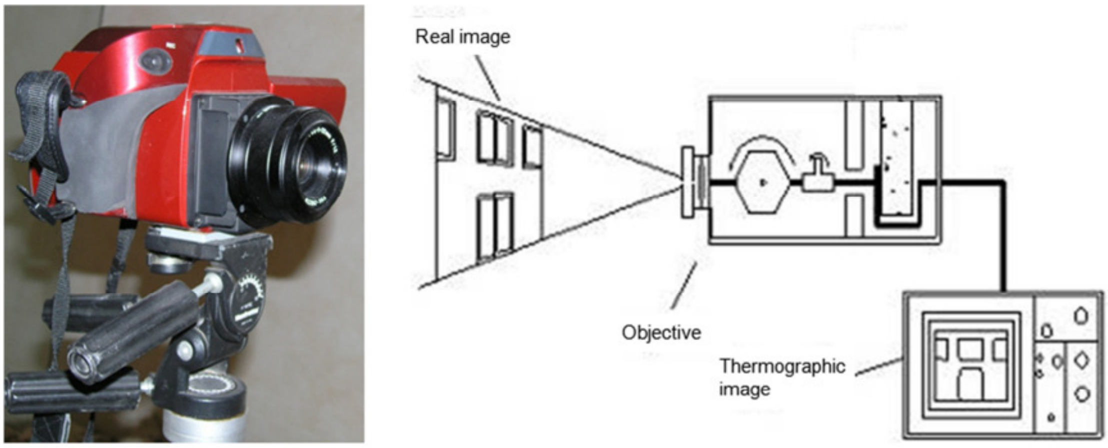
[110] C. Maierhofer, M. Röllig, *Active thermography for the characterization of surfaces and interfaces of historic masonry structures*, in *TCE `09 - 7th International symposium on nondestructive testing in civil engineering*, 2009. (Maierhofer, 2009)

Impulse thermography (IT) and pulse-phase thermography (PPT) are active approaches for a quantitative thermal scanning of the surface of various structures and elements. The surface of the structure to be investigated is heated by using a radiation source. After switching off the heating source, the cooling down behaviour is recorded in real time with an infrared camera (Figure 3.8). Infrared camera is composed a special body-lens (formed by materials able to be passed through infrared rays) and a sensor. The sensor is constituted by a material that converts the stimulus of the infrared radiation into a tension that is further converted into a grey scale or a colour scale image: it is defined “thermogram” and each pixel of the image represents a temperature detected on the framed surface.



a) b)

Figure 3.8: a) IR camera (picture by the author); b) layout of the test (from A. Bellini, "Tecniche della conservazione", 1996).

While observing the temporal changes of the surface temperature distribution with the infrared camera, near surface inhomogeneities will be detected if they give rise to measurable temperature differences on the surface (Figure 3.9).

The main approach of IT in analysing the thermal data is to interpret the function of surface temperature versus cooling time for selected areas with and without inhomogeneities.

PPT is based on the application of the Fast Fourier Transformation (FFT) to all transient curves of each pixel. Thus, one obtains amplitude and phase images for all frequencies. Amplitude images show the internal structure of a specimen up to a maximum available depth depending on the frequency (low pass filter behaviour). Phase images show the internal structure within a certain depth range depending on the frequency (band pass filter behaviour).

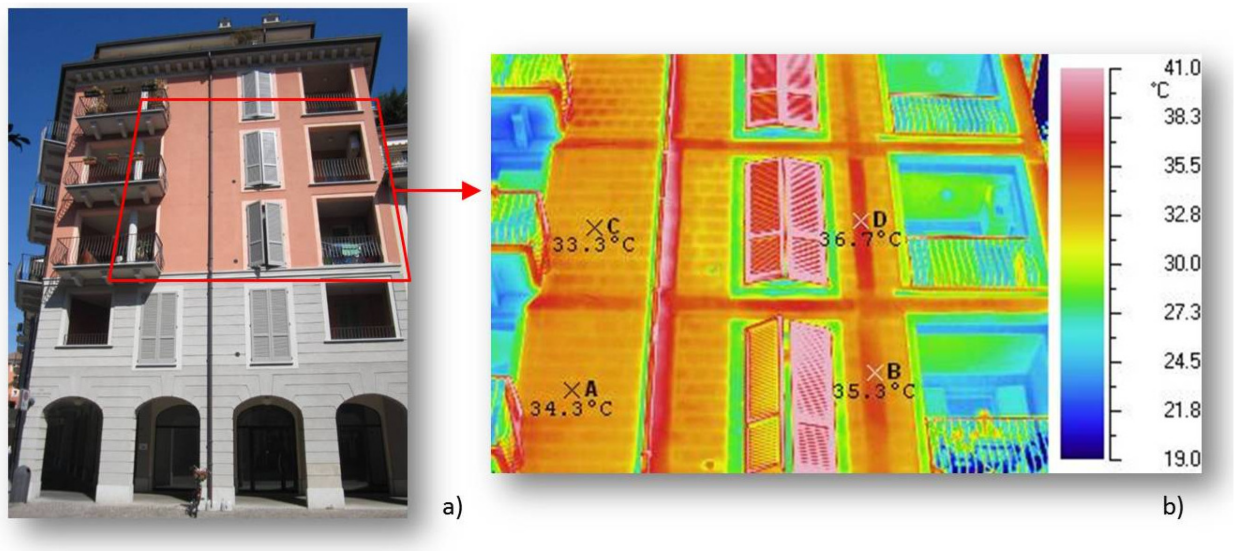


Figure 3.9: Example of identification of the structural elements in a wall tested by thermovision: a) view of the building with the indication of the framed area; b) relative thermogram framed by the IR camera (pictures by the author).

Active methods have proven their usefulness for locating defects in the near surface region like voids and honeycombing in concrete and delaminations of tiles, plaster and glued carbon fibre reinforced laminates. Further developments and applications in civil engineering are using the sun as a natural heat source, e.g. for the inspections of bridge decks and of paving in general.

Considering the potentialities of thermovision for the cultural heritage field, deeper description of its characteristics, with reference to specific case-studies, will be presented in chapter no. 4.

<u>Pulse sonic test</u>

This test is used for the qualification of the masonry morphology[111]. This technique is useful to detect the presence of voids and flaws and to find crack and damage patterns. It can be suitable for controlling the effectiveness of repair by injection technique.

The testing technique is based on the generation of elastic waves in the frequency range of sound (20 Hz-20 kHz), by means of mechanical impulses at a point of the structure. The pulse velocity is related in a homogeneous and isotropic solid to the modulus of elasticity and density.

[111] A. Saisi. L. Binda, L. Zanzi, *Diagnostic Investigation of the Stone Pillars of S. Nicolò L'Arena*, Catania, *9th Canadian Masonry Symp*., Fredericton, New Brunswick, CD-ROM, 4-6 June, 2001 (Saisi, 2001)

The relationship is independent of the frequency of the vibrations. In the case of masonry, due to its heterogeneity, the pulse velocity qualitatively represents the characteristic of the masonry.

A signal is generated by percussion with an instrumented hammer or by an electrodynamics or pneumatic device (transmitter) and is received by means of an accelerometer (receiver), which can be placed in various positions (Figure 3.10).

a) b) c)

Figure 3.10: Sonic test device: a) instrumented hammer; b) accelerometer; c) signals stored in the PC (pictures by the author).

According to the disposition of the transmitter (T) and the receiver (R), three tests layout are possible: i) direct sonic tests, when T and R are placed on the opposite sides of the structure, at the same height and with their hypothetical joining line perfectly perpendicular to the faces; ii) semi-direct sonic tests, when T and R are on opposite sides, but not connected by an hypothetical line perpendicular to the faces of the structure or when are located on perpendicular faces of the structure; iii) surface tests, when T and R are placed on the same side of the structure.

The data processing consists in measuring the transit time between the transmitter and the receiver and in calculating the pulse velocity dividing the distance between the devices by the transit time. Signals are stored by a waveform analyser coupled with a computer for further processing.

Data are used to estimate the so called “time of flight” of the conic waves between the emission point and the receiving point. Many commercial devices for sonic tests are able to calculate automatically this parameter, but the reliability of the results depends on the quality of the acquired signals, which sometimes can present several noise. For this reason, the result is usually a mean value between different numbers of acquisitions for each point of the sonic test.

Due to a large number of experiences, in Politecnico di Milano, a method based on the real-time visualization of the acquired signals and the direct control of the operator is used.

Using a pre-ordered grid of points, the test can be carried out on representative areas of masonry structures. If the points of the geometrical grid have a close range, the data can be represented through specific software, able to calculate the mean values between the tests points: through the association of grey or colour scale with the velocities, maps representing the distribution of the sonic velocities can be obtained (Figure 3.11). This kind of representation is a valid method for interpreting the macroscopic characteristics of the masonry sections.

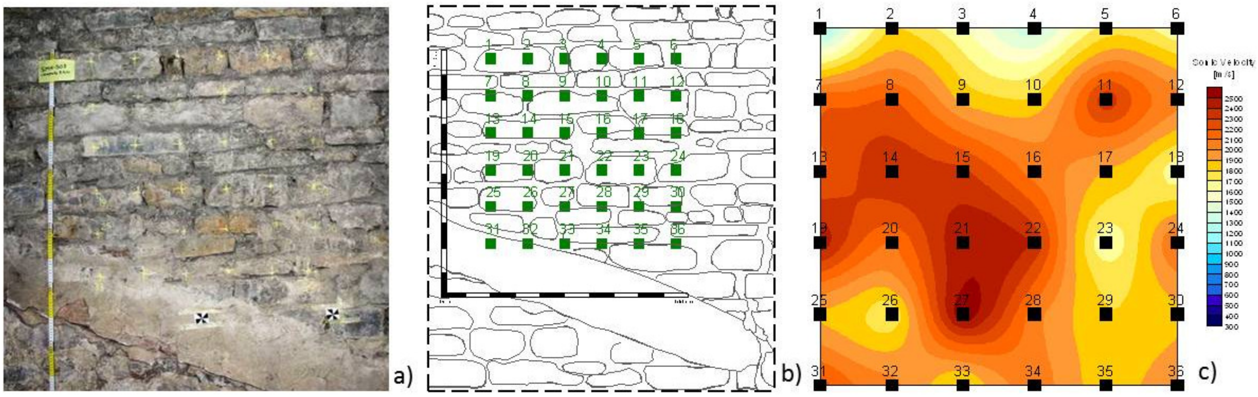


Figure 3.11: Example of representation of the results obtained by direct sonic tests: a) view of the masonry texture with the testing points; b) layout of the grid of points; c) map of the velocities distribution (layout by the author).

Being a non-destructive methodology for characterising qualitatively the properties of building structures, direct sonic tests are often used in cultural heritage preservation. The relationship between the propagation velocity of elastic waves in a medium will be treated in depth in chapter no. 4.

Ultrasonic tests

The method is based on the transmission and/or reflection of ultrasonic waves generated by an ultrasonic transducer or transducer array. Compared to the previous described sonic tests, ultrasonic technique utilizes higher frequency (40 kHz 200 kHz). As a consequence, ultrasonic tests are characterized by low wavelengths and for this reason this technique is particularly indicated for compact and fairly homogeneous materials (like wood, monolithic stones and concrete). Multiple leaves structures are on the contrary not indicated for ultrasonic tests, due to their heterogeneity: in this cases only long wavelength are able to travel across the different materials forming the structure and the low frequency adopted for sonic tests can satisfied this condition. Also in this case the velocity of propagation depends on mechanical parameters of the structure: above all the reflection on the contrast of the acoustic impedances at the interface[112]. The use of high frequencies has a positive response on the resolution of the ultrasonic method: details having a lower dimension respect to the wavelength can be better investigated. In the cultural heritage field, ultrasonic tests are indicated for testing single stone elements or timbers. Different transducers can be available for the different materials: flat for the regular shaped elements and with the addition of wedges for timbers or stone elements with irregular shape (Figure 3.12).

a) b)

Figure 3.12: Two different transducers and receivers used for direct ultrasonic tests: a) flat devices and b) devices with wedges (pictures by the author).

The principle of the ultrasonic echo technique with separated transmitter and receiver is based on the emission and reflection of impulses generated by a transducer. Inner voids in a specimen can be regarded as an interface between two different materials, (brick/air), for the propagation of sound and lead to total reflectance of the ultrasound waves. The propagation time of the reflection echo is proportional to the depth of the reflector (assuming a constant velocity of propagation). This principle will be used for further descriptions of this tests in the next chapter.

112 UNI EN 12504-4: *Prove sul calcestruzzo nelle strutture - Parte 4: Determinazione della velocità di propagazione degli impulsi ultrasonici*, 2005 (UNI EN 12504-4, 2005)

The aims of the technique are: determination of the thickness of walls and single leaves, location of voids having sizes in the order of the wavelength of the ultrasonic waves (20.0 to 100.0mm) depending on frequency of the emitted pulses, characterisation of cracks, correlation of ultrasonic velocity to compressive strength. As shown in Figure 3.13, ultrasonic tests present a considerable sensitivity for limited discontinuities: comparing the results obtained using the same configuration on two different marble columns, the velocities of the second columns indicate the presence of a diffused damage in the element.

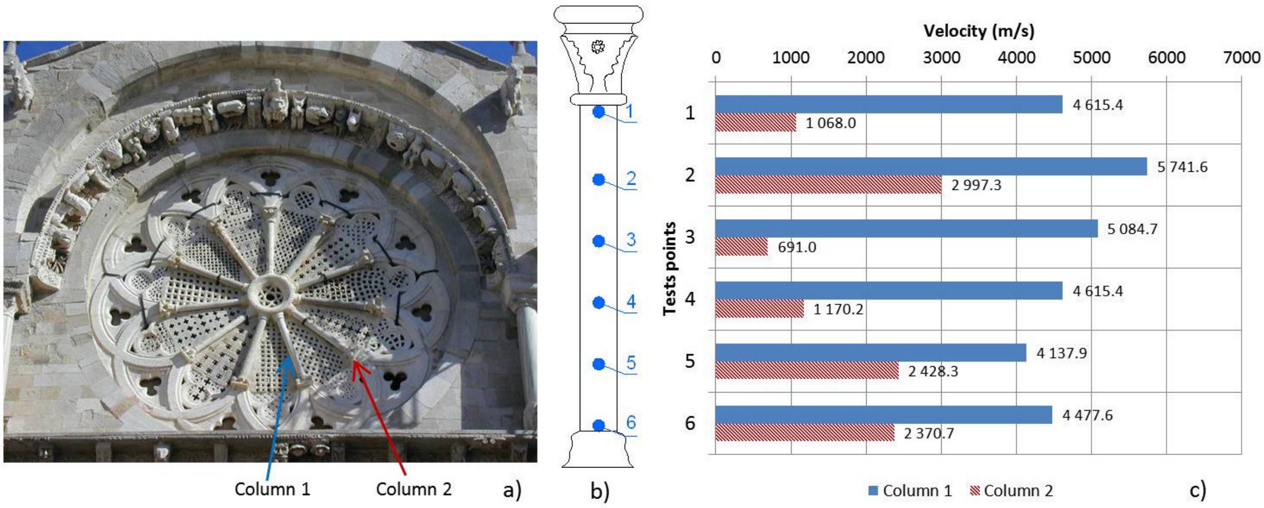


Figure 3.13: Comparison between ultrasonic velocities measured on two columns of the rose window of the Troia Cathedral in Apulia: a) view of the rose window, b) test points layout; c) results of the tests (picture and bar chart by the author).

Impact-echo method

Impact-echo is a wave propagation-based technique which uses frequency domain analysis for data interpretation. Frequency spectrum analysis is performed on the waveform obtained from a mechanical impact applied to the surface of the concrete element. By applying a point impact on the surface of the test object, a transient stress pulse is generated and propagates into the material as compression, shear and surface waves. The compression and shear waves, which travel through the material, are partly reflected by any internal interface or discontinuity such as reinforcements, ducts, defects, delaminations. These waves are almost totally reflected if the second material is air, such as in the presence of a void or at the external boundaries of the element under investigation. Therefore, the principle of Impact-echo testing is based on multiple reflections of an acoustical wave impulse between the surface and any internal reflector (Figure 3.14).

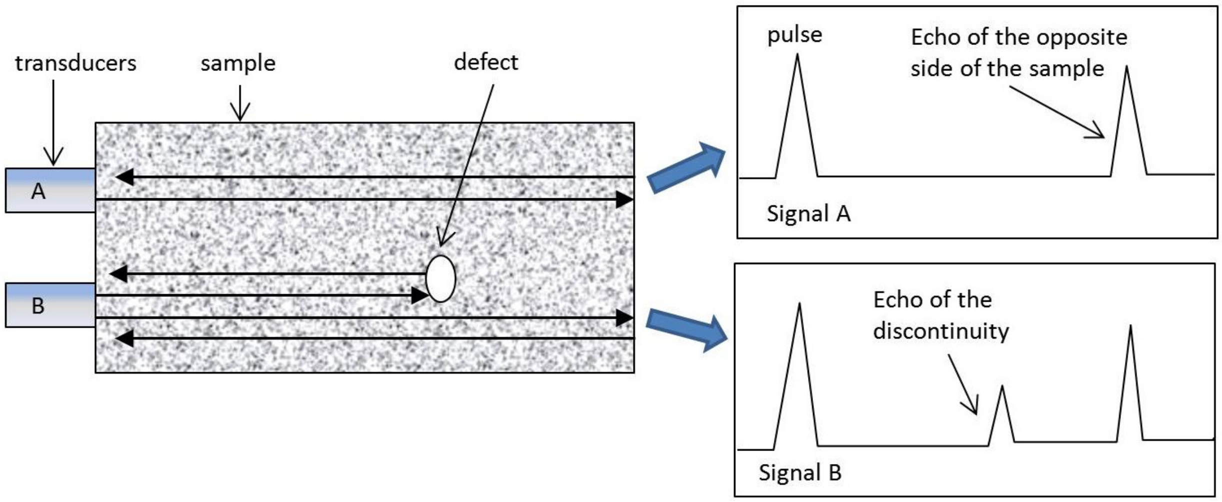


Figure 3.14: Layout of the impact echo method (layout by the author)

The test, developed by M. Sansalone and N. J. Carino[113], is used for the following applications:

- Determination of the thickness of walls and single leaves;
- Detection of detachment of leaves;
- Location of voids;
- Location of deteriorated areas;
- Location of cracks;
- Correlation of sonic velocity to compressive strength (limited).

In impact-echo a mechanical point impact is used to generate an acoustical impulse, which propagates into the material. Multiple reflections of low frequency waves between the external surface and internal reflectors (ducts, delaminations and defects) are used to measure transient resonance frequencies and to evaluate structural integrity. The test proved its effectiveness on fairly homogeneous structures (reinforced concrete or monolithic elements), where ultrasonic

[113] Mary J. Sansalone, *Impact-Echo: The Complete Story*, in *ACI Structural Journal*, no.94-S71 I, December 1997; M. (Sansalone, 1997); and M. Sansalone, N. J. Carino, *Detecting Delamination in Reinforced Concrete Slabs with and without Asphalt Concrete Overlays Using the Impact-Echo Method*, in *Material Journal of the American Concrete Institute*, Vol. 86. 2., 1989, page 175-184. (Sansalone M. C., 1989)

impulses could be used, but positive results were observed even on standardized brick-block masonry.

Acoustic Emission (AE)

Diagnostic methods employing the propagation of elastic waves are based on the artificial generation of a vibratory motion. Acoustic emission (AE) are a sort of passive method, based on the measurement of the waves frequency produced by the environmental effects. AE are detected at the surface of a specimen by a transducer that converts an acoustic-pressure pulse into an electrical signal of very small amplitude. By knowing the relative arrival times, the P-wave velocity of the material, and the coordinates of each sensor, the eventual presence of discontinuities can be estimated[114].

The major element of an AE transducer is a piezoelectric ceramic mounted with little backing, so that the response is under damped. At the optimum sensitivity, the voltage generated by a 1 mbar acoustic pressure has a typical value of 0.3 mV. AE sensors can be attached directly to the material; a consistent coupling (or gluing) procedure should be used to reduce the variability in bonded-transducer response.

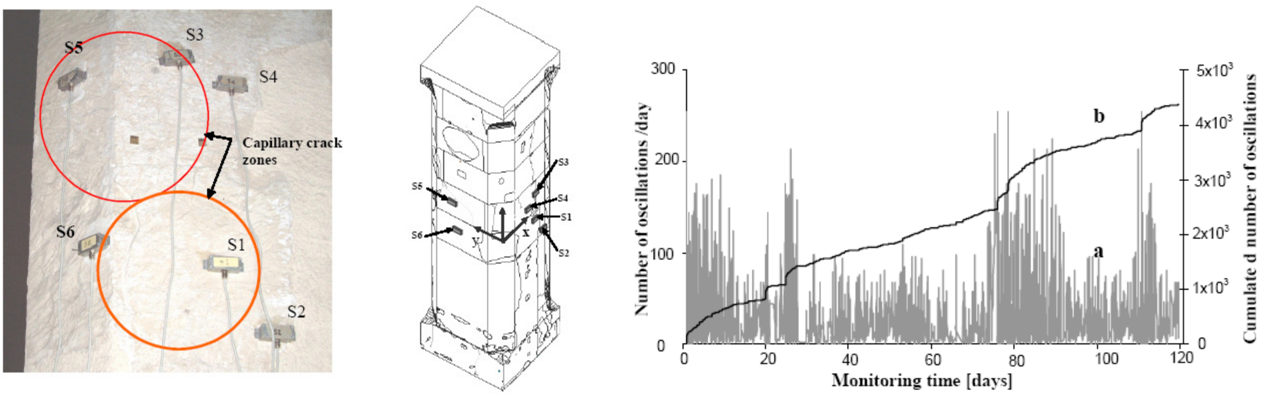
The wave forms should be stored automatically and sequentially on a hard disk for post-processing. Preamplifiers (40 dB gain) and filters (band pass 0.1 to 1.2 MHz) are usually required to maximize amplification, minimize noise, and assure matched frequency response.

During a mechanical test on masonry specimens, AE are useful to localize the first cracks and to identify the features of the process zone. The technique has been experimented also on historical masonry buildings, being particularly suitable for the analysis of long term behaviour[115]. AE are even well promising for monitoring the cracking conditions in historical damage structures, in order to assess their durability taking into account cumulative damage after continuous

[114] Mitsuhiro Shigeishi, S. Colombo, M. C. Forde, *Acoustic emission application to masonry structure*, in L. Binda, R. de Vekey, "*RILEM Workshop on Site Control and Evaluation of Masonry Structures and Materials*", 2003. (Shigishi, 2003)

[115] A. Carpinteri, P. Bocca, A. Grazzini, G. Lacidogna, A. Manuello, D. Masera, *Cyclic damage analysis by acoustic emission in reinforced masonry walls*, in "Proceedings of the First International RILEM Symposium On Site Assessment of Concrete, Masonry and Timber Structures" (SACoMaTiS 2008), pp. 443-452, 2008. (Carpinteri A. B., 2008)

monitoring. Cracking, in fact, is accompanied by the emission of elastic waves which propagate within the bulk of the material. These waves are received and recorded by piezoelectric transducers applied to the external surface of the structural element. The signal is therefore analysed by a system counting the emissions that exceed a certain voltage threshold. Applying a procedure known as *Ring-Down Counting*, cumulative curves reflecting the count number of emissions can be obtained[116]. In this way, the oscillations per unit time can be compared with the quantity of energy released during the monitoring process and the relative sums (cumulative function, may be assumed to increase with the widening of the damaged zone (Figure 3.15).



a) b) c)

Figure 3.15: Example of AE application on a pillar of the Cathedral of Syracuse (Sicily): a) view of the piezoelectric transducers applied on the pillar; axonometric representation of the test layout; c) differential and cumulated number of AE oscillations during the monitoring of the pillar (from A. Carpinteri, C. Lacigogna, A. Manuello, L. Binda, "Monitoring the structures of the ancient temple of Athena incorporated into the Cathedral of Syracuse", in 14th Brick and Block masonry conference, Sidney, 2008, figures 6 and 7).

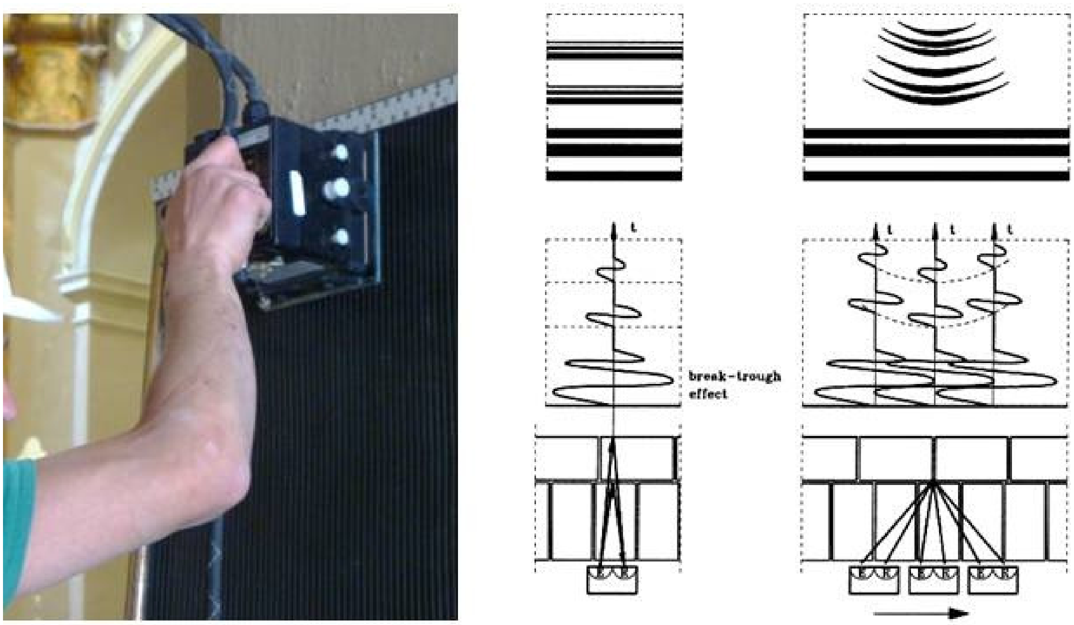
<u>2D and 3D echo-radar</u>

Developed in geophysical field, for the study of the ground, the RADAR technique was successfully employed in archaeological investigations and new applications are even available for building structures.

The method is based on the propagation of short electromagnetic impulses, which are transmitted into the building material using a dipole antenna, composed by an emitter and an

[116] A. Carpinteri, G. Lacidogna, A. Manuello, L. Binda, *The Ancient Athena Temple in Syracuse (Sicily): an investigation on structural stability*, in "Proceedings of the First International RILEM Symposium On Site Assessment of Concrete, Masonry and Timber Structures" (SACoMaTiS 2008), pp. 727-736, 2008. (Carpinteri A. L., 2008)

acquisition unit[117]. The impulses are reflected at interfaces between materials with different dielectric properties (Figure 3.16), i.e. at the surface and backside of walls, at detachments, voids, etc[118]. The possibility to assess in depth the investigated structure depends on the frequency of the equipment: antenna with high frequency (2 or 5 GHz) is recommended for detailed analysis of the external layers of the composite structures, ensuring the propagation of electromagnetic impulses with short wavelength. On the contrary, antenna with low frequency (i.e. 600 MHz) generates long wavelength, indicated for characterising large structures, but not always able to guarantee an appreciable resolution.



a) b)

Figure 3.16: a) RADAR antenna applied on a masonry pillar (picture by the author); b) Typical features in radar sections due to the leaf and to the joint reflections (layout taken from L. Binda, A. Saisi, C. Tiraboschi, "Investigation procedures for the diagnosis of historic masonries", in "Construction and Building Materials", June, 2002, Vol. 14, No. 4, pp. 199-233).

According to the layout of the test, radar is able to provide profiles representing the sequence of layers and discontinuities contained in the investigated structure. The execution of the tests

[117] M. C. Forde, N. McCavitt, *Impulse radar testing of structures*, in Proc. Instn Civ Engrs Structures & Buildings, 1993, 99, February, pp. 96-99. (Forde, 1993)

[118] M. C. Forde, *Georadar for the investigation of existing structures*, in in "Proceedings of the First International RILEM Symposium On Site Assessment of Concrete, Masonry and Timber Structures" (SACoMaTiS 2008), pp. 829-837. (Forde M. C., 2008)

consists in moving the antenna box on the surface of the tested element (masonry wall, pillar, floors, etc.), along a pre-assigned trajectory. Following a rectilinear profile, 2D cross section radargrams can be obtained. Moving the antenna along many parallel profile regularly spaced by using a Pad System for Georadar, 3D cross section radargrams are detectable[119]. The coordinate along the profile is measured by an odometer (e.g., an encoded wheel). The data are processed to put in evidence the reflection from internal interfaces (e.g., masonry leafs) or the diffractions from small target (e.g., voids, wooden beams, metal joints or chains) [120].

The GPR system is usually constituted by a central unit and a set of shielded antenna boxes (for instance 500MHz and 1GHz central frequencies). The unit is connected to a notebook for setting the acquisition parameters and for quality control of the data. Odometer systems like encoded wheel and hip-chain can be connected to the antenna. The antenna must be in contact with the masonry surface but the surface can be protected with a plastic or paper sheet in case frescos or other decorations could be damaged.

The main targets of the tests in cultural heritage field are: detection of the internal morphology of the masonry; layer detachment; 3D reconstruction of internal inhomogeneities or elements (voids, wooden or metal elements). Data are processed by 2D and 3D software tools in order to apply band-pass filtering, time calibration and a gain function to the original stored data. Using a velocity analysis function to calibrate the time-depth transformation, 2D and 3D migration algorithms can be applied. As a result, radargrams can be represented in different systems of coordinates: usually the horizontal axis represents the position or the recorded trace number, whilst the vertical axis represents the propagation time (expressed in nanoseconds) or the penetration depth of the signal (in centimetres). The example reported in Figure 3.17 shows the detection of the depth of the external stone layer of a masonry pillar investigate through radar test, with a 2 GHz antenna.

[119] G. Mirabella Roberti, L. Zanzi, F. Trovò, Detecting hidden ties in historic Venetian palace by means of GPR, in "Proceedings of the First International RILEM Symposium On Site Assessment of Concrete, Masonry and Timber Structures" (SACoMaTiS 2008), pp. 965-974, 2008. (Mirabella Roberti, 2008)

[120] C. Colla, M. C. Forde, P. C. Das, *Radar imaging in composite masonry structures*, in "Proceedings of 7th International Conference on Structural Faults and Repair", Edinburgh, Scotland, July 9, Vol. 3,1997, pp. 493-504. (Colla, 1997)

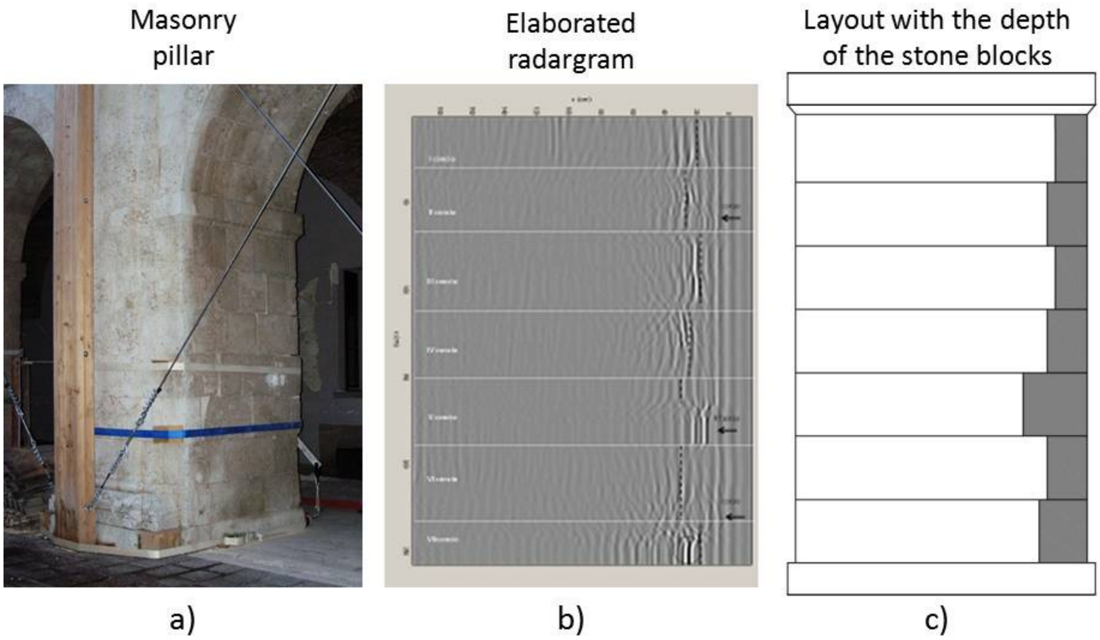


Figure 3.17: RADAR test interpretation. a) view of the tested structure; b) elaborated radargram; c) layout showing the depth of the first layer of stones (courtesy of professor L. Zanzi and Eng. S. Munda)

Sonic and radar tomography

Among the ND applications the tomographic technique is quite attractive for the high resolution that can be obtained[121] [122]. 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 imagining is a computational technique which utilises an iterative method for processing a large quantity of data. Standard pulse velocity data or radar data could be used to reconstruct a velocity distribution within a solid material, thus providing an "image" of the masonry interior. Tomography's principle is the Fourier Slice theorem[123] that shows how a complete slice of an

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[121] M. P. Schuller, M. Berra, R. Atkinson, L. Binda, *Acoustic Tomography for Evaluation of Unreinforced Masonry*, in "VI International Conference Structural Faults and Repair", 1995, Vol. 3, pp. 195-200. (Schuller, 1995)

[122] S. Valle, L. Zanzi, G. Lenzi, G. Bettolo, *Structure Inspection with Radar Tomography, in* "International College Inspection and Monitoring of the Cultural Heritage", IABSE-ISMES, 1997. (Valle, 1997)

[123] A. C. Kak, M. Slaney, *Principles of Computerized Tomographic Imaging*, IEEE Press, 1994. (Kak, 1994)

object can be extracted from a proper set of measurements. The testing technique gives a map of the velocity distribution on a plane section of the structure under investigation. The method consists of obtaining numerically the time taken by a wave along several directions, which uniformly cover the section under investigation. The computation is made by using the inversion process which, starting from the time of signal propagation, reconstructs the field velocity. The section of the masonry is marked by a mesh grid whose dimension is related to the distance between two subsequent transmission or receiving points. Assuming that the distance between emission and receiving points tends to zero, a punctual velocity *Vp* and a punctual slowness *S*=1/*Vp* can be defined. The physical behaviour of a section can be defined when the *S*, considered as function of the position *S*=*S*(x,y), is known for each point belonging to the section itself. The function *S*(x,y) can be approximated dividing the section into N rectangular cells: in each cell the velocity, and the slowness, are assumed as constant. The tomographic problem consists in the reconstruction of the distribution of the slowness *S* in the *N* cells, knowing the *M* times of propagation of the waves measured along a series of paths connecting generic couple of points source-receiver distributed along the border of the section.

For the correct execution of the sonic tomography, both sides of the masonry structure must be accessible. A series of receivers (usually small geophones) is positioned on one side of the wall and connected to a multi-channel seismograph. On the other side of the wall a series of pulses are generated by hitting the surface along a profile in correspondence to the receivers line. For every shot the arrivals to all the receivers are recorded. The source-receiver rays cover a section across the wall.

The interpretation consists in a tomographic reconstruction of the distribution of the sonic velocities across the section (which is divided in pixels). This velocity distribution is expressed, via graphical routines, in a grey-or in a colour scale (Figure 3.18).

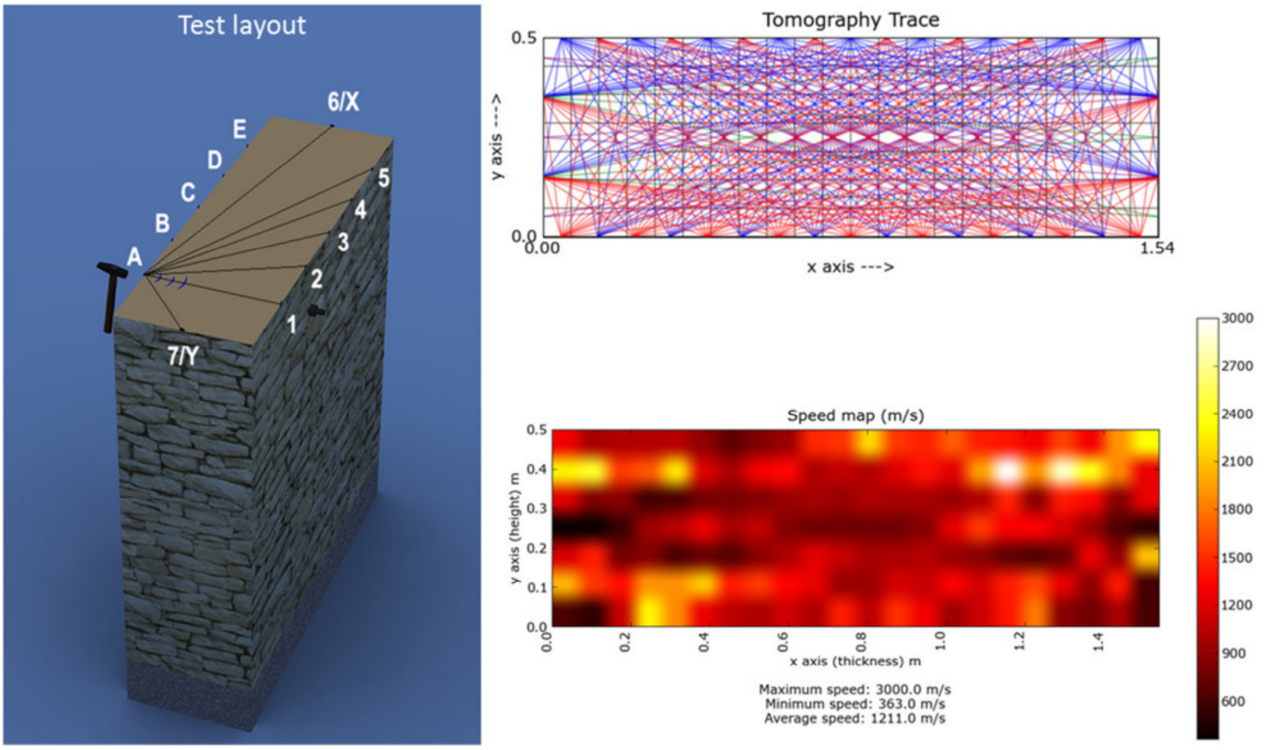

Figure 3.18: Layouts and result of a sonic tomography (courtesy of M. Meana and Eng. R. Felicetti).

Pendulum Hammer Testing (PT)

The pendulum hammer is a rebound hammer which measures surface hardness, and the particular pendulum hammer used for earthen buildings is a Schmidt type PT, which is specified as appropriate for low strength materials[124].

The rebound hammer given by the pendulum readings is calibrated for each particular material. Despite the wide scatter of results, by using the average of a large number of readings, one can achieve a good approximate value non-destructively (Figure 3.19). The validity of using the Schmidt hammer for adobe is arguable, since the hammer would only assess the compressive strength of the masonry units, not of the homogeneous properties of masonry.

[124] RILEM TC 127 – MS-D-7 Determination of pointing hardness hammer (RILEM TC 127-MSD7)

a) b) c)

Figure 3.19: Description of the test phases: use of a grid-template to report the testing points on the surface; b) the testing grid reported on the surface; c) application of the pendulum on a mortar joint (pictures by the author)

Water absorption under low pressure (Karsten pipe method)

This test was design the moisture presence. A calibrated pipe is fixed on a surface of the wall and filled with water to measure the water absorption over a defined time[125].

A first procedure consists in filling the water to a certain height and water absorption is measured over a defined time. The water absorption coefficient is defined as the difference in volume absorption between 5 and 15 minutes, starting at the highest level of the pipe (98 mm).

A second procedure take into account to fill the pipe stepwise: in this case, the height of the filled column corresponds to the water pressure that causes water absorption.

The stem of the pipe is calibrated in ml or mm. The bowl is provided with a rim to fix the device to the surface of the wall, making use of sealant. The highest level of the pipe is 98 mm.

The Karsten pipe is useful to give an objective measurement of the water absorption of the surface materials on site and of the rate of water absorption of treated and untreated stone and brick masonry.

3.3.2 Minor Destructive Tests (MDT)

This definition is commonly used for those diagnostic techniques which produce some alteration to the existing structures. Generally speaking, these techniques are not able to preserve

[125] R.P.J. Van Hees, L.J.A.R. Van der Klugt, E. De Witte, H. De Clercq, L. Binda, G. Baronio, *Test Methods for the evaluation of the in situ performance of water-repellent treatments*, in *Surface Treatment of Building Materials with Water Repellent Agents*, Delft, pp. 14-1/14-16, 1995. (Van Hees, 1995)

the material integrity of the elements on which they are applied. Anyway, minor destructive tests produce limited alterations or damages, easily remediable. Respect to the non-destructive tests, minor destructive tests can provide quantitative results, ensuring a deeper level of knowledge of the building characteristics. Among the available MDTs, the application of single, double flat jack tests, coring, videoboroscopy, powder drilling test to architectural heritage showed positive results. A short descriptions of these methodologies is presented as follow.

Single flat jack test

This test ensures the determination of the compression stresses acting in a masonry structure[126]. Its application was developed since the 80s of the last century[127]. The test is carried out by introducing a thin flat-jack into the mortar layer. The test is only slightly destructive. After the test is completed, the flat-jack can easily be removed and the mortar layer restored. Providing quantitative results, the test was also considered useful to validate mathematical models through an on-site application and for this reason it was also standardized (only for regular brick masonry) by international organisms:

- ASTM C 1196-91 – *In situ compressive stress within solid unit masonry estimated using flat jack measurement*s (ASTM-C1196, 1991);
- RILEM Lum 90/2 Lum.D.2. – *In situ stress based on the flat jack* (Lum.D.2., 1990).

The determination of the stresses is based on the stress relaxation in a compressed masonry caused by a cut perpendicular to the wall surface; the stress release is caused by a partial closing of the cut slot, i.e. the distance between the edges of the slot after the cutting is lower than before. The variation of the distance induced by the cut is controlled through a previous application of displacement transducers: potentiometric linear variable digital transducers (LVDT) or a removable comparator (by fixing special targets). The distance is measured along vertical

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[126] L. Binda, L. Cantini, C. Tiraboschi, *Caratterizzazione e classificazione di murature storiche in zona sismica mediatne prova con martinetti piatti*, XI Cong. Naz. "*L'Ingegneria Sismica in Italia*", ANIDIS, Genova, 25-29 Gennaio 2004, CD-ROM, E4-07, 2004 (Binda L. C., 2004); and L. Binda, L. Cantini, G. Cardani, A. Saisi, C. Tiraboschi, *Use of Flat-Jack and Sonic Tests for the Qualification of Historic Masonry*, in *10th Tenth North American Masonry Conference (10NAMC)*, St. Louis, Missouri, 3-6/06/07, Session 6C, CD-ROM, pp. 791-803, 2007. (Binda L. C., 2007)

[127] P. Marconi, *Arte e cultura della manutenzione dei monumenti*, Laterza, Bari, 1984. (Marconi P. , 1984)

benchmarks, previously fixed on the wall, before and after cutting. A thin flat-jack is placed inside the slot and the pressure is gradually increased to restore the distance measured before the cut. A short description of the phases of the single flat jack tests is presented in Figure 3.20.

Figure 3.20: Layout of the single flat jack test. a) example of flat jacks with different shapes and dimensions; b) control of the distances between reference points by a removable comparator; c) execution of the cut; d) insertion of the flat jack; e) control of the variation of the distances between the markers (pictures by the author).

In a brick masonry, the cut can be easily made in the horizontal joints. For this type of masonry a rectangular flat-jack is used (120*240*8mm / 400*200*8 mm). The test can also be extended to stone masonry. The cut can also be made by a steel disk, with a diamond cutting edge. Flat jacks can have different shapes and dimensions: the shape of the flat jack must match the shape of the cut. Pf corresponds to the pressure of the hydraulic system driving the displacement equal to those read before the slot is executed. The equilibrium relationship is the fundamental requirement for all the applications where the flat-jack are currently used:

$$S_f = K_j \cdot K_a \cdot P_f \qquad (3.1)$$

where:

S_f = calculated stress value

P_f = flat-jack pressure

Ka = slot/jack area constant (<1)

Kj = jack calibration constant (<1)

The use of flat-jack tests for stonework made with irregular stones is not easy, due to the lack of regular joints; therefore the cut for the insertion of the jack is done directly in the stone courses. In this case a steel disk with a diamond cutting edge is used and the jack has the same shape of the cut. It must be pointed out that the flat-jack test in the case of multiple-leaf walls gives results concerning only the outer leaves.

As frequently happens in the case of in-situ tests on masonry, one of the most difficult task is the elaboration and interpretation of the results. As a first step the correct interpretation of the measurements has to be established. Once the cut has been carried out, the values of the displacements measured at the reference points are not constant; they tend to be greater in the centre of the cut due to the new distribution of stresses (Figure 3.21a). In any case the measurements carried out in the four chosen points will never give the same value and very seldom the original distance will be attained in all the measuring points[128]. It has been observed only for some regular masonry texture (Figure 3.21b).

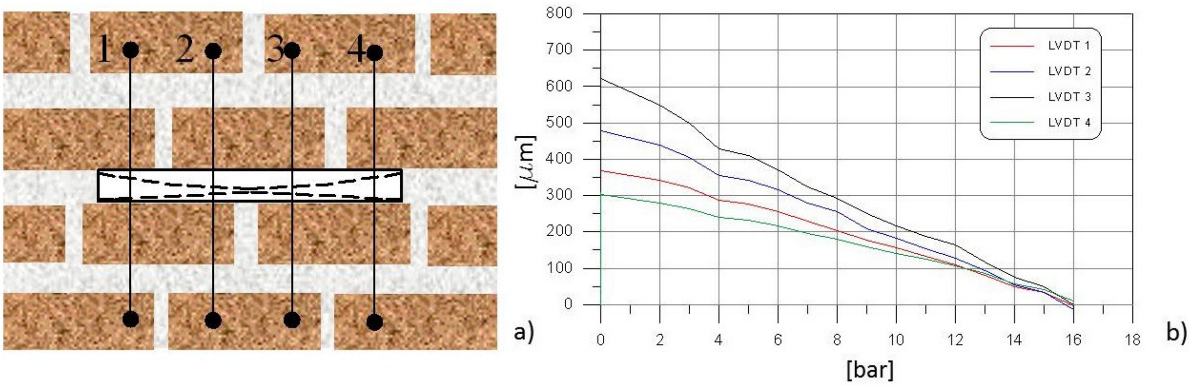


Figure 3.21: a) layout of the test and representation of the result in a distance variation - pressure graph (courtesy of Arch. C. Tiraboschi).

A common example of a single flat jack test carried out in a wall characterised by very irregular stone texture is presented in Figure 3.22. In this case, local interlocking between stones and pebbles, during the displacements generated by increasing the pressure in the flat jack, can disturb the vertical movement of the benchmarks: instead a vertical translation, partial rotations can affect the final result. For this reason the vertical displacement is controlled by applying more

[128] L. Binda, C. Tiraboschi, *Flat-Jack Test as a Slightly Destructive Technique for the Diagnosis of Brick and Stone Masonry Structures*, in “Int. Journal for Restoration of Buildings and Monuments”, “Int. Zeitschrift fur Bauinstandsetzen und Baudenkmalpflege”, Zurich, 1999, pp. 449-472 (Binda L. T., 1999).

than one benchmark. In this situation, the interpretation of the result is always influenced by the subjective judgment of the operator who elaborates the results.

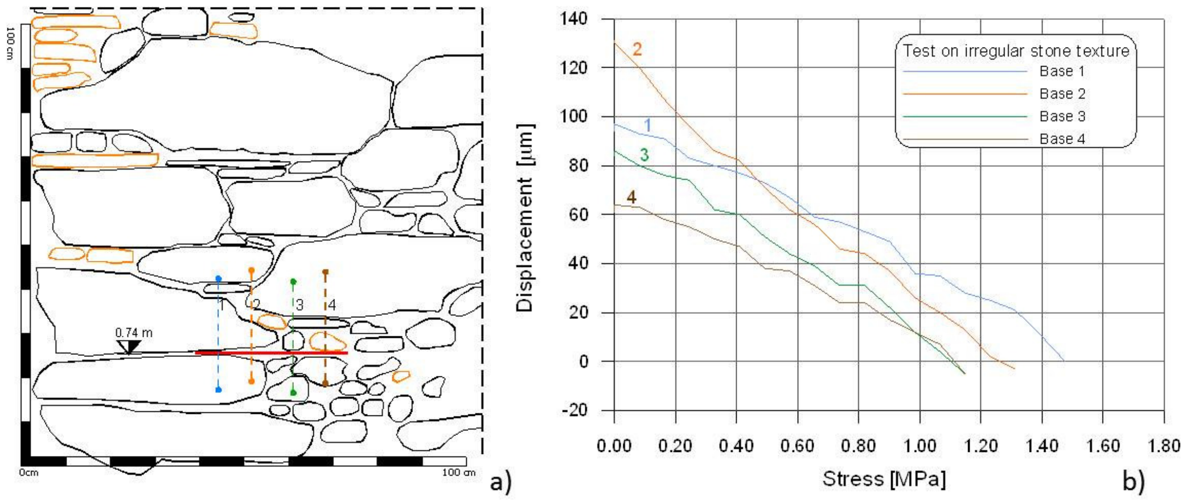


Figure 3.22: Example of single flat jack applied to an irregular stonework masonry: a) layout of the masonry texture and of the test; b) graph displacement-stress obtained by the test (layout and elaboration by the author).

Considering that historical masonry walls of monumental buildings can have multiple leaves, and knowing that the flat jacks are designed for a limited penetration of the wall section, the application of the single flat jack on the opposite sides of massive structures is recommended. As shown in Figure 3.23, this test layout is useful to detect inhomogeneous stress distributions in masonry structures.

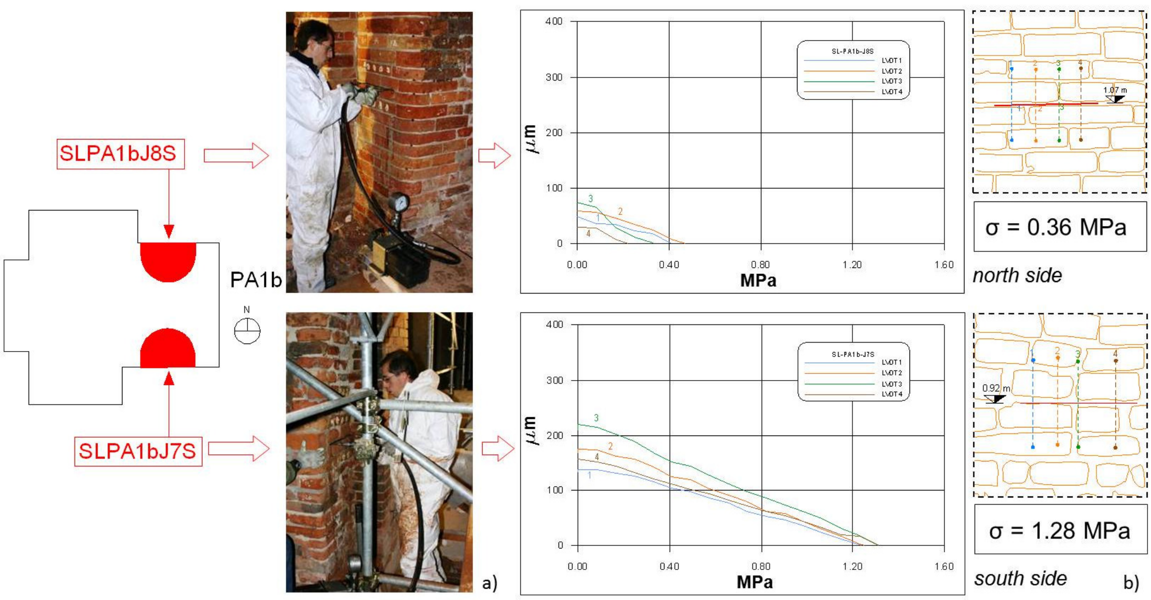


Figure 3.23: Eccentricity detection through single flat jack tests carried out on the opposite sides of a pillar: a) test layout with pictures; b) results with the layout of each test (layout, pictures and elaborations by the author).

Double flat jack test

The double flat jack test can be defined as an on-site simulation of an instrumented compressive test on a portion of the masonry of a building. The test layout consists in isolating an area of the wall by performing two parallel horizontal cuts, further used to host flat jacks: the compressive strength is obtained by increasing the pressure of the flat jacks and consequently the portion of the wall comprised among them will be subjected to a uniaxial compression state. Being a slight invasive test[129], double flat jack test is not conceived to reach the final resistance of the isolated masonry element, otherwise it should damage a considerable portion of a load bearing wall. Through the application of vertical and horizontal displacement transducers (usually LVDTs), deformations due to the stress level produced by the flat jacks is measured in order to obtained a stress-strain graph. This graph represents the mechanical properties of the investigated structure and can be used for the following applications:

- Determination of the deformability characteristics of a masonry under compression.
- Study of the stress-strain behaviour of the masonry.

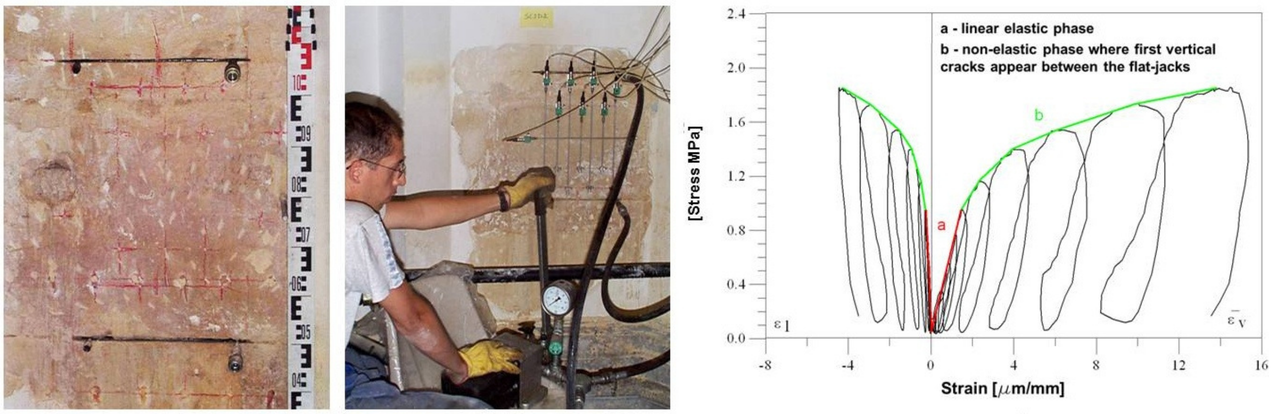
The elastic behaviour of the historical buildings is a very important parameter for the global comprehension of the mechanical properties of the building and for this reason double flat jack tests has been developed for standardized applications. The main standards are:

- ASTM C1197-91 - Standard test method for in situ measurement of masonry deformability properties using flat jack method (ASTM-C1197, 1991);
- RILEM Lum 90/2 LumD3 - In situ strength and elasticity tests based on the flat jack (RILEM-Lum-90/2-LumD3, 1990).

According to the standards, calibrated for regular brickwork masonry, two parallel cuts are made in the wall, at a distance of about 40 to 50 cm from each other. Two flat jacks are then inserted in the parallel cuts (see Figure 3.24a). The two jacks delimit a masonry sample of

[129] L. Binda, C. Tiraboschi, *Flat-jack test as a slightly destructive technique for the diagnosis of brick and stone masonry structures*, in *8th Conf. on Structural Faults and Repair*, London, July 13-15, 1999 (Binda L. T., 1999); and L. Binda, L. Cantini, G. Cardani, A. Saisi, *Prove con martinetti piatti e prove soniche per caratterizzazione della qualità muraria*, in "*Dalla conoscenza e dalla caratterizzazione dei materiali e degli elementi dell'edilizia storica in muratura ai provvedimenti compatibili di consolidamento*", 18-19/12/2006, DIS – Politecnico di Milano, pp. 1-12, 2007. (Binda L. C., 2007)

appreciable size to which an uniaxial compression stress can be applied. Measurement bases for removable strain-gauge or LVDTs on the sample face provide information on vertical and lateral displacements (see Figure 3.24b). In this way a compression test is carried out on an undisturbed sample of large area. Several loading-unloading cycles may be performed at increasing stress levels in order to determine the deformability modulus of the masonry during loading and unloading phases (see Figure 3.24c).



a) b) c)

Figure 3.24: Double flat jack test. a) The masonry portion comprised between the two parallel cuts; b) LVDTs applied to the masonry and the hydraulic pump connected to the flat jacks; c) example of a stress-strain graph obtained by the test (pictures by the author).

In a brick masonry, the cut can be easily made in the horizontal joints. For this type of masonry a rectangular flat-jack (120*240*8mm) or rectangular flat jack (400*200*8 mm) is used. The cut can also be made by a steel disk, with a diamond cutting edge. In this case, the flat-jack has the same shape of the cut (350*250*4mm).

As remarked for the single flat jack test, also double flat jacks can be applied on stonework masonry. The main problems for the correct execution of the test are connected to the vertical and horizontal displacements measured by the transducers: if the movements are affected by partial rotations, the obtained stress-strain graph could not be totally representative of the mechanical behaviour of the masonry.

Difficulties or impossibility in applying the double flat jack test can be found in the case of low rise buildings (one or two story high) due to the lack of stress response in the upper masonry caused by the low stresses acting on it. In fact in order to respect equilibrium, the applied stresses should not overcome the ones measured by the single flat-jack.

More examples of double flat jack tests will be described in chapter no. 5, where the relationship between qualitative and quantitative parameters, provides by different diagnostic techniques, will be investigated.

Powder Drilling test: method for the determination of moisture content in building materials

Powdered Samples of the building materials are removed by drilling at different height and different depth (see Figure 3.25 a and b). The water and salt content of the powdered sample is then determined by oven drying[130].

Each drilling starts with the bit at room temperature. The bit has a diameter of 16 mm. The hole is drilled horizontally. To collect the sample an aluminium chute is placed under the hole. A sample tube is clipped to the bottom of the chute and this is stopped immediately after collecting the powder sample. Methylated spirit contained in a small bottle is used to cool the bit after each drilling.

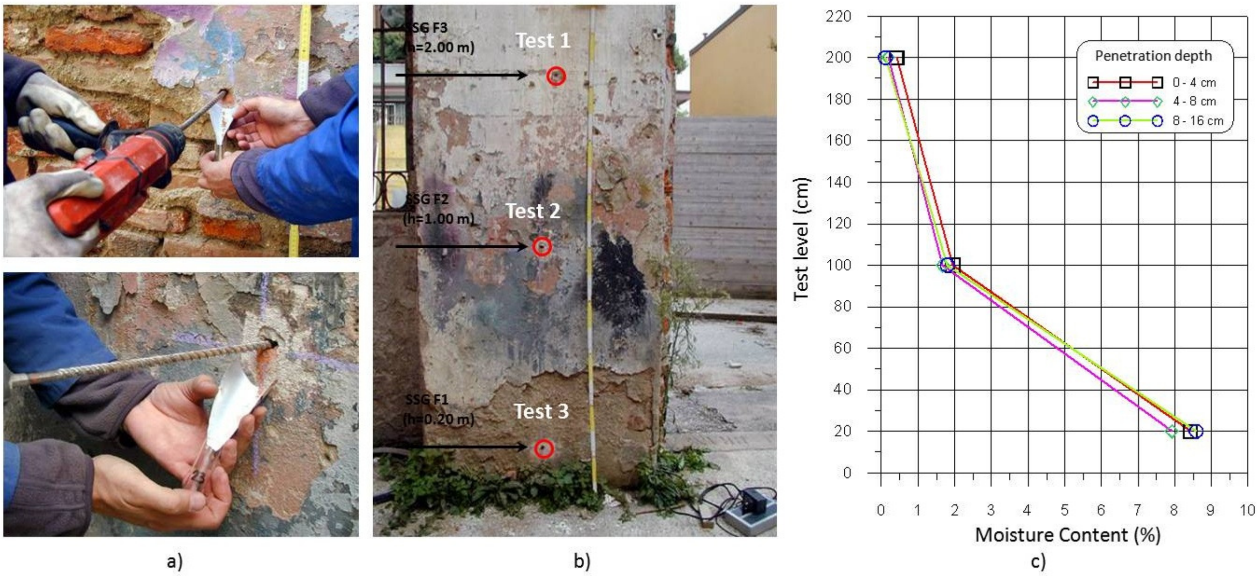


Figure 3.25: a) extraction of the powdered samples; b)example of a test organized along three levels; c) graphical representation of the result with the comparison of the moisture content for each level of the test (pictures by the author).

[130] L. Binda, G. Cardani, L. Cantini, C. Tiraboschi, *Long Term Effects of Floods on masonry Walls: NDTs to Measure the Drying Rate*, in *8th Int. Masonry Conference*, 4-7/07/2010, Dresden, Germany, 2010, (Binda L. C., 2010)

This site test shows the large variation in moisture content from place to place in a naturally exposed wall and in different materials (see Figure 3.25c). This is particularly useful for distinguishing between rising damp, condensation and rain penetration.

Hardness, drilling energy and pull out tests

Other slightly destructive tests can be used to give more information about masonry and its 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:

- the Schmidt hammer rebound test[131] 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. Furthermore the depth of penetration is low, so only the repointing mortars are usually detected;
- the pull-out tests can only be used on bricks and stones, very rarely on mortar joints, unless they are not very thick.

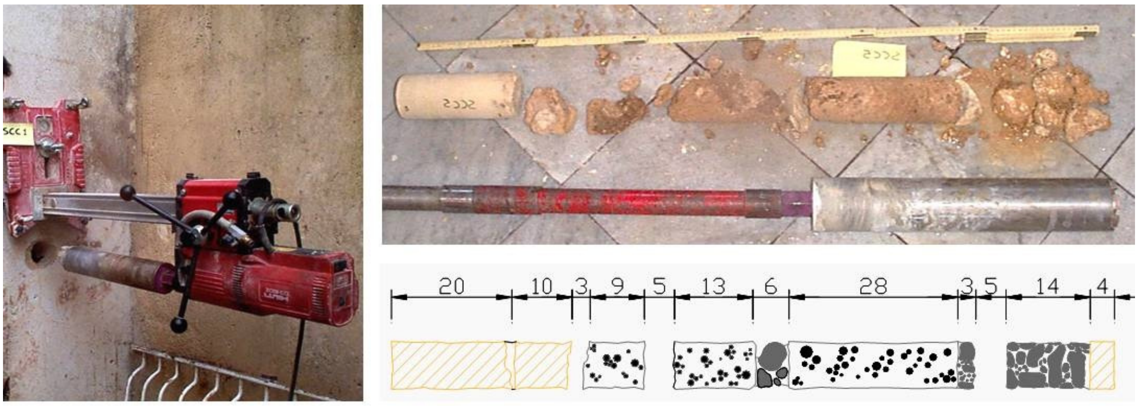
Other surface tests have been proposed so far; all of them can be useful to have an overall rough idea of the masonry condition on the surface and they can be meaningful for a preliminary survey of the structure, but they only give the possibility of qualitative interpretation of masonry condition. All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

[131] ONSITEFORMASONRY, Results and Research Methodologies of ONSITEFORMASONRY, EC Project financed by the European Commission, CD-Rom, 2005. (ONSITEFORMASONRY, 2005)

<u>*Core drilling, boroscopy and videoboroscopy*</u>

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

In some cases it is possible to core boreholes[132] in the most representative points of the walls. Coring should be done with a rotary driller using a diamond cutting edge (Figure 3.26a). This operation is rather simple but has limits. The drilled core is usually very decohesioned so it is almost impossible to detect the quality of the original materials (Figure 3.26b). Inside the boreholes additional investigations can be made by the use of a video-boroscope. A small camera may be inserted into the borehole allowing a detailed study of its surface and try a reconstruction of the wall section. The results of this study may be recorded in a video-cassette for further analysis. The information obtained includes the measurements of large cavities and a general view of the materials. Nevertheless the interpretation of the photograms is a very difficult operation, sometimes hopeless; it should be remembered that boroscopy can only give a stratigraphy of the section.



a) b)

Figure 3.26: a) core sampler applied to a masonry structure; b) fragments of the sampled materials and its representation (pictures and layout by the author).

[132] L. Binda, L. Cantini, M. Lualdi, C. Tedeschi, A. Saisi, L. Zanzi, *Investigation procedures based on the complementarity of non-destructive and slightly destructive on site tests: application to the two Castles of Avio (Italy) and Pisece (Slovenia)*, in *10th Canadian Masonry Symposium*, Banff, Alberta, June 8-12/6/2005, CD-ROM, Section 4A, pp. 441-453, 2005. (Binda L. C., 2005)

The equipment supports a fix objective, for direct frontal inspection at 120°, or interchangeable objectives, with a motorised head controlled by an external joystick. The joystick, placed on the video-camera grip, selects the different views (Figure 3.27). The objectives regulates the image by an automatic focus. The lightening system is composed by miniaturised 8.4 W lights, placed at the extremity. A videorecorder documents and memorises the whole test phases.

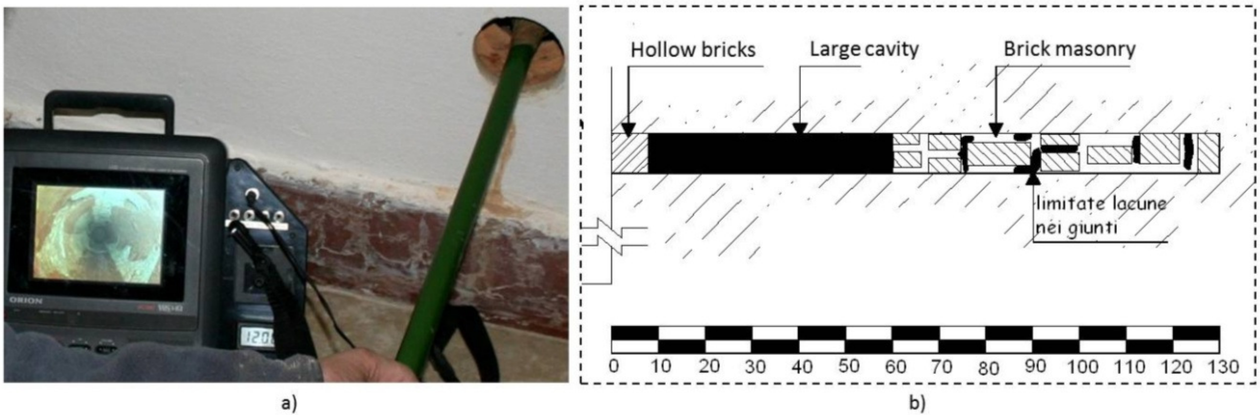


Figure 3.27: a) execution of a videoboroscopy; b) representation of the cored section of the wall (picture and layout by the author).

3.3.3 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 on-site material. The aims of these tests are the followings:

- to characterise the material from a chemical, physical and mechanical point of view,
- to detect its origin in order to use similar materials for the repair,
- to know its composition and content,
- to measure its decay and the durability to aggressive agents from new materials used for restoration.

Since it is very difficult to sample representative prisms of the walls, only single components or small assemblages are removed. A synthetic description of the main recommended laboratory tests are given in the following paragraphs.

Optical analysis by stereomicroscopy

The stereomicroscopy analysis allows a colour investigation by reflected light of a polished section or of a fracture surface of the material[133].

- The main targets of the test are:
- evaluation of the mortar aggregates;
- evaluation of the grain size distribution of mortar aggregates by imaging analyser;
- evaluation of the surface morphology characteristics of the materials.

Imaging Analyser is able to automatic classify distinct elements in a polished section observed by the stereomicroscopy. It can measure diameter, perimeter and area of the elements. It is used to evaluate the grain size distribution of the mortar samples (Figure 3.28).

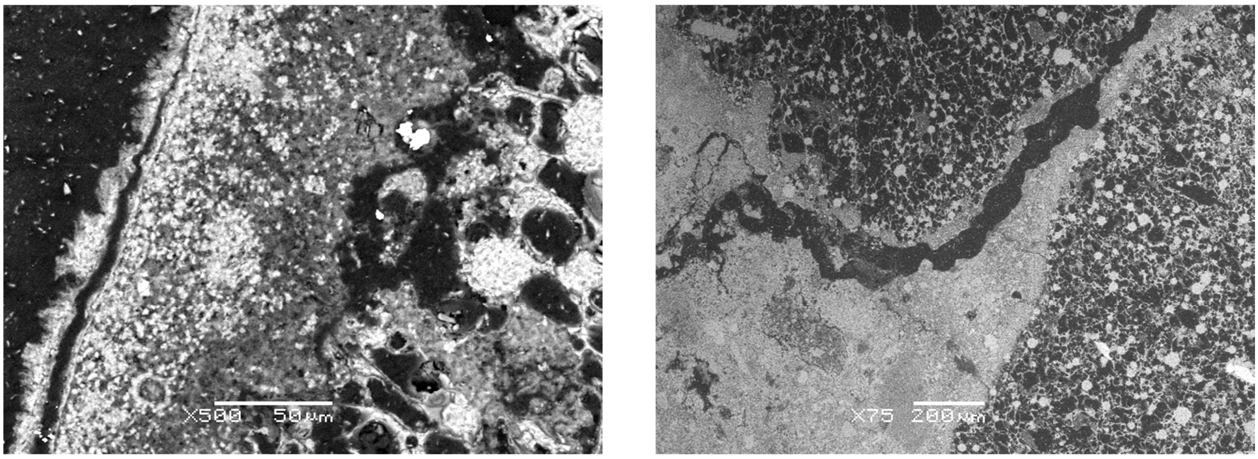


Figure 3.28: Two examples of images obtained by microscopic analysis of the reactive areas of a mortar sample (courtesy of G. Baronio).

More information about the composition of the sampled materials can be achieved by X-ray test. The X-ray diffraction measurements can detect crystallographic characteristics of the material (Figure 3.29), indicating the type of salts found inside or on the surface of a decayed masonry.

[133] G. Baronio, L. Binda, C. Tedeschi, C. Tiraboschi, *Characterization of the Materials Used in the Construction of the Noto Cathedral*, in *Construction Building Materials*, Special Issue, Vol.17, 2003, pp. 557-571. (Baronio G. B., 2003)

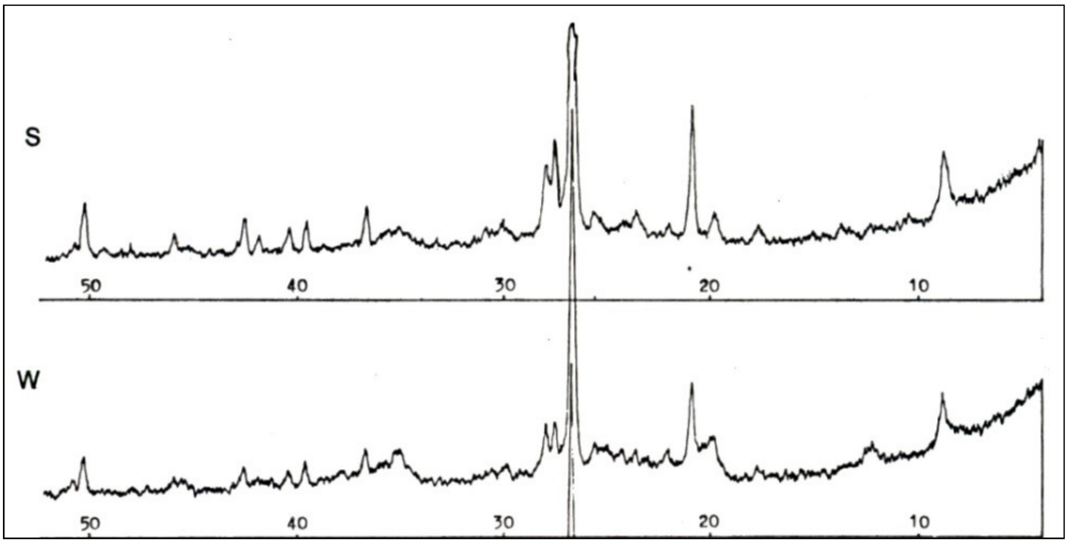


Figure 3.29: Exapmple of x-ray diffraction measurements on a brick sample. (courtesy of Professor L. Binda).

The performance of the materials under aggressive agents can be further controlled through the execution of freeze/thaw and salt crystallization tests. This kind of tests are even requested for new bricks and stones in order to determine their durability.

Mechanical tests

Compressive and indirect tensile tests (splitting tests) are standardized in order to provide resistance parameters[134] [135].

Compressive tests on sampled materials or on assembled masonry elements are used to identify the failure value of the compressive stress. Measuring the stress-strain behaviour during the test, through the application of vertical and horizontal transducers (Figure 3.30), other mechanical characteristics (such as the Elastic Modulus and the Poisson Coefficient) are detectable.

[134] UNI EN 772-1, *Metodi di prova per elementi di muratura. Determinazione della resistenza a compressione*. (UNI EN 772-1, 2002)

[135] UNI EN 12390-6:2002, *Prova di trazione indiretta*. (UNI-EN12390-6, 2002)

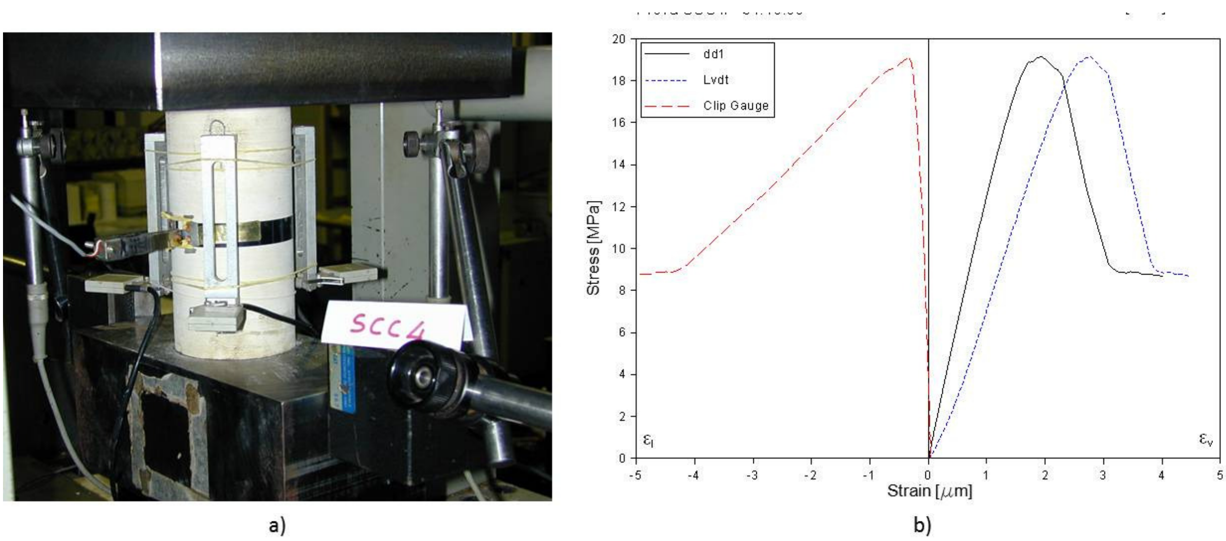


Figure 3.30: Compressive test: a) execution of the test and b)stress-strain graph obtained by the test (picture and graph by the author).

Tensile stress resistance can be studied through direct and indirect applications: splitting test on cylindrical samples is widely considered an effective methodology to determine the resistance of the material to tensile stress. The configuration of the test (see Figure 3.31) is based on the relationship between the compressive stress applied on the sample and the area of the rectangular section (A) that is subjected to the compressive stress (P). The tensile strength (R_t) is calculated indirectly by a compressive test as following:

$R_t = 2P/\pi A$ (3.2)

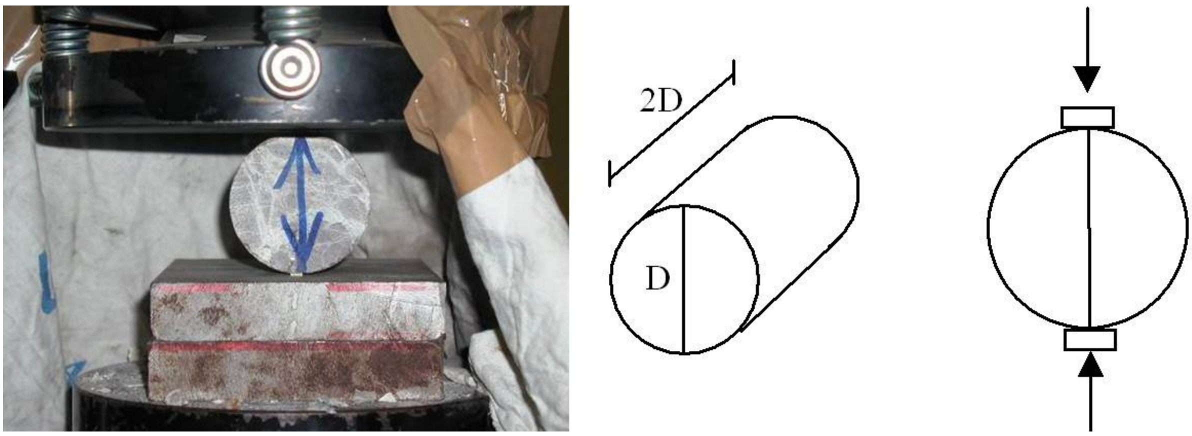


Figure 3.31: Splitting test: picture and layout of the test (pictures by the author).

Other categories of mechanical tests (see Figure 3.32) can be used to study mortars (realized in laboratory): bending tests can be applied on mortars specimens or on stone slabs. Hardness tests on different points of the brick or stone sections are useful to determine the depth of the decay. Micro-hardness tests can be even associated to the microscope analysis of the samples: in this case the dimension of the trace left by a punch on the surface of the material corresponds to a scale indicating the hardness of the element. Shock tests are requested for covering materials (usually slabs): they consists in the empirical observation of the condition of the surface of the material after the impact with a 1Kg metal sphere.

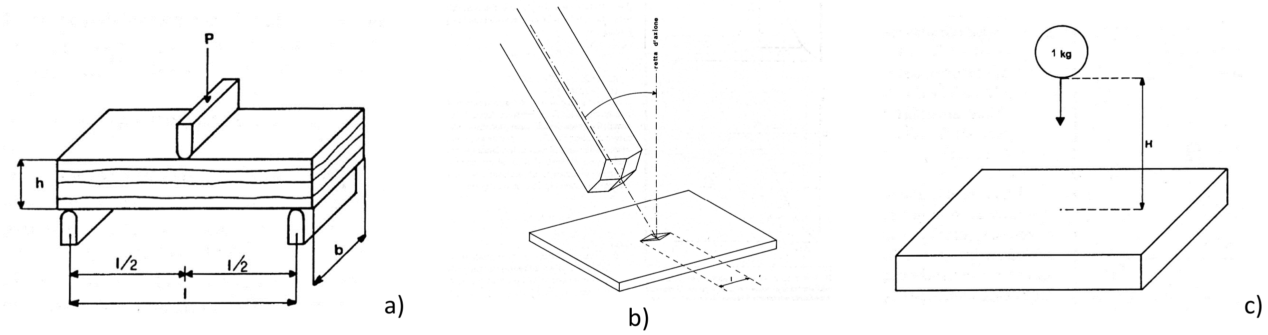


Figure 3.32: Other mechanical tests: a) bending test; b) microhardness test; c) shock test (pictures from G. Amoroso, "Il restauro della pietra monumentale", 1995, pp. 41, 43).

Physical tests

The attitude of building components to face the decay processes generated by the environment is an important parameter to define the durability of the material. The life expectations of building materials can be strongly influenced by these conditions of the environment:

- thermal dilation;
- frost seasonal cycles;
- moisture concentrations;
- salt presence in the air, in the ground or in the water
- a salt crystallization test

Natural and artificial building materials can have different morphological characteristics and these differences must be taken into account for the determination of the most appropriate use of each typology of material. One of the main parameter that influence the attitude of a material to be or not subjected to decay process is its porosity. The water, being one of the main vehicle for numerous decay forms, can penetrate into materials presenting a porosity constituted by pores connected by cavities (Figure 3.33). The presence of water can have different sources (meteoric origin or absorbed by capillarity rise from the ground, for example), and for this reason building materials should be compact and without an excessive quantity of pores.

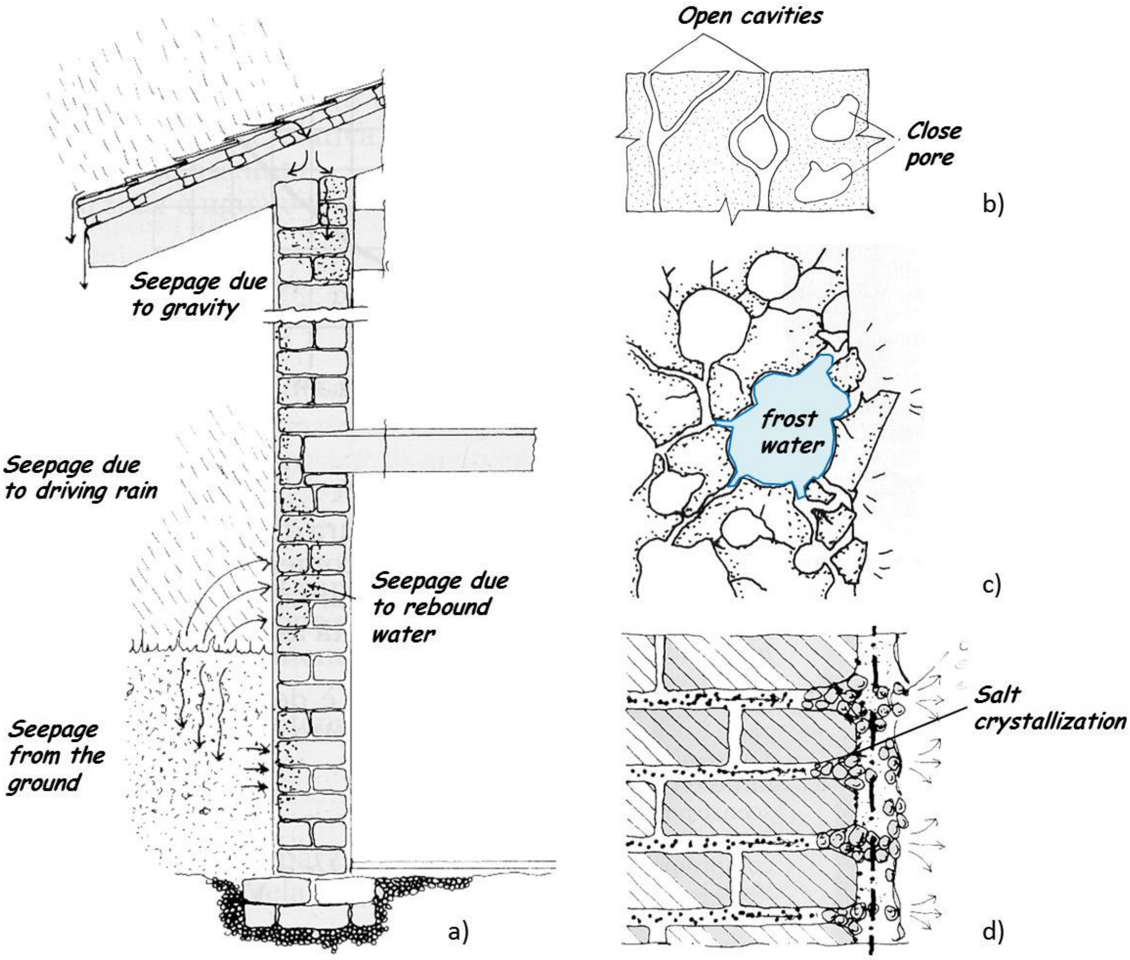


Figure 3.33: Description of moisture sources in a building and of the main decay processes: a) LAyout of the main causes of seepage; b) layout of pores morphology; layout of material desegregation due to frost cycles; layout of material pulverization due to salt crystallization (layouts from I. Mundula, N. Tubi, "Umidità e risanamento negli edifice in muratura", Maggioli, San Marino, 2006 pp. 13, 23, 47 (Mundula, 2006) and modified by the author).

Porosimetry

Pores, inside a material can present different sizes: micro-pores are not visible and water can penetrate in them only due to high pressure; meso-pores present a dimension that is suitable for a fast water absorption and to keep it; macro-pores are on the contrary so large that water can be easily absorbed and then quickly lost. The porosity of new and sampled historic materials can be studied through the porosimetry. The mercury porosimeter, for example, is able to determine the distribution of the radius of the pores (Figure 3.34) characterizing the material through the relationship between the pressures used for the penetration of the mercury in the sample/specimen, its mass properties and the diameters of the pores. The concentration of micro, meso or macro pores will indicate the attitude of the material to contrast the water absorption.

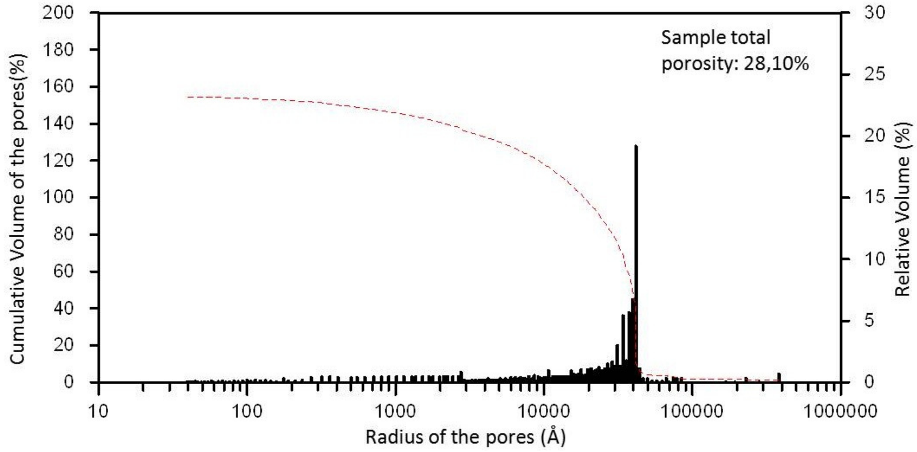


Figure 3.34: Example of bar chart showing the distribution of the radius of the pores (courtesy of Arch. C. Tedeschi).

<u>*Other physical tests*</u>

The volumetric mass[136], the water absorption by total immersion, the water absorption by capillary rise[137] (Figure 3.35) are important characteristics needed to determine the durability of the materials and the effects of surface treatments. The initial rate of suction of bricks and stones and the water retentivity of mortars can be useful when choosing mortars and grouts for repairs.

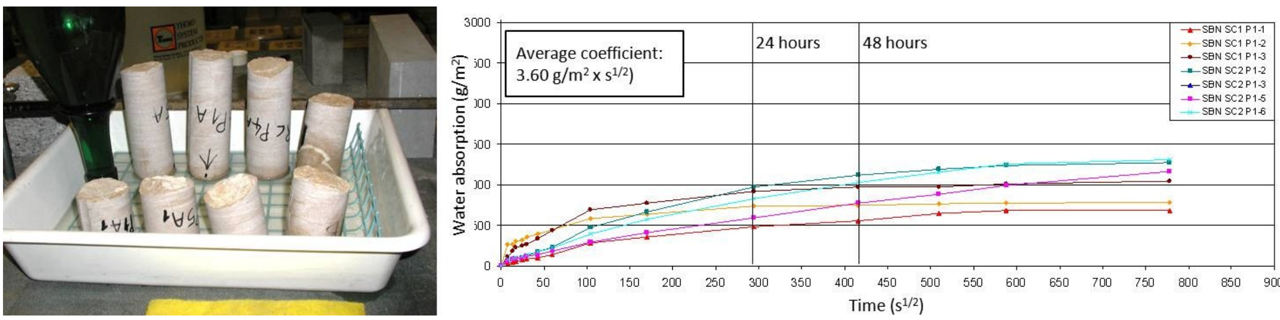


Figure 3.35: Determination of the water absorption by capillarity rise. Samples in the water and example of diagram showing the average coefficient of suction (courtesy of Arch. C. Tedeschi).

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[136] EN 9724/2, *Materiali lapidei: determinazione della massa volumica apparente e del coefficiente di imbibizione*, 1990. (EN9724/2, 1990)

[137] UNI EN 772-11. *Metodi di prova per elementi di muratura: determinazione dell'assorbimento d'acqua degli elementi di muratura di calcestruzzo. di materiale lapideo agglomerato e naturale dovuta alla capillarità ed al tasso iniziale di assorbimento d'acqua degli elementi di muratura di laterizio*, 2001. (EN772-11, 2001)

Chemical tests

The chemical characterization of sampled materials is mainly use to obtain information on sampled mortars and plasters. The test can also provide information concerning specific type of alteration/decay afflicting stone or brick samples.

Tests for alkaline sulphate can be conducted on materials sampled at different depth of the masonry section, in order to detect the presence and quantity of these very aggressive salts[138].

The result of the chemical characterization is the determination of the chemical composition of the analysed sample. Taking into account mortar samples, this determination can be used to reproduce the same type of mortars for further tests requiring some characteristics (above all quantity and specific dimensions) which are not easy to obtained by sampling.

Granulometry

Grain size distribution can be obtained through granulometry analysis by sieving[139]. The distribution of the aggregates in mortars is a fundamental requirement to guarantee a low porosity of the material and a higher mechanical resistance.

The test is carried out following these steps: a) mortar samples are placed in oven with a temperature of 105°C; b) each sample has to be crushed in order to separate the binder from the grains; b) the pulverized mortar is introduced in sieves, having squared openings with different dimensions (strictly controlled). The residue is classified, in this way, in different granulometric fractions. According to UNI EN 933-1 e UNI EN 1015-1, the material must pass through 10 sieves with the following openings: 32, 16, 8, 4, 2, 1, 0.5, 0.25, 0.125, 0.063 mm.

According to DIN 18123, where sieve analysis is combined with sedimentation analysis, particles can be divided in the following components:

- Clay particles, dia < 0.002mm
- Silt particles, 0.002<dia<0.06mm

[138] UNI 11088, Ancient mortar and mortar for restoration. Chemical characterization of a mortar - Determination of siliceous aggregate and of some soluble analytes content, 2003. (UNI11088, 2003)

[139] UNI EN 933-1, Grain size distribution in mortar, 1997 (UNI-EN-933-1, 1997), and UNI EN 1015-1, Metodi di prova per malte per opere murarie. Determinazione della distribuzione granulometrica (mediante stacciatura), 2000 (UNI-EN-1015-1, 2000)

- Sand particles, 0.06<dia<2.mm
- Gravel particles dia>2.0mm,

An irregular distribution of these particles can be associated to mortars having low mechanical performance and limited durability (Figure 3.36).

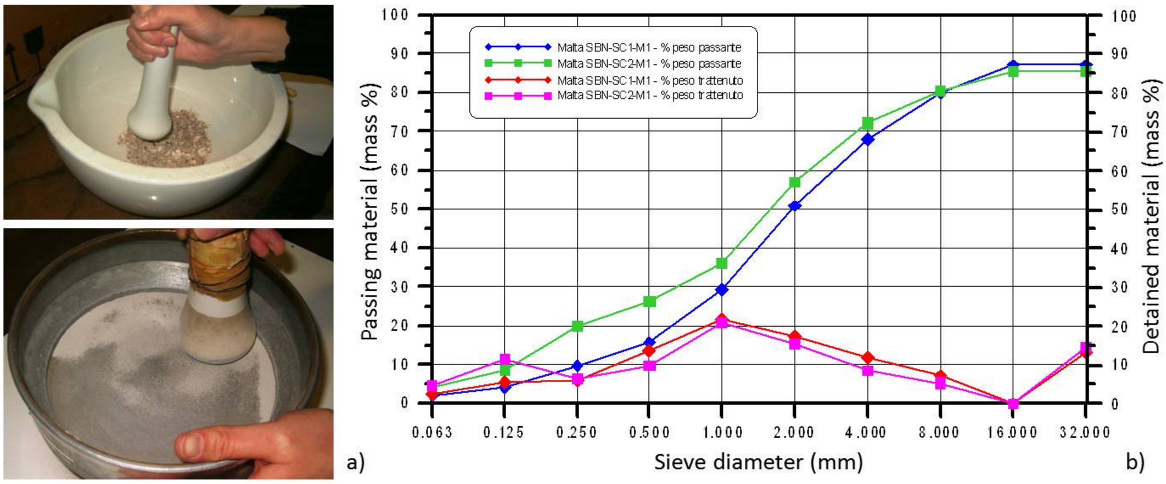


Figure 3.36: Example of grain size distribution analysis: a) breakdown of the sampled mortar and further passage in the seive; b) granulometric curves showing the differences between the grain size distribution in 4 samples taken in differnt depth of the masonry section (courtesy of Arch. C. Tedeschi).

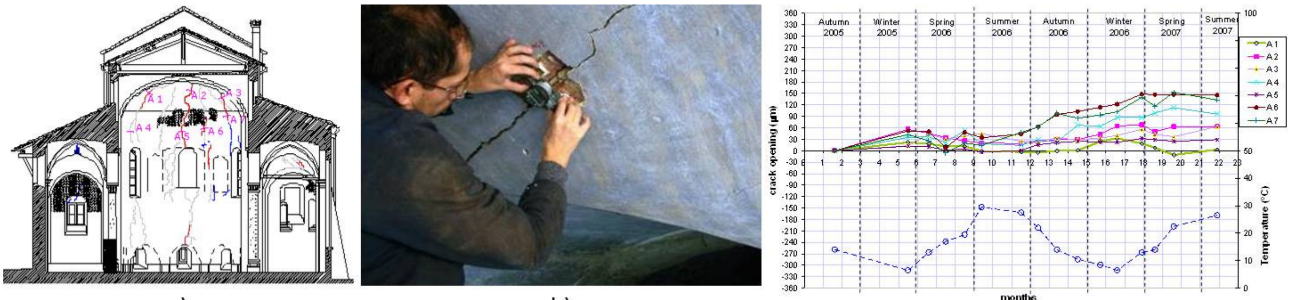
3.3.4 Structural control for static and dynamic monitoring

Static 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; in some cases the knowledge of the crack pattern evolution can help preventing the collapse of the structure[140].

[140] L. Binda, A. Anzani, G. Mirabella Roberti, *The failure of ancient Towers: problems for their safety assessment, in* "International Conference on Composite Construction - Conventional and Innovative" - IABSE, Zurich, 1997, pp. 699-704 (Binda L. A., 1997)

Very simple monitoring systems can be also applied to some of the most important cracks in masonry walls, were the opening of the cracks along the time can be measured by removable extensometers with high resolution (Figure 3.37). This simple system can give very important information to the designer on the persistence of settlements, etc. Also in this case the monitoring should be a long term one, not less than one year and a half, in order to rule out the influence of temperature variation at every reading of the eventual displacements.



a) b) c)

Figure 3.37: Example of structural monitoring of the crack pattern in an apse: a) crack pattern representation; b) application of the extensometer on a crack; c) trend of the displacements in time with the indication of the thermal changings (courtesy of Arch. G. Cardani).

<u>*Dynamic testing and monitoring*</u>

The application of dynamic tests to historic buildings (above all towers) is rather recent experience in diagnostic field[141] [142]. Ambient vibration testing (AVT) and operational modal analysis (OMA) are used for the following reasons:

- to measure the structural response under ambient excitation;
- to provide a method of testing, that does not interfere with the normal use of the structure and does not induce additional overloads (dead loads, wind and micro-tremors);
- the multiple-input nature and the wide-band frequency content of ambient excitation, ensuring that the response includes the contribution of a significant number of normal modes;

[141] S. Bennati, L. Nardini, W. Salvatore, Journal of Structural Engineering ASCE, Vol. 131, No. 11, 2005, pp. 1656-1664. (Bennati, 2005)

[142] C. Gentile, A. Saisi, *Ambient vibration testing of historic masonry towers for structural identification and damage assessment*, in "Construction and Building Materials", Elsevier, 2007, Vol. 21, No. 6, pp. 1311–1321. (Gentile, 2007)

- the possibility to use the technique as a periodical survey for monitoring building structures into a preventive maintenance programme.

These tests are suitable for detecting 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 to predict the structure behaviour to dynamic actions like, for example, winds effects and seismic actions.

The key to this vibration analysis/preventive maintenance programme is a systematic, scheduled check of the structures, before, during and after the repair phases. The analysis should be able to assess the condition and the general trend of the structural behaviour and advise, for instance, whether there could be a change of the controlled parameters. Results are then compared to the original records from which any long-term change in the structure can be observed. Since only long-term trends are being monitored, subsidiary effects, (e.g. temperature effects), are not considered to affect the results significantly.

The investigation therefore could involve the use of environmental vibration or forced vibration and include a systematic vibration recording and comparison of the analysed data to the model results.

An accelerometer net is installed in predetermined significant parts of the structure. Cracks, if present, are controlled by displacement transducers (see Figure 3.38a and b). Spectral analysis can be used to extract modal parameters from vibration data. The frequency-domain technique involves frequency analysis of the vibration signal and further processing of the resulting spectrum to obtain clearly defined information (see Figure 3.38c and d). With the modal analysis the vibration response consists of summing up the contribution of the infinite number of natural modes, each multiplied by a function of time; the normal modes, detected from the vibration tests analysis are functions of the system properties and the boundary conditions only.

The vibration tests allow detecting the frequencies, the modal shapes and the correspondent modal damping of a structure. Spectra analysis provides a frequency domain resolution of these component physical relationships. These parameters are characteristics of the local and global behaviour of a structure. They could be used both to verify the results of a theoretical or numerical model and to monitor the behaviour throughout time.

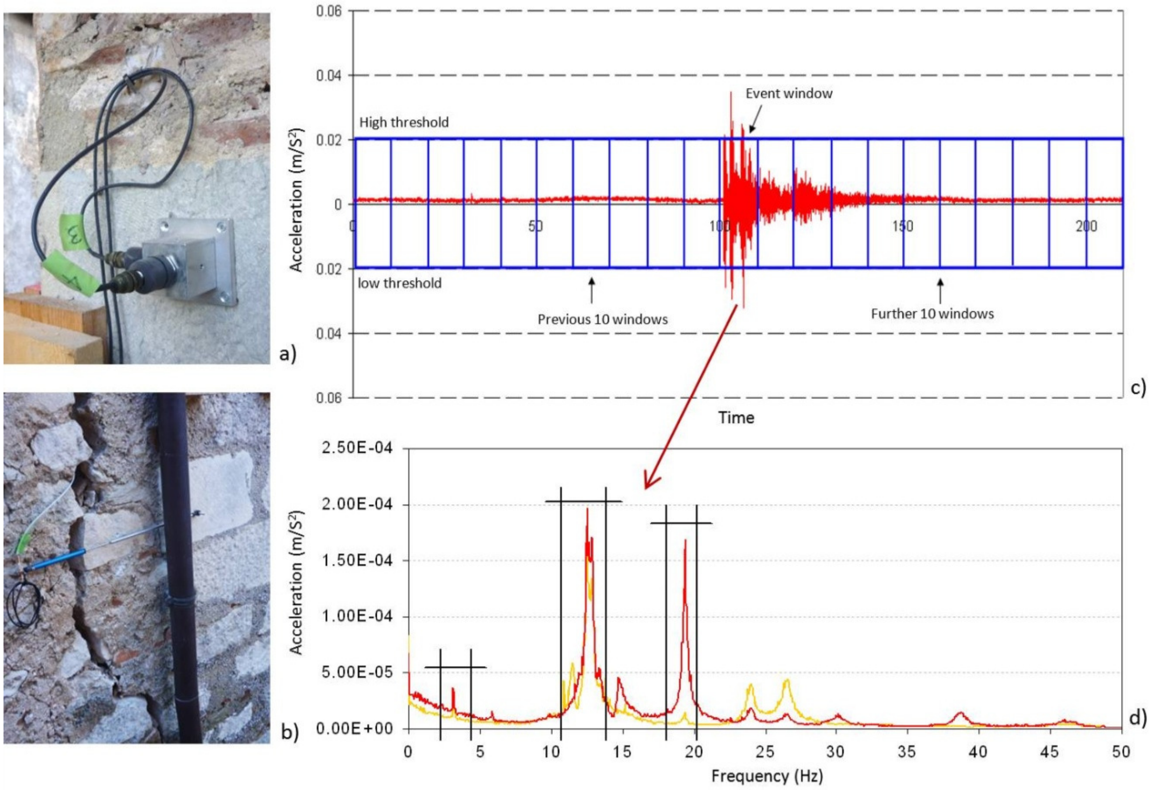


Figure 3.38: Example of dynamic monitoring: a) accelerometer placed on a masonry wall; b) displacement transducer above a vertical crack; c) accelerogram showing an event produced by a micro-seismic vibration; d) analysis of the frequency domain (courtesy of Professor C. Modena and Eng. F. Casarin).

<u>*Control of the tensile stress in tie-rods*</u>

This test is particularly useful for ancient buildings presenting ached and vaulted structures where diagonal stresses are usually contained through the application of tie rods. It allows to detect the tensile stress characterizing the tie-rod in order to verify the presence of structures providing diagonal thrusts.

The test is carried out by producing a perturbation: an impulse is generated on the tie-rod and the further accelerations of the element are registered by an accelerometer placed in its centre (Figure 3.39). The method consists in the experimental determination of the first natural frequency of the oscillations[143]. According to the reduced dimension of the tie-rod, the stiffness of the element is not considered and the following hypothesis are taken into account:

[143] T. Javor, *Damage classification of concrete structures*, Report RILEM Technical Comitee 104-DCC *Material and Structures*, 24, 142., Paris, 1991, pp. 253-259 (Javor, 1991)

- The element is considered to have a rectilinear layout;
- The constraints are assumed to be non-vulnerable.

According to the theoretical background, the natural frequencies, next to the first one, are multiple of the fundamental one[144].

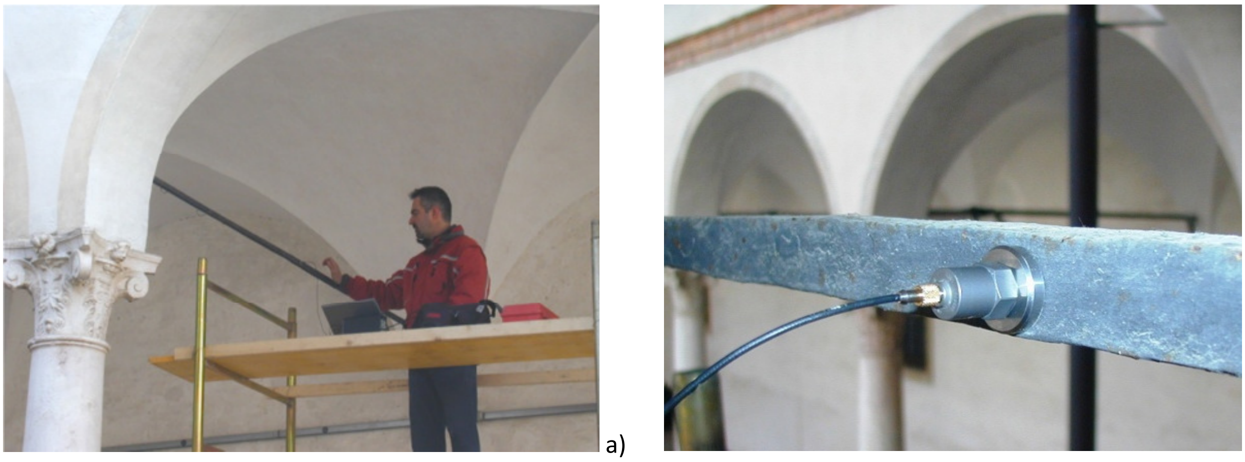

a) b)

Figure 3.39: Example of execution of the measurement of the tensile force in a tie rod: a) perturbation of the element; b) accelerometer applied on the tie-rod (pictures by the author).

Through the analysis of the acquired accelerogram, further converted in frequency spectra, the fundamental frequency is determined (Figure 3.40) and is used to estimate the axial stress characterising the investigated element.

The fundamental frequency is obtained by the following[145]:

$$f_n = \frac{n}{2} \cdot \frac{1}{l} \sqrt{\frac{N}{m}} = \frac{n}{2} \cdot \frac{1}{l} \sqrt{\frac{Ng}{A\gamma}} \qquad (3.3)$$

[144] J.R Casas., *A Combined Method for Measuring Cable Forces: The Cable-Stayed Almillo Bridge, Spain*, in *Structural Engineering International*, n. 4, 1994, pp. 235-240 (Casas, 1994)

[145] 3. Belluzzi O., "Scienza delle Costruzioni", vol. IV, Bologna, 1973 (Belluzzi, 1973)

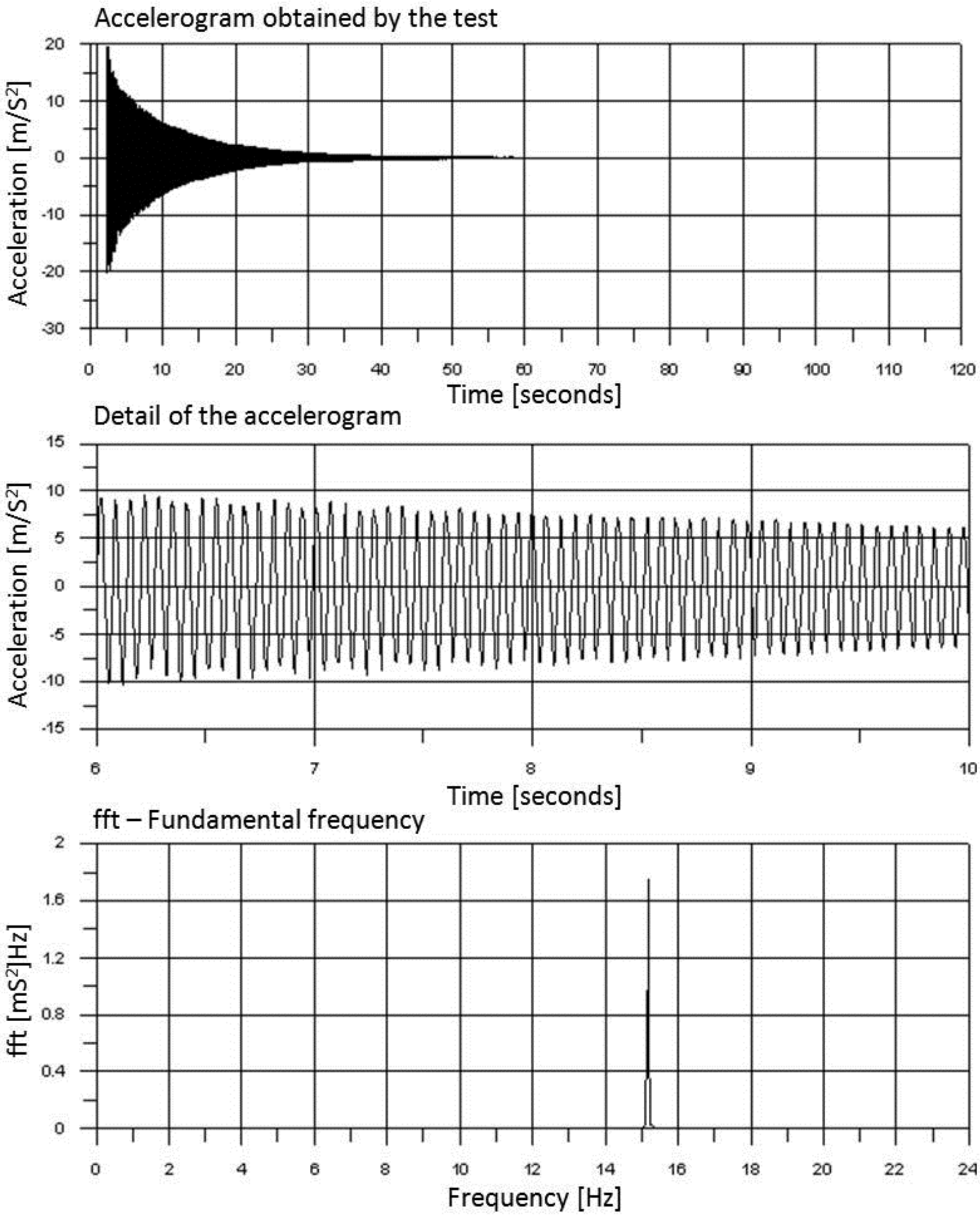


Figure 3.40: Common elaboration of the data: from the accelerogram obtained by the test, the FFT is applied to determine the fundamental frequency (courtesy of Arch. C. Tiraboschi and Geom. M. Cucchi).

The axial stress is determined as:

$$N = \frac{4}{n^2} m l^2 f_n^2 = \frac{4}{n^2} \cdot \frac{A\gamma}{g} l^2 f_n^2 \qquad (3.4)$$

Where:

n= 1
f_n: is the fundamental frequency determined by the test
m: mass of the system (tie-rod)
g: gravity acceleration
A: area of the tie-rod section
N: is the axial stress
l: is the length of the tie-rod
γ: is the density of the material

The list of diagnostic techniques for building investigations could proceed with many other examples. The testing methods described in this chapter are considered to be the most known and well promising techniques for the characterization of a peculiar aspect: the mechanical behaviour of the masonry structure, a fundamental component of the architectural heritage. Deeper descriptions of the potentialities offered by some of the presented diagnostic tests will be given in the following chapters.

Chapter 4. Contributions to the research on some Non-Destructive Techniques: thermography and sonic tests

4.1 Diagnostic approach and design

Any structural design activity on existing building should take into account many different aspects requiring a knowledge in depth of the following characteristics: geometry, state of conservation and mechanical behaviour of the building. As mentioned in the third chapter, a diagnostic project should be prepared for each building in order to provide this knowledge. It should be based on an evaluation of the main ambiguities presented by the building: identifying the elements or the parts which are not accessible, the designer should evaluate case by case the choice of the most appropriate testing techniques.

As shortly described in the previous chapter, non-destructive tests are easily applicable to large portions of existing buildings, due to their non-invasive nature. The diagnostic design is just a part of the whole design process, but the further choices for the final project are based on its accuracy and for this reason the continuous updating of these techniques is important.

According to the craftsman's ability described by R. Sennett, many diagnostic techniques were set by engineers or architects during their practical experiences. The typical example is the first application of the flat jack test into the masonry wall of the *Palazzo della Ragione* in Milan in the 80s: in that occasion P. P. Rossi made the first application of the single flat jack test to determine the state of compression of the masonry, proposing a technique previously used in rock mechanics that later on became a RILEM and an ASTM recommendation. In the same ways, the university research developed in recent years many tests to characterise the existing building from chemical, physical and mechanical point of view.

In the next paragraphs the most recent studies made on two non-destructive techniques are presented. Thermovision and sonic tests are two techniques which are usually requested for the preliminary characterization of masonries in historical buildings: their results support many aspects of the initial study of the building and they can also control at the end the effects of the interventions, if necessary. The research on new applications of thermovision was developed in the Material Testing Laboratory of the Department of Structural Engineering of the Politecnico di Milano also thanks to the collaboration with the research group held by Christiane Maierhofer from the *Federal Institute for Materials Research and Testing (BAM) in Berlin*. The research on new applications of sonic tests was firstly developed within different research contracts of the group *Historical Buildings: Diagnostics, Vulnerability and Conservation* of the Department of Structural

Engineering of the Politecnico di Milano, trough the research development continued under the responsibility of prof. Anibal Costa in the Laboratory of Earthquake and Structural Engineering of the University of Porto.

4.2 Thermovision: decay analysis and support to the knowledge of the construction

Used in different fields, for monitoring activities, energetic performance control or human and animal well-being, infrared thermography knew since the eighties of the last century a wide success also for the study of works of art (especially frescos and paintings), archaeological ruins and historical buildings. Based on the acquisition of the infrared radiation produced by objects, this technique presents the benefit of an application that can be performed on large areas without a direct contact.

Thermovision provides results in short times, if the tests are carried out during the phases of significant transmission of the warmth from the investigate structures[146] [147] [148]. IR Thermography reveals the infrared radiations emitted from a heated surface of an object in a certain time. As a result, a thermal image of the object is obtained, by a colour scale or a grey scale. Working in the infrared radiations range, this technique is able to detect the energy emitted by any material as electromagnetic radiations. This property of the materials is strictly connected to their thermal conductivity and their heating capacity: the first parameter determines the capability of a material to transmit heat, while the second one defines the attitude of a material to hold heat. Therefore, each building structure composed by different materials (such as historic masonry or timber systems), after being heated, will present a distribution of temperatures according to their different capability in transmitting and holding heat. Thermography is based on the acquisition of thermal images by an infrared camera: by observing with this device the changes in time of the

[146] E. Rosina, J. Spodek, *Using infrared thermography to historic wood framed buildings in north America*, APT Bullettin, n. 34. (Rosina, 2007)
[147] E. Rosina, *La percezione oltre l'apparenza: l'architettura all'infrarosso*, Alinea, 2004. (Rosina E. , 2004)
[148] R. Arndt, C. Maierhofer, M. Rolling, *Quantitative Pulse-Phase Thermography for Masonry and Concrete structures*, Proceedings of the 9th European Conference on NDT, Berlin, September 25-29, 2006 (Arndt, 2006)

surface temperature, near surface characteristics of structure can be detected[149]. In order to obtain measurable temperature differences on the surface of an observed element, a previous heating of the surface is necessary. This can be done by solar radiation (passive method) or using heating systems (active method). Recording images during the cooling down phase, when the solar radiation is no more present or after removing the heating source, the results are detectable. Differences in the distribution of the temperature on an area that has been previously heated in a uniform way, can be connected with significant information concerning the composition and the presence of defects in the structures of traditional buildings[150].

The main problem in the detection of the state of conservation of ancient structures is the correct survey of the component they are made of. In the architectural field the thermovision provides results concerning: i) masonry texture behind plaster; ii) plaster delaminations; iii) detachments of stone plates veneer; iv) presence of defects like inhomogeneities or lack of material in the near surface; v) geometry and connection of the elements of timber frames in floors, arches or vaults. In the research the attention was focused on three main aspects: a) the survey of the geometry of the masonry texture; b) the determination of the characteristics of wooden structures; c) the presence of detachments of large stone plates. The tests that will be described in further paragraphs were collected during different research works carried out by the research-unit Historical Buildings, Diagnostic, Vulnerability and Conservation of the Department of Structural Engineering of the Politecnico di Milano. The infrared camera used for the tests is a Nec-AVIO TVS 500E model (Figure 1a), equipped with a photographic camera, based on a detector formed by a matrix 320 (H) x 240 (V), Vanadium Oxide microbolometer type. The spectral field of this device is 8 – 14 µm. When active thermography was applied, the heating system consisted of an infrared lamp (Figure 1b), with a heat output of about 1.5 kW, and/or by a warm air generator (Figure 1c), with a heat output of about 12.4 kW (10.700 kCal/h).

[149] T. E. Xavier, P. V. Maldague, "Theory and practice of infrared technology for non-destructive testing", Wiley & Sons Ltd., 2001 (Xavier, 2001)

[150] (Rosina E. , 2004),

4.2.1 Thermography application: short description

Thermography, as said before, is a non-destructive testing technique that can be useful to evaluate the external layers of hidden surfaces in building structures. The surface of the structure to be investigated is heated by using a radiation source. For large volumes the source of radiation is usually the light of the sun (passive thermography). For areas not exposed to the natural illumination, heating systems can be used to warm up the surface. After switching off the heating source, or when the surface stop to be directly lighted, the cooling down behaviour is recorded in real time with an infrared (IR) camera. While observing the temporary changes of the surface temperature distribution with the infrared camera, near surface discontinuities will be detected if they give rise to measurable temperature differences on the surface. The main approach of thermography in analysing the thermal data is to interpret the function of surface temperature versus cooling time for selected areas with and without inhomogeneities.

4.2.2 Technical specifications

A thermo-camera, set for applications on building structures, should have the following characteristics

- Temperature measurement range: at least from – 40°C to + 500°C;
- Wavelength: 8-14 µm (near infrared frequency)
- Measurement distance: at least from 30 cm to ∞
- Spatial resolution: at least 320(H) x 240(V)

In order to ensure the correct heating of the surfaces, the acquisition performed by an infrared thermo-camera should be supported by additional devices like warm air generator or infrared lamps (Figure 4.1), required in the interiors of the buildings.

The positive outcome of thermovision is dependent on three main factors:

a) The environmental conditions, such as the presence of a high percentage of humidity in the air or a not good exposition to solar radiation; they represent a limit for the correct acquisition of active thermographic images by the thermo-camera.

b) The distance from the object to study and the angle of framing have influences on the resolution of the final result and on the accuracy of the correct evaluation of the distribution of temperatures.
c) The resolution and focal width of the thermo-camera can be different according to the use of the device: in order to study building structures, the resolution of the device can limit the dimension of the area that has to be acquired and wide angle lens are requested to frame wide surfaces.

Commercial software provided with the thermo-camera are usually set for the main analysis of the distribution of the temperatures acquired by the device. If the data contained in the radiometric images stored by the thermo-camera are accessible (open-source), further elaborations are possible, considering also other parameters like the recorded frequencies, that are not usually taken into account by the issued software.

Figure 4.1: Devices used for the thermographic test: a) IR camera; b) IR lamp; c) warm air generator

4.2.3 Some application of thermographic tests

4.2.3.1 <u>Application to laboratory inspection or monitoring</u>

In general, thermovision is mainly a non-destructive technique issued for the monitoring and control of processes of transformation. In laboratory, it can provide information about alteration of materials subjected to physical characterizations.

Thermovision can detect the water rising in porous materials during the absorption tests. This technique is very useful also to evaluate the detachments of plasters or protective films from common building materials like bricks and stone blocks.

In laboratory, thermovision can be applied to single structural elements and to assembled specimens. The main use which was done is related to the control of the effectiveness of strengthening techniques for traditional structures. For example, the effects of delamination in FRP layers represent a problem that can effect negatively the effectiveness of this repairing technique, commonly applied on structures like bridges and large beams Figure 4.2 and Figure 4.3 refer to laboratory application of thermography to the control of FRP detachment when applied to brick masonry.

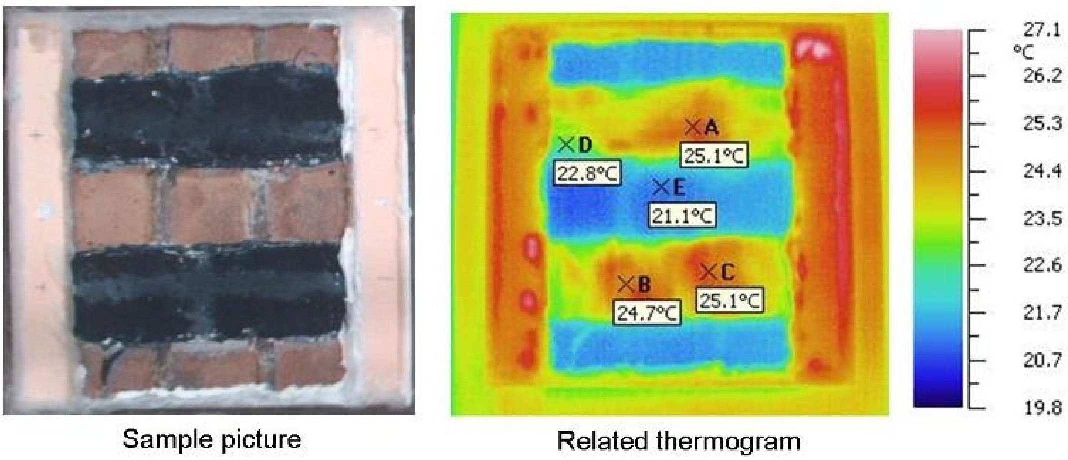


Figure 4.2: Thermographic test on a sample reinforced by RFP. The higher temperatures on the FRP surface correspond to detachments between the FRP layer and the specimen

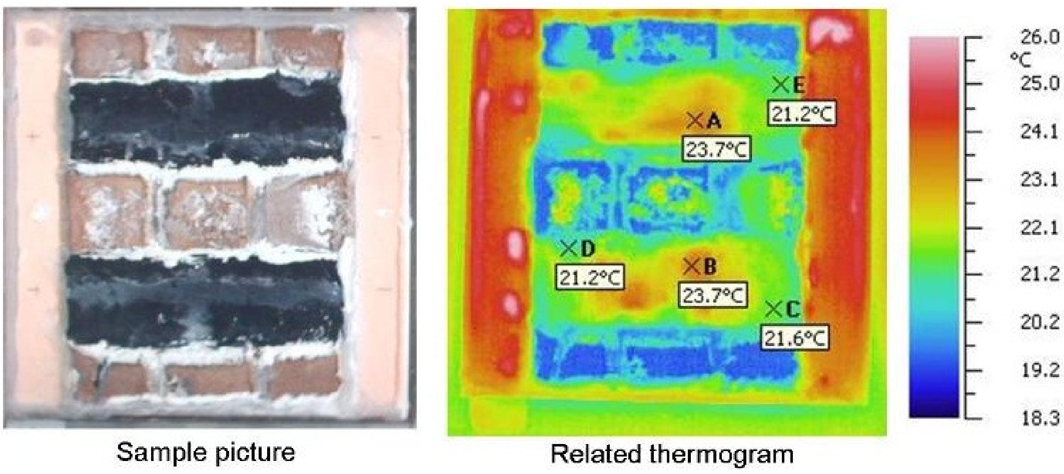


Figure 4.3: Thermographic test on a sample reinforced by RFP and affected by sub-efflorecence phenomena.

4.2.3.2 Application to in-situ inspection or monitoring

Thermovision can provide significant information concerning masonry textures and hidden structures for buildings that present wide surfaces covered by rendering, plaster, frescoes or painting. It can support the geometric survey, indicating the presence of different textures, providing the proportions and even the dimensions of the main components (stone blocks, development of joints, etc.). It can also provide information concerning the presence of closed openings or hidden structures like pillars or beams in order to improve the study of the stratigraphy of the building. At the same time these characterizations are useful as geometric surveys for the understanding of the mechanical behaviour of the building (see Figure 4.4 and Figure 4.5).

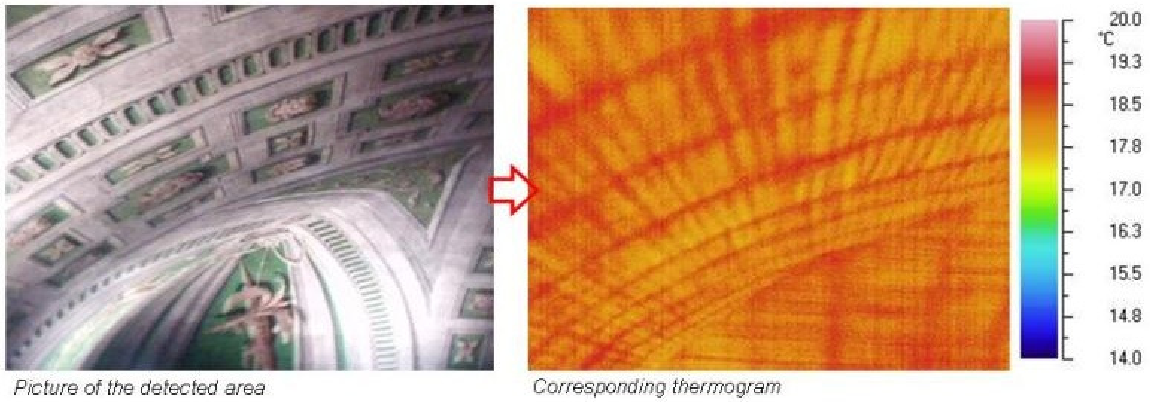


Figure 4.4: Identification of the constructive system of a timber vault by thermovision

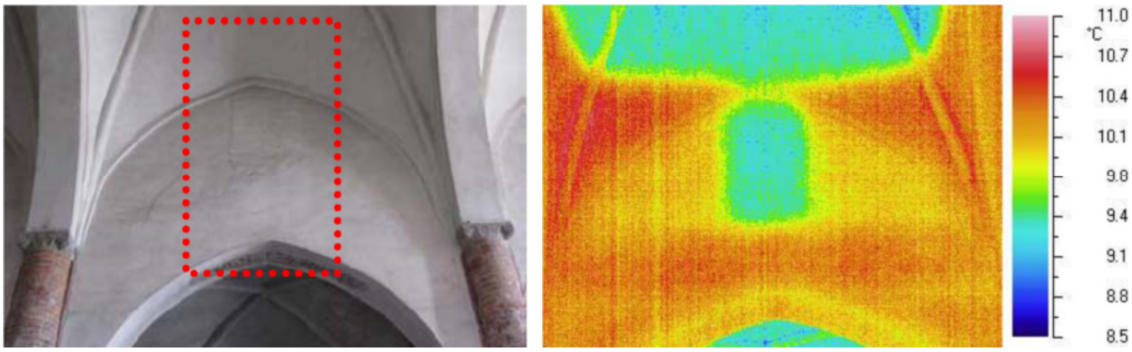


Figure 4.5: Example of use of thermovision for the identification of closed openings in ancient buildings.

Thermovision can be used to improve the interpretation of the crack pattern: the presence of cracks hidden under the plaster or the identification of passing through cracks can support first warning studies (see Figure 4.6).

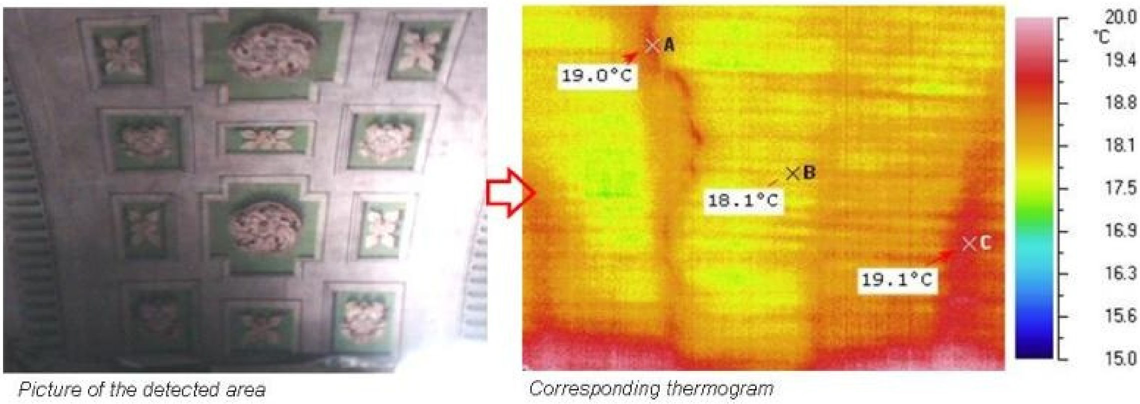


Figure 4.6: Study of the crack pattern by thermovision

By the detection of the distribution of temperatures on the framed surfaces, thermovision can also provide a map of the decay, indicating the detachments of materials (like plaster layers or stone plates) and the presence of water.

The identification of box-like behaviour in ancient buildings is an important requirement for the mechanical characterization of its vulnerability, especially in seismic areas. By the identification of hidden texture using thermographic tests (Figure 4.7), it is possible to evaluate the connections between different structural elements, such as load bearing walls, pillars, arches, vaults.

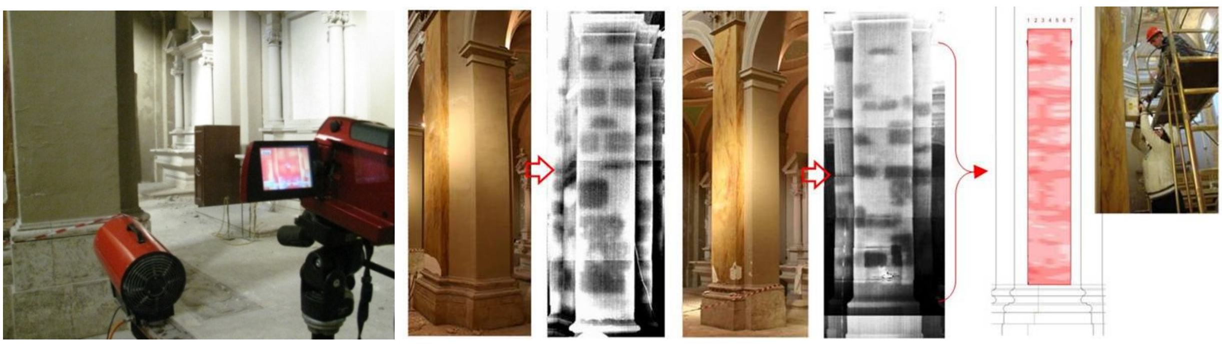


Figure 4.7: Examples of different masonry textures identified in a church and comparison of the result obtained by GPR.

4.2.3.3 Application to assessment of intervention strategies

Thermovision can be considered an application able to identify the presence of defects or decay processes and eventually to study the effectiveness of specific repairing or reinforcing techniques. The use of FRP strips to reinforce damaged structural elements is actually largely diffused. This technique achieves good results if the connections between the fibers and the damaged structure is provided by the correct working out of the glue (primer) used to bond the strips to the surface of the structural elements. Concrete beams are frequently repaired by FRP strips. Lacks of continuity between FRP strips and the surface of the structural elements can produce very negative effects for the safety of the entire structural systems. Thermovision can be applied to control the presence of detachments or delaminations between the FRP strips and their support or between the layers of the strips (if they are more than one). Thermograms showing uniform distribution of temperatures indicate a good application of the primer and a correct connections between the elements (Figure 4.8). In this case the test can be carried out by pulse thermography: heating by lamp pulses the surfaces for very short times, in order to heat only the FRP layers and to observe the presence of discontinuities between them and the supporting surface (Figure 4.9).

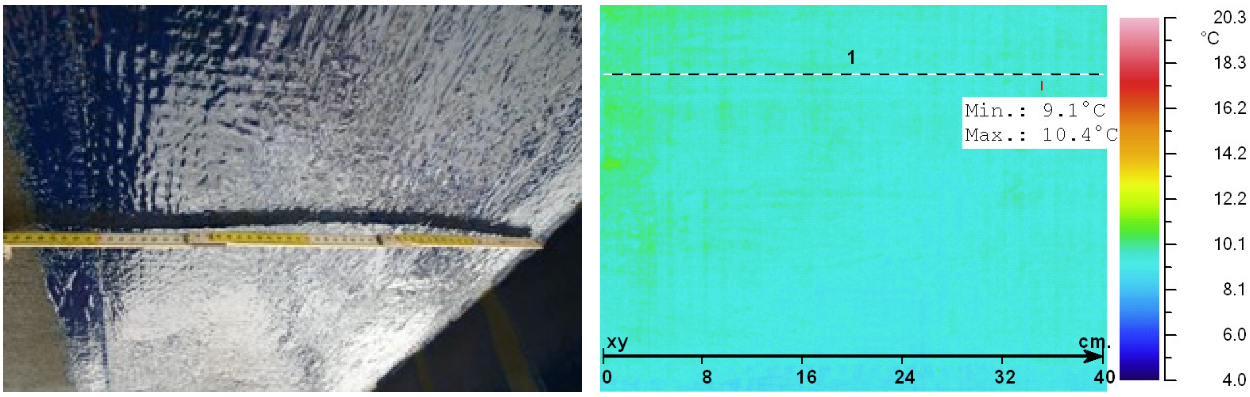


Figure 4.8: Example of uniformly glued FRP application on a concrete beam detected by pulse thermography

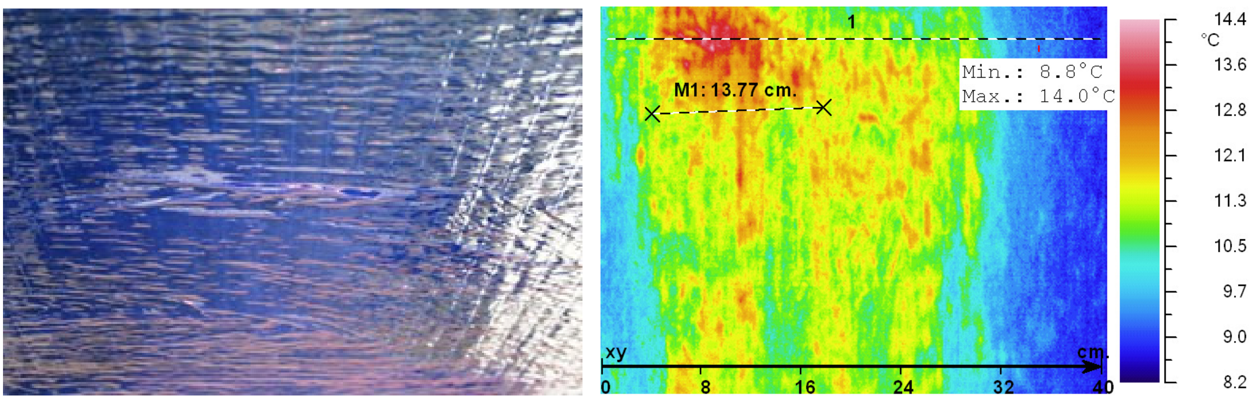


Figure 4.9: Example of detection of detachment between FRP strips applied on a concrete beam observed by pulse thermography

4.2.4 Effectiveness in the application to architectural heritage

Thermovision is a technique suitable for applications to Cultural Heritage. Being based on the acquisition of the IR component of the spectrum, it does not require any contact with the surfaces under investigation. For this reason thermography is one of the main non-destructive techniques in this diagnostic field. Its use is especially suitable for the study of surface layers: masonry textures or the decay of external layers can be investigated without removing the finishing of the walls, like frescos, stuccoworks and other decorations.

4.2.5 Innovative aspects

Similar information can be provided for the external layers of masonry structures also by other NDTs, as RADAR. This non-destructive technique, based on the propagation of electro-magnetic waves in a medium, allow the identification of the presence of layers and different materials (like stones, bricks and joints). By an accurate processing of the acquired data, RADAR can also identify the masonry texture.

Although RADAR tests are able to provide very refine images of the masonry textures or layering, their elaboration requires rather long times and the results can be not easily interpretable. Thermovision, on the contrary, provides immediate images that can be elaborated in short time. The precision of the final results depends on the accuracy of the acquisition: by creating the conditions for correct gradient between the external layers of the masonry and the environment, it is possible to achieve clearer thermograms.

4.2.6 Calibration and validation of thermographic tests

Results obtained by thermovision are strictly connected to the resolution of the devise. IR cameras can present different technical specifications and their efficiency requests periodically calibration tests: in specific the calibration on black body is necessary to set the measure of temperatures of the device.

By the complementary use of other conventional techniques, the results achieved by thermovision can be controlled. The application of thermographic tests in wet conditions can be difficult: results are usually affected by environmental humidity. In this case the complementary use of devices like digital laser thermometers or thermo-hygrometers can support the control of the quality of the data acquired by the IR camera.

4.2.6.1 *On-going calibration and validation works*

The use of thermovision for the detection of FRP detachments is contained in specific standards and calibration are on-going on masonry and concrete samples. Specimens were set up in order to present artificial lack of adhesion between the FRP layer and the materials. Thermovision was applied in order to detect some artificial voids and to control the estimation of their known dimensions using the software utilities provided with the IR camera. In order to improve the results, a specific routine has been set up in Labview environment in order to evaluate the area of the defects. The elaboration of the data took into account also the range of frequencies acquired by the IR-camera. The estimation of the first results is well promising and new tests are scheduled.

Fiber reinforced polymers (FRP) composites are now considered an efficient method in the strengthening of civil structures. Most of the FRP systems are applied using a wet lay-up method in which the fibers are impregnated on site. For this reasons the system can contain air voids or non-uniform distributions of the epoxy resin used as bonding material. The performance of these applications is due not only to the quality of the materials but mainly to the accuracy of the application and therefore to the experience of the workers. Therefore the inspection and monitoring of these applications is essential. Some national guidelines[151] report specific indications and acceptance criteria to assess the mechanical properties of the components of the composites (i.e. fibers and adhesives) and of the reinforcing system. Defects are an important

[151] The main references are contained in:

- ACI Committee 440. (2002), ACI 440.2R-02-Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures, Farmington Hills, MI; (ACI-440.2R-02, 2002)
- CNR (National Research Council). (2004), Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures, Advisory Committee on Technical Recommendations for Construction of National Research Council, Rome, Italy; (CNR, 2004)
- fib, (2001). *Externally bonded FRP reinforcement for RC structures* Bull. No 14, Technical Report prepared by Task Group 9.3, Lausanne. (FIB, 2001)

issue that is examined by some guidelines[152] that give the allowable defect size in proportion to the strengthened area. The first inspection at the end of the installation process is of primary importance for the acceptance of the strengthening. The surveyor can use different types of inspections mainly based on non-destructive evaluation (NDE)[153]. All the guidelines recognize that Infrared Thermography (IRT) is a possible NDE technique. IRT reveals the intensity of the infrared radiations emitted from heated surfaces at a certain time. Different materials, after heating, present different temperatures due to their different capability in transmitting and holding warmth. For this reason IRT is an effective technique for the detection of bonding defects, voids and damages and the characterization of the surface layers without a direct contact between the device and the observed area. On the other hand, in the guidelines no clear indications are given about the inspection procedure.

A series of thermographic tests was performed in laboratory to verify the capabilities of IRT technique to estimate the presence of defects, their location and size.

4.2.6.2 Performance of thermographic tests

As active IRT is based on the application of heat to a surface to generate a thermal front into the material. In this case, the heating source was applied for a period from 5 to 15 seconds using an infrared lamp positioned at a distance of about 30-40 cm from the specimen. The electric power of the lamp was 1.5 kW and the surface was equal to 0.29 ×0.14 m2.

After external heating, the temperature of the sample surface during the cooling phase was recorded in real time by using a thermographic camera positioned at a distance of about 30-40 cm from the specimen. As said before, the IR camera produces images of 320×240 pixels composed of Vanadium Oxide microbolometer detectors allowing to visualize temperatures in a range from -

[152] Mirmiran, A., Shawhawy, M., Nanni, A. and Kharbari, V. (2004), Bonded Repair and Retrofit of Concrete Structures Using FRP Composites,"Report 514, National Cooperative Highway Research Program, Washington, D.C., pp. II-27 to II-28. (Mirmiran, 2004)

[153] Starnes, M., Carino, N.J. and Kausel, E.A. (2003), Infrared thermography for non-destructive evaluation of fiber reinforced polymer composites bonded to concrete (Starnes, 2003); and J. Mat; Starnes, M. and Carino, N.J. (2005), Active Infrared Thermography for NDT of Concrete Structures Strengthened with Fiber-Reinforced Polymer, in Civil Engineering, vol. 15, n 3, pp. 266-273

40°C to 500°C. The distance between the camera and the specimen was of 1.40 m, that is the standard distance used for onsite tests. In the specimen, the dimension of the area analysed by IRT was chosen to ensure an adequate image resolution for the detection of the defects.

After removal of the heating device the temperature changes, can indicate near surface inhomogeneities and the presence of defects in the structure if they give rise to measurable temperature differences. The results are images recorded during the cooling down phase; a thermal image of the object is obtained on the basis of a colour scale or a grey scale.

4.2.6.3 Masonry and concrete specimens description

The masonry specimens of dimension 25×52×102 cm^3 was reinforced using unidirectional CFRP wraps. The dimensions of the solid clay bricks used for the masonry wall were 250×120×55 mm3. CFRP reinforcements were bonded on a side of the masonry wall using a thixotropic epoxy resin. The mixing ratio of the epoxy was 1:4, i.e. four parts of component A (resin) to one part of component B (hardener) by volume. Lack of bonding of the FRP to the masonry substrate was simulated by the interposition of double Teflon foils with different dimensions and the geometric shapes as reported in Figure 4.10. The detection of the defects was performed with 1, 2 or 3 layers of FRPs for both the specimens (Figure 4.10).

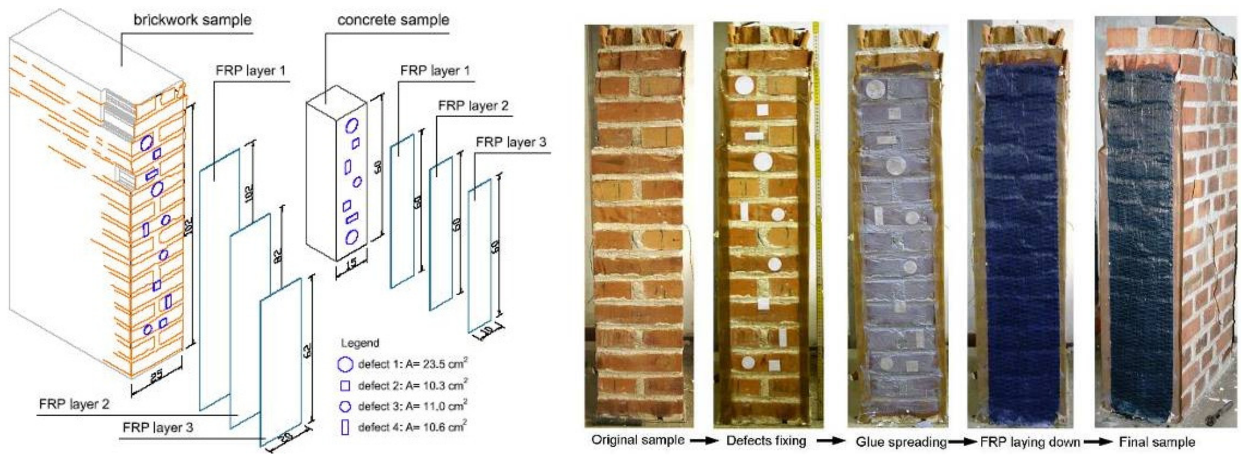


Figure 4.10: Layout of the specimens and preparation of the masonry sample for the calibration of thermografic tests on specimens with artificial defects between FRP layer and the materials

The concrete specimen consisted of a C25/30 concrete block (150×150×600 mm^3) reinforced using CFRP wraps. This specimen was reinforced using the same materials and procedure as for the masonry specimen.

4.2.6.4 Test procedure

The procedure consisted in two subsequent time periods: t1, the heating interval and t2 the waiting time to shoot the picture. After calibration the optimal t1 times, reported in Table 1, were defined while the t2 times were obtained at the beginning of the cooling phase (from 3 to 15 s after the removal of the IR lamp).

Temperature differences have peaks at the defect zone after heating, and they represent a valuable parameter for the location and sizing of the defects.

Specimen	1 FRP layer	2 FRP layer	3 FRP layer
brickwork	5 seconds	10 seconds	15 seconds
concrete	5 seconds	5 seconds	5-10 seconds

Table 4.1: Heating times used to carry out the thermographic tests in relation with the number of the FRP layers.

4.2.6.5 Test results

The thermographic tests, carried out on brickwork and concrete specimens presenting one single FRP layer provided a reasonable estimate of the presence of the artificial defects. Reliable results were also obtained in specimens reinforced with two FRP layers, except for a very limited area at the bottom of the masonry sample. In such area the position and the shape of the artificial defects were not clearly recognizable due to debonding between the first and second FRP layer. Thermal images of this area, taken at different times after the end of the heating stage show that the highest temperatures are maintained for longer periods in the debonded area. More difficulties were encountered in detecting the defects on the masonry specimen after the application of the third FRP layer, i.e., if the defect is far from the external surface, identification is more troublesome.

Results are more clear for the concrete specimen: the homogeneity of its surface allowed a better adhesion of the strips. The brickwork specimen presents evident detachments along the mortar joints and the shape of the artificial defects is not clearly recognizable when they are superimposed. In both cases the heating time can be limited to 10 seconds when three layers are applied. More heating time could be applied for the stonework specimen, but it must be remarked that the application of the IR lamp at a short distance to the surface can rapidly increase the temperature to the fusion temperature of the glue (around 70°C).

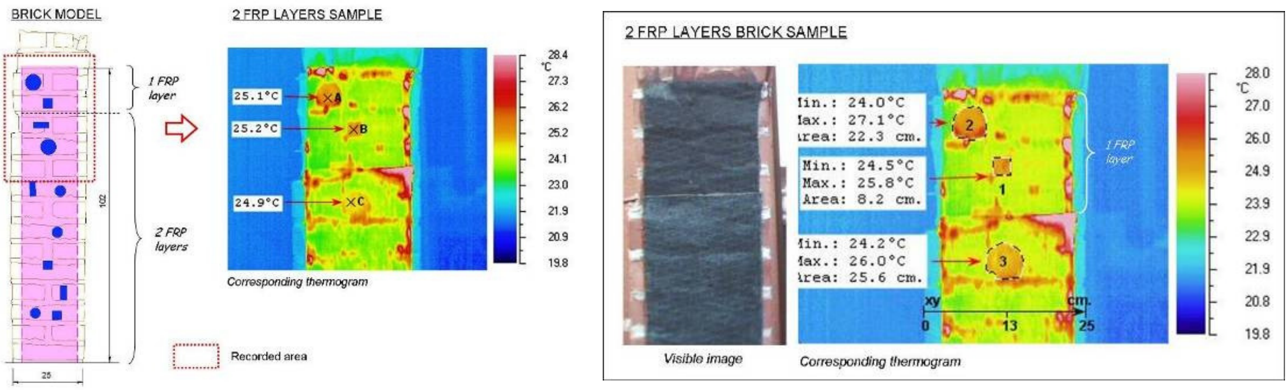


Figure 4.11: results obtained by the calibration of thermographic tests for the identification of artificial defects between FRP layer and the specimen and for the estimation of the area of the defects

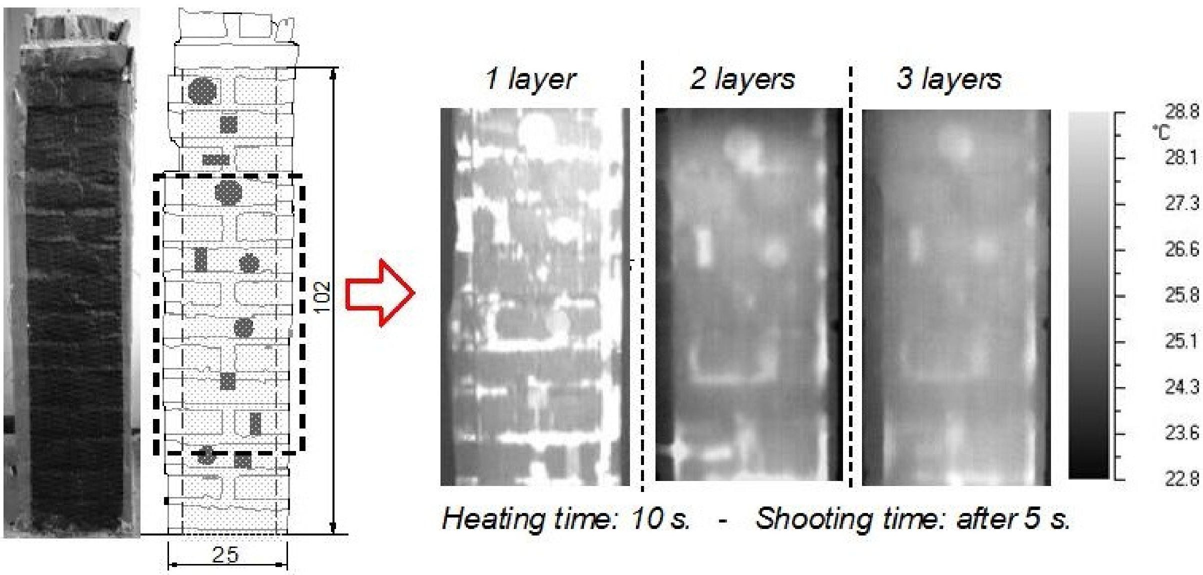


Figure 4.12: Comparison between the results obtained by thermographic tests carried out on the central area of the brickwork sample with 1, 2 and 3 FRP layers.

4.2.6.6 Study of different layers application

As shown in the thermal images reported in Figure 4.13, the data elaboration allowed to optimise the temperature differences for the best identification of the position and shape of the artificial defects. The commercial software used for the elaboration is Thermography Studio (Goratec Technology). It is set to modify the temperature field of the thermogram in order to select the most suitable range for the visualization of the results. The analysis of the thermographic test is based on the image sequence. The sequence is formed by the thermograms acquired during the cooling phase, maintaining the IR camera During the cooling phase, the estimation of the defect dimension presented some differences from the beginning to the end of the test. The influence of the FRP thickness is evident from Figure 4.13: as the number of layers increases, the differences in terms of measured defect dimensions are higher.

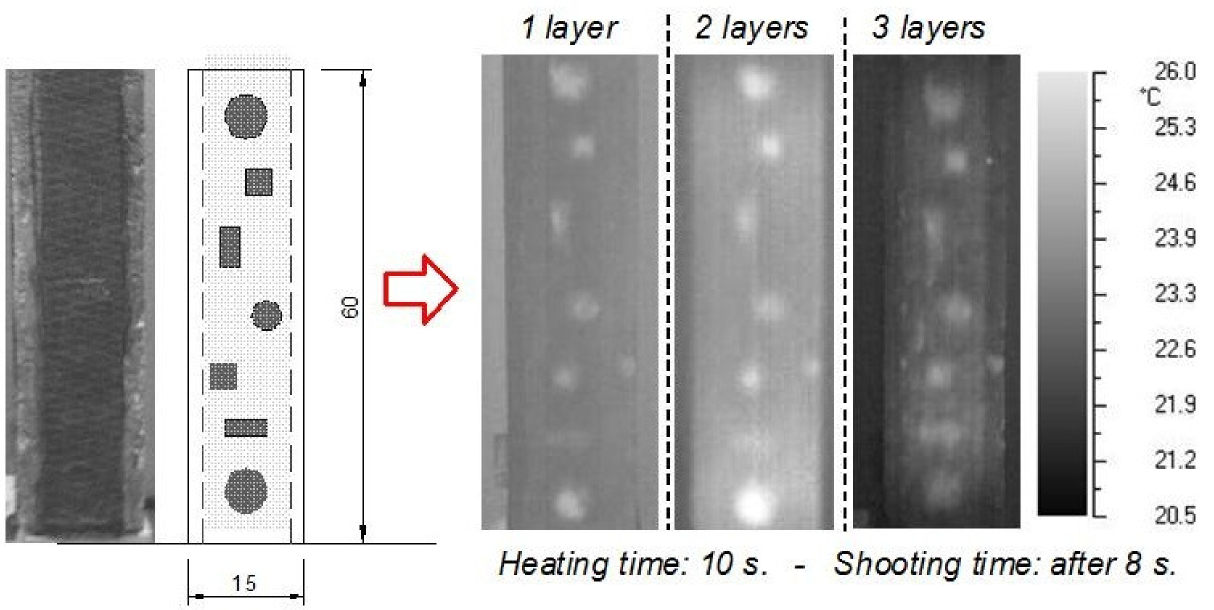


Figure 4.13: Comparison between the results obtained by thermographic tests carried out on the concrete sample with 1, 2 and 3 FRP layers.

Table 4.2 shows, for example, the differences between the estimated areas of 4 categories of artificial defects and the original one fixed on the same framing. The period of the sequence shows the variation of the distribution of the temperatures on the surface of the framed specimen. Through the passage of the warmth from the inner layers of the specimen to the external surface, the distribution of the temperatures characterising elements with different thermal conductivity is captured in the image sequence. The images which present the better results can be later modified to improve their quality.

The main steps of the elaboration are here described:

a) *Temperature and emissivity settings:* the calculation of the real temperature for each point of the thermographic image (each pixel) is a fundamental step of the data elaboration. Each object has a proper emissivity and the software provides a table of values for the most common materials used in building field. The emissivity is defined as the intensity of infrared radiation coming from a point on an object, resulting from the sum of the radiation emitted by the object itself and the ambient radiation reflected by the object. Its determination is basilar for the calculation of the temperature emitted by the framed object.

b) *Range of interest.* This option of the software allows to estimate the temperatures which emphasise the result, in order to exclude the temperatures of other parts of the image (like parts in the background which can be excluded from the elaboration).

c) *Trend analysis.* This option of the software provides point, area or profile trend device, useful to estimate the homogeneous areas of the thermogram, characterised by the same temperature range. Through the trend analysis, the main information about hidden materials, texture and defects are identified.

d) *Proportion and dimension.* The software provides some devices to estimate the real size of the framed object, in order to measure the extension or the geometry of the recognized defects or to evaluate the proportion of the hidden texture.

	Defect no.	Real shape	Real area (cm^2)	Area - 1 layer (%)	Area - 2 layer (%)	Area - 3 layer (%)
masonry specimen	1	Circle A	23.5	-3.4	+8.9	+10.6
	2	Square	10.3	-5.8	-25.6	+23.3
	3	Circle B	11.0	-13.6	+3.5	+22.7
	4	Rectangle	10.6	-6.6	-5.0	+33.0
concrete specimen	1	Circle A	23.5	-10.6	-10.3	-4.3
	2	Square	10.3	-4.9	+18.3	+28.2
	3	Circle B	11.0	+2.7	+11.3	+16.4
	4	Rectangle	10.6	+17.0	+24.3	+34.0

Table 4.2: Defect areas estimation on both specimens.

4.2.6.7 Errors in the defect estimation

In the estimation of the defects, the error is influenced by the image resolution and by the accuracy of the operator in recognizing the borders of the defects. Besides this operation is actually time-consuming and partially influenced by the interpretation of the thermal image on the surface of the sample. In order to improve the research, other routines are under exam. The aim is to set an algorithm for the analysis of the thermographic sequence of images recorded after the test. This is based on a technique, also referred as Thermographic Signal Reconstruction (TSR). The aim is to detect during the cooling phase the best thermal image, aimed to improve the observation of the appearance of the defects and to automatically identify the shape and the area of each defect.

Furthermore, a Labview routine was developed by Marco Cucchi, technician of the *Laboratory for testing materials* in the Dept. of Structural Engineering of Politecnico di Milano. This software applies the Fast Fourier Transform (FFT) in order to switch from the time-temperature domain to the time-frequency domain. The variation of the frequency of the IR radiation is another parameter to take into account in order to evaluate the information contained in the recorded thermograms. Interesting results through the analysis of the frequency were shown by C. Maierhofer and M. Rolling and[154] the development of a dedicated software for this characterization is an important step to evaluate also this aspect of the problem.

4.2.7 Thermovision: applications in conservation field to detect hidden characteristics of building structures

The difficulty in applying thermographic test is to obtain the peculiar condition in which the materials in a structure (e. g. wall) reach a uniform temperature that later on can be returned by surface emission, to the environment. Only in that case during the cooling phase, the distribution of temperatures on the external surface will be significant to identify the features of materials and elements. This observation will be allowed up to 3-6 centimetres depth when the external surface

[154] R. Arndt, C. Maierhofer, M. Rolling, Quantitative Pulse-Phase Thermography for Masonry and Concrete Structures, Proceedings of the 9th European Conference on NDT, Berli, September 25-29, 2006. (Arndt, 2006)

is covered with plaster or frescoes. Creating these conditions, the thermographic tests can provide important information, about the geometric characteristics of the hidden elements also concerning their state of conservation without removing and hence destroying the rendered surface.

The two first important steps to improve the knowledge of a historic building are represented by the historical investigation and the geometrical survey of the building. At this level of the work a NDT like IR thermography can support and improve both aspects providing information that can confirm the transformations documented by the historical research and reveal the presence of hidden elements that the normal devices used for the geometrical survey (as total station and laser-scanner) are not able to show.

4.2.7.1 Masonry Texture

The first approach to the study of an historical building is the evaluation of the geometrical dimensions of their structures. The information acquired by the geometrical survey are usually related to the one obtained by the historical research with the aim of detecting the evolution of the building along its life. In the past many buildings were subjected to transformations, according to the change of use. Nevertheless the information given by both approaches, geometrical survey and historical research, are not complete or present uncertainties depending on areas of the building that cannot be inspected or on the lack of documentation. At this point, the study can be supported by different NDTs. IR thermovision can provide more details and, at the same time, can reveal the points of connection between the geometrical characteristics of the building and its historical evolution.

This is the case illustrated in Figure 4.14, where a synthesis panel shows the above mentioned parallelism between the information obtained by the study of the history of the castle of Brivio (Italy) and its geometrical survey. Built as a roman fortification, the castle was deeply transformed during the second half of the 19th century, with the addition of two floors over the original defensive wall. The presence of the plaster on the wall did not permit to identify clearly the texture of the masonry in order to recognize the original height of the defensive wall. In order to solve this problem, IR thermography was performed on the facade of the castle and the results allowed to see the hidden texture of the masonry. As shown in Figure 4.15, differences between the original texture of the roman wall and the one of the added floors could be found.

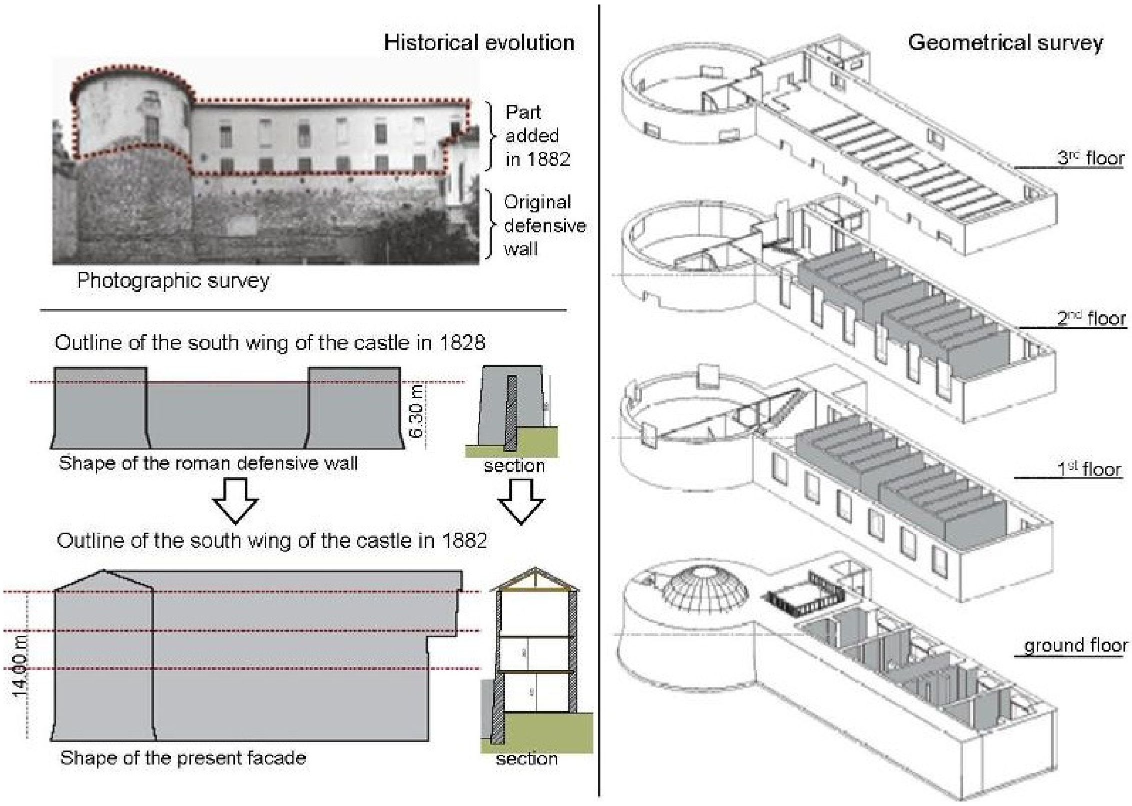


Figure 4.14: Synthesis panel showing the parallel research on the historical evolution of the south wing of the Castle of Brivio (Lombardy – Italy) and the geometrical survey of the today's organization of the complex.

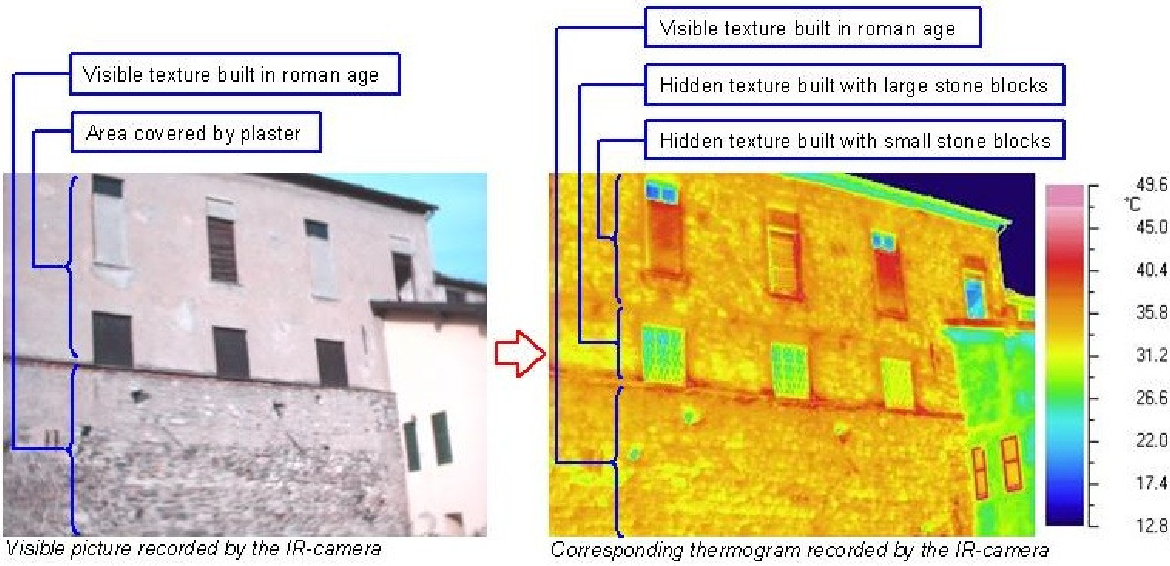


Figure 4.15: Detection of the masonry texture of the south wing of the Castle of Brivio (Lombardy – Italy) performed by thermographic test.

In this case a clear detection of the different texture was reached. Nevertheless in some cases it is not possible to identify clearly the materials component of the masonry. IR thermography presents two main problems: a) the resolution of the IR camera and b) the depth of the rendering layers. The low resolution of the device imposes to perform the tests at a certain distance from the surfaces of the investigated buildings: the closer the recording is performed, the highest will be the resolution of the masonry texture. The required close distance can cause another problem: for high buildings the shooting angle can influence the quality of the result (see Figure 4.16).

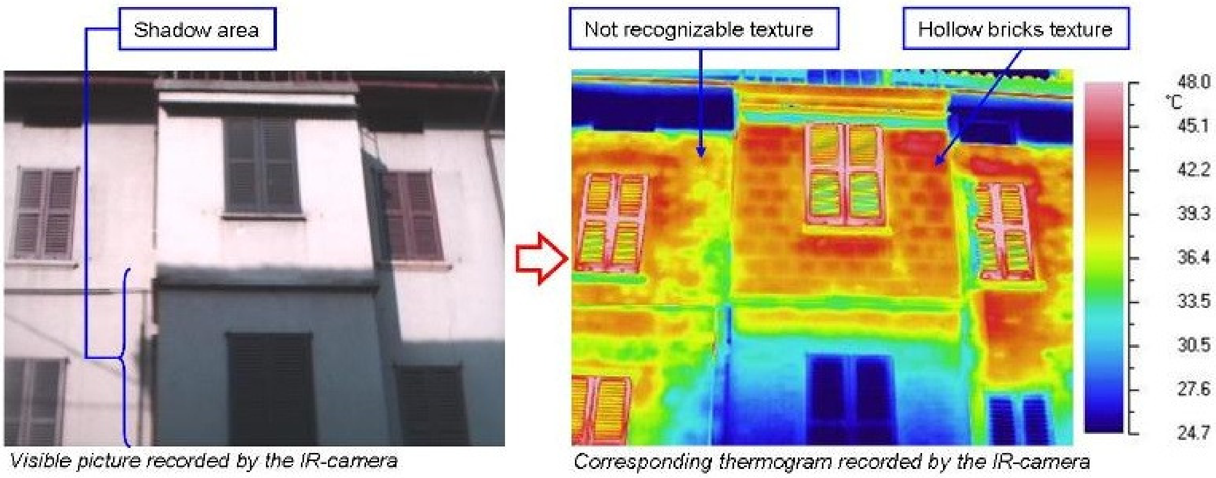


Figure 4.16: Detection of the masonry texture at the second floor of an historical building. The elaborated thermogram shows an added body composed by hollow bricks but the texture of the original masonry wall is not recognizable due to the thickness of the plaster

The thickness of the plaster in existing buildings can be very variable: a traditional plaster, prepared following precise rules, should be 3-4 cm thick, but renewals and transformations in time can increase the layers of plaster. This problem is usually visible on external facades, where IR thermography can be performed only in passive way: in this case the solar radiation can be not enough powerful to interest the surface of the walls in certain period of the year. Figure 4.16 shows a case in which the modern addition of hollow clay bricks is clearly detectable due to the limited thickness of the plaster, respect to the thicker one on the original part, which caused a low performance for the thermal insulation.

4.2.7.2 Survey of Hidden Textures as a Support for the Correct Use of other Testing Techniques

Significant results were obtained in the church of St. Biagio in the centre of L'Aquila. In this case several non-destructive and minor destructive tests were required to study the state of conservation of the monument after the 2009 earthquake. Figure 4.17 shows the results of thermographic tests applied to a) a portion of the internal side of the façade of the church and b) a pillar of the nave. The built-in pillars of the facade and the pillar showed a similar texture, while the masonry wall has a different one. In each case an unexpected arrangement of the elements forming the structures was identified. The built-in pillar and the pillar presented a regular sequence of bricks and large stone blocks; the wall is built with a different texture, by small irregularly shaped stones.

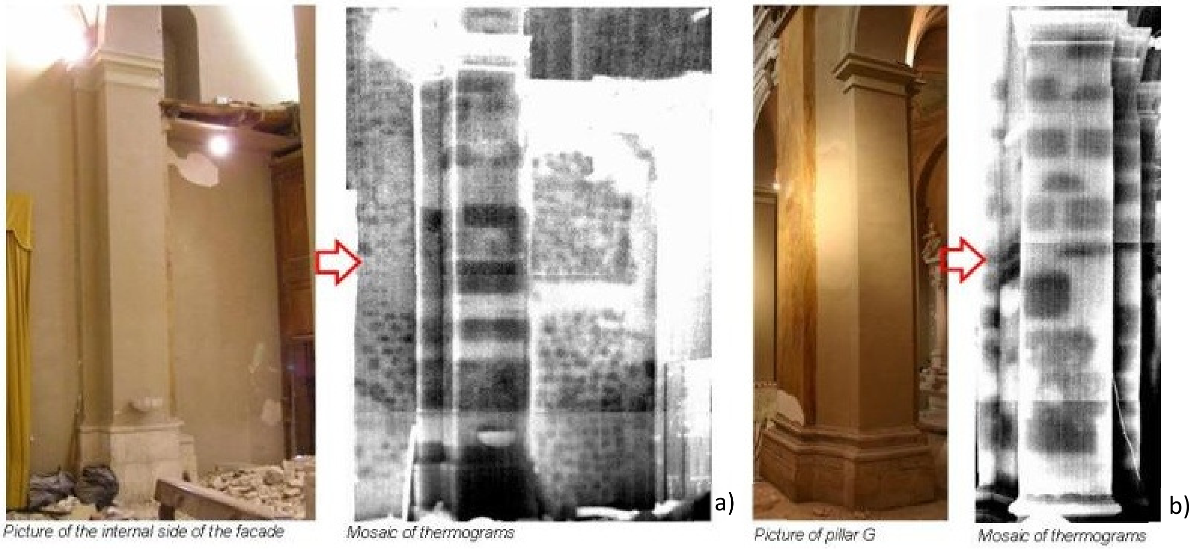


Figure 4.17: Differences of the textures of the built-in pillar, the wall and the pillar detected by active IR thermography in St. Biagio Church in L'Aquila.

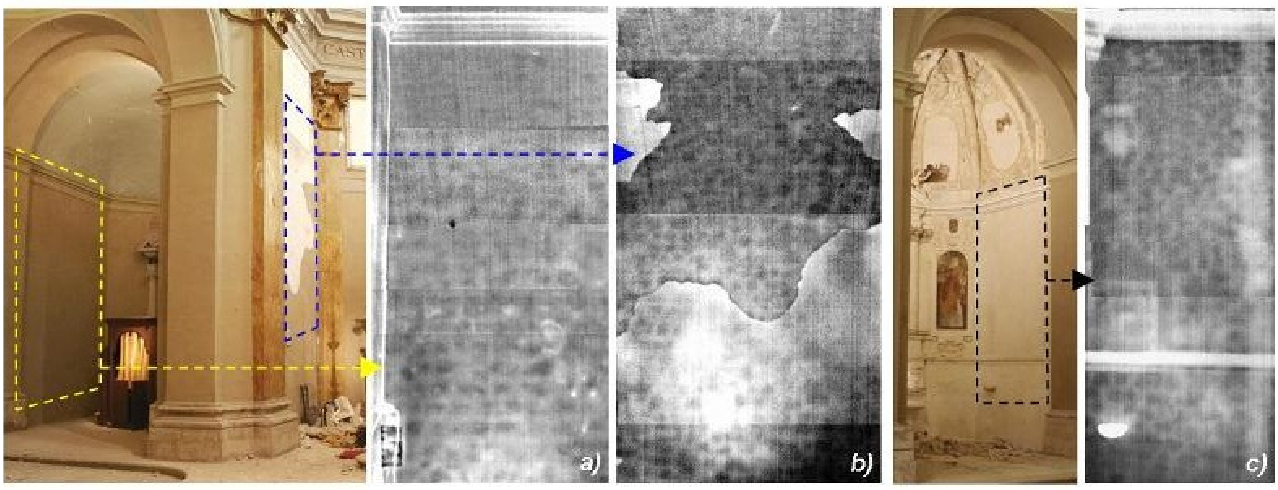


Figure 4.18: Localization and results of thermographic tests performed in the south-east (a), central (b) and south-west (c) apse of the church of St. Biagio Church.

The detection of the masonry texture can provide also information to locate other diagnostic tests to study in depth the characteristic of ancient masonry structures. Figure 4.19 shows the texture identified by thermography on two internal walls of the Castle of L'Aquila. The building, recently damaged by the 2009 earthquake, had to be studied by different testing techniques. Single and double flat jack tests had to be performed in two significant load bearing walls of the building in order to detect the mechanical behaviour of the masonry. In this case it was very important to select the best position where to perform the tests. IR thermography was preventively carried out to avoid the risk of performing a difficult and expensive test in a wrong position of the masonry that was totally covered by a 5 cm thick plaster.

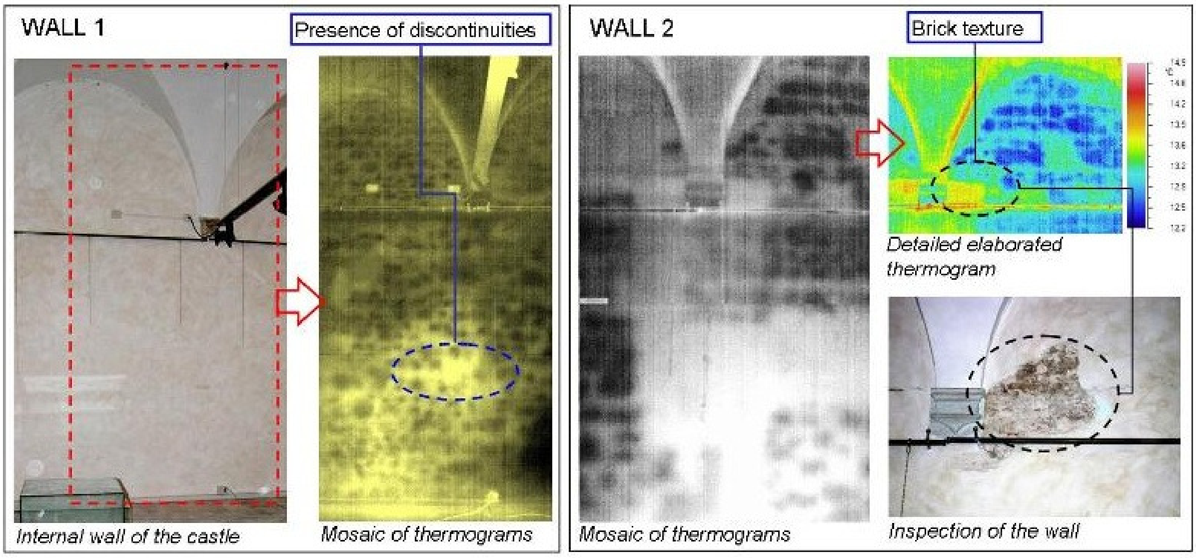


Figure 4.19: Texture of two masonry walls inside the Castle of L'Aquila.

4.2.7.3 Detachments of Stone Cladding

The presence of detachments and defects under the surface of stone slabs can be detected by IR thermography[155]. A study to verify the presence of detached travertine slabs was carried out at the Palace of the Prime Minister in Tirana (Albania). In this case the problem was connected to the absence of mortar joints between the vertical slabs: the contact between the slabs increases during deformations caused by the thermal dilation of the material and no joints to reduce this effects were taken into account in the design dated back to the 30s of the last century.

[155] L. Binda, L. Cantini, P. Condoleo, A. Saisi, L. Zanzi, *Investigation on the pillars of the Syracuse Cathedral in Sicily*, *3-Day Int. Conf. Structural Faults & Repair*, Edinburgh 13-15/6/2006, M.C. Forde (Ed.), Engineering Technics Press, Edinburgh, pp. 1-12, 2006.

The presence of a superficial treatment in some areas of the facades had to be taken into account in order to verify the influence of a darker surface in the distribution of the superficial temperatures recorded by the IR camera. Considering an area presenting treated and still not treated stones, thermographic tests showed that even if the solar radiation was the same, the final result was different: darker treated materials presented a higher temperature of about 3 or even 5 degree (Figure 4.20 and Figure 4.21).

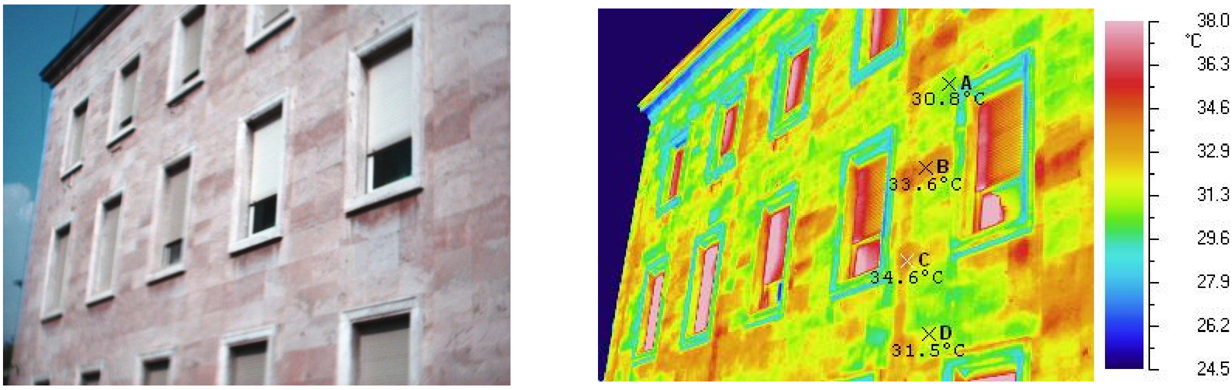


Figure 4.20: Distribution of temperatures on the surfaces of the main façade of the Palace of the Albanian Prime Minister.

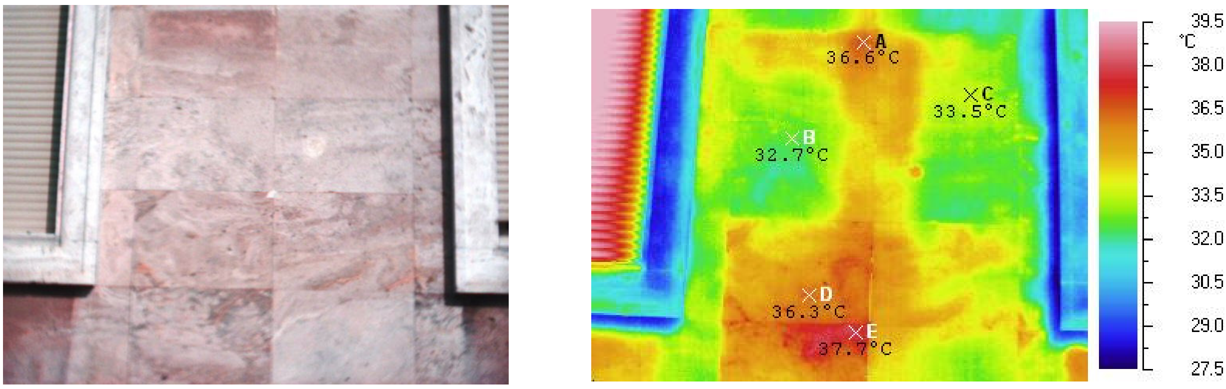


Figure 4.21: Distribution of temperatures on a detailed area of the main façade of the Palace of the Albanian Prime Minister.

As a second step, an application of the thermovision was set up by observing an area presenting known large detachments of the slabs from the internal structure. The detachment was clearly visible by the resulting thermogram, in which the presence of air under the stones is indicated by a concentration of higher temperatures. The difference between the temperature characterizing the detached area (higher) and the one still attached (lower) was estimated in about 5°C.

The identification of the hidden drainage system of the palace, obtained performing the tests after the sunset (Figure 4.22), allowed to recognize a recurring temperature for those areas characterized by cavities. After this final calibration, mapping the distribution of temperatures and interpreting the areas presenting more than 5 degree of difference, it was possible to identify the detached stone slabs.

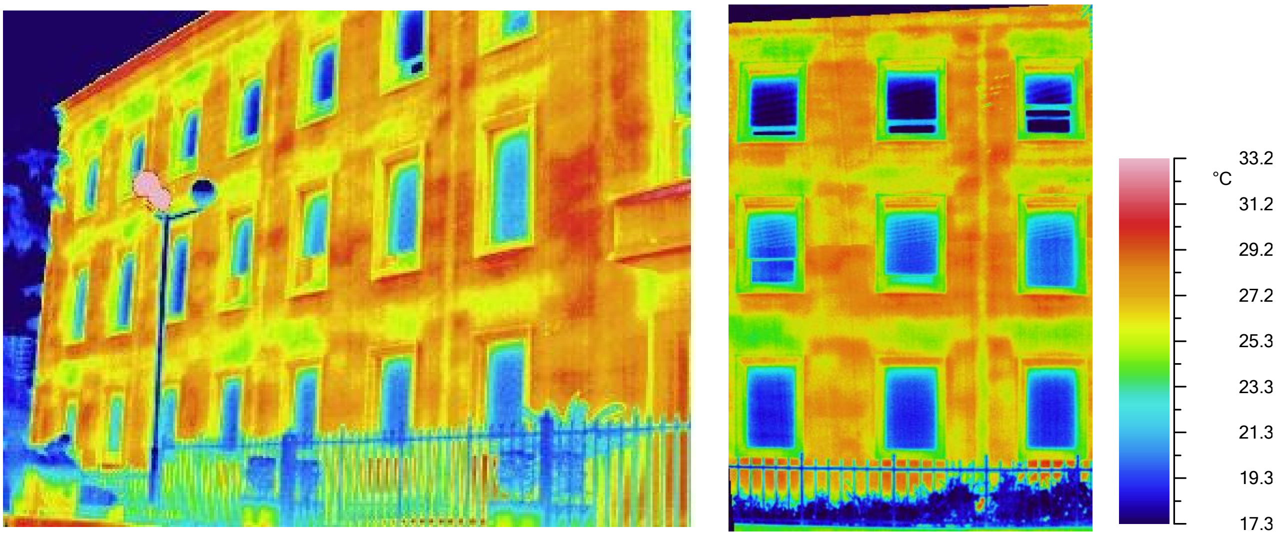


Figure 4.22: Thermograms of a general view of the west facade and of a frontal view of bays 6 and 7 of the same side.

4.2.7.4 Details of a Vault made by Timber Elements

Carrying out thermographic tests from the intrados of the vault of the Academy of Science of Turin, the wooden frame of the structure was detected (Figure 4.23). This kind of vaults are not very well known, due to the difficulties connected with access to the extrados and the presence of decorations covering the surface of the intrados. Manuals of the traditional techniques suggest an interpretation of the most common timber vaults diffused in Italy, but each single case, studied in depth, presents own peculiarities[156].

The thermovision test carried out on the vault of the Assembly Room showed the distribution of the load bearing system and wooden elements to which the plaster with paintings is attached (Figure 4.24a). The use of thermovision provided many information to identify the real structure of

[156] F. Giovanetti, "Manuale del recupero del comune di Città di Castello", DEI (ed.), Roma, 1993.

the vault that presented important differences with the known examples of timber vaults reported in manuals. For example the typical mat formed by plaited canes was absent, except for the base of the extrados of the vault.

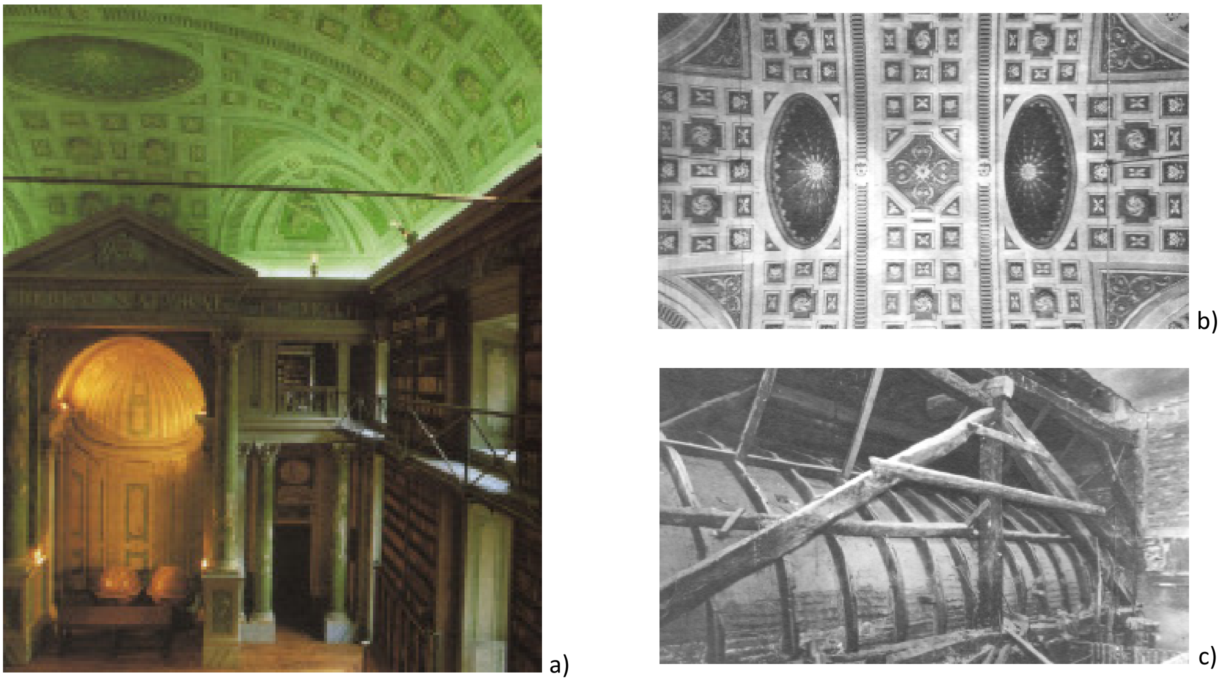


Figure 4.23: View of the Assembly Room (a); digital straightening image of the intrados of the vault (b) (courtesy of professor M. Chiorino from Politecnico di Torino); view of the extrados of the vault (c).

By the IR thermography, also the interpretation of the diffused crack pattern was possible. The presence of passing through cracks was characterized by a higher temperature of the cracks due to the air (Figure 4.24b). The presence of air was even important to detect the phenomenon of delaminations between the timber elements and the plaster layer (Figure 4.24c).

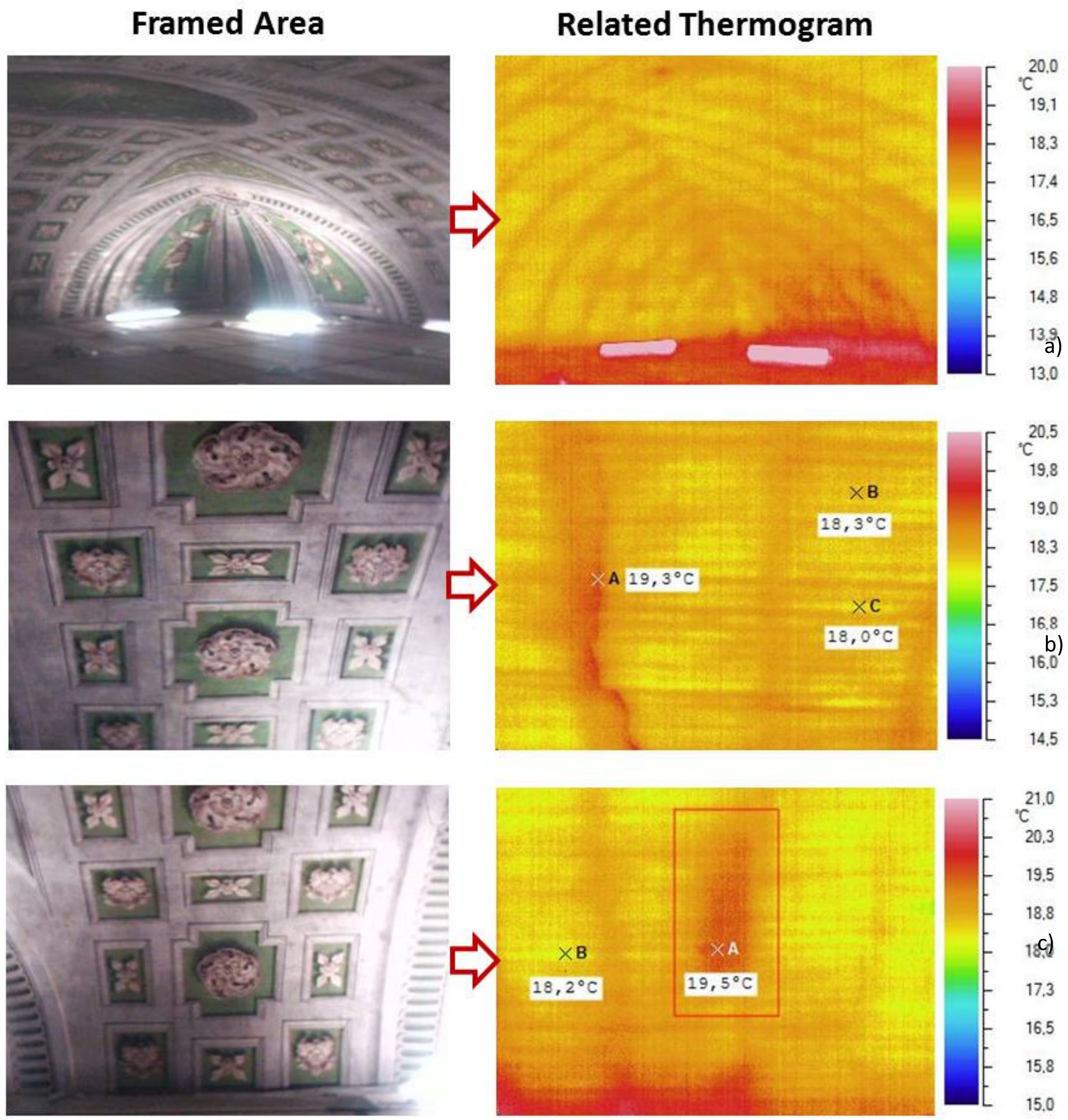


Figure 4.24: Thermograms of the intrados of the vault showing: a) the timbering system, b) a deep crack of the shell; c) a detachments between the painted plaster and the substrate (pictures and graphs by the author).

The application of thermovision allowed to support the survey of the structure through the identification of the main parts composing the shell of the vault (Figure 4.25). At the same time, a map with the positions of the supposed delaminations obtained by active IR termography was obtained (Figure 4.26).

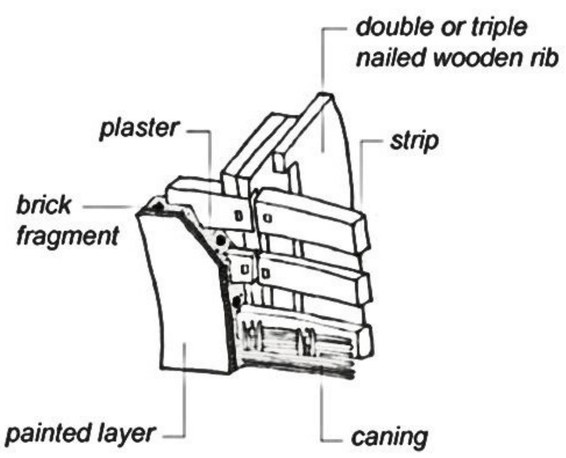


Figure 4.25: Sketch representing the structural elements forming the shell of the vault.

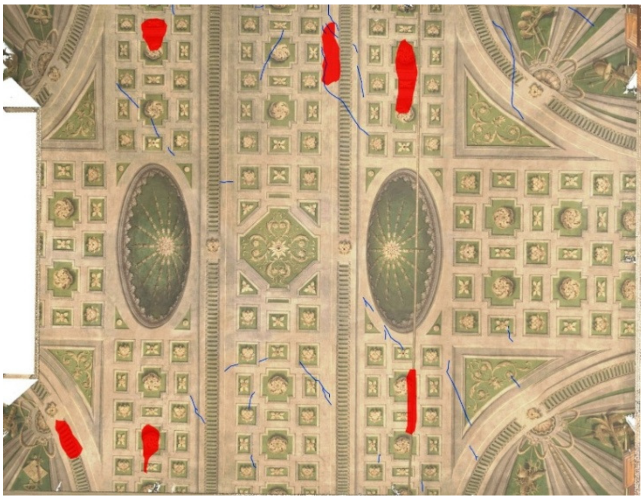


Figure 4.26: Map of the supposed detachments reported on the intrados of the vault.

4.3 Application of sonic tests for the assessment of masonry structures

A new chance to work on some experiments about the application of sonic tests arrived from the research group directed by prof. Joao Guedes and the PhD student Luis Miranda from the University of Porto. They had before three months stage at DIS (Dept. of Structural Engineering), working at the experimental work on-site. Their research started by considering the theoretical background of the propagation of elastic waves and was supported by experiments carried on in laboratory and on-site. By comparing the results obtained by destructive tests with those obtained by non-destructive sonic tests, a relative contained dispersion of between the two series of values was noticed[157][158].

[157] Luis Miranda, Joao Guedes, Joao Rio, Anibal Costa, *Stone Masonry Characterization Through Sonic Tests*, CINPAR Conference 2010, (Miranda, 2010)

[158] Luis Miranda, Joao Guedes, Joao Rio, Anibal Costa, *Propagation of Elastic Waves on Masonry Walls*, 8th International Masonry Conference 2010 in Dresden (Miranda, 2010)

4.3.1 Sonic tests: theoretical background

The testing technique is based on the generation of elastic waves in the frequency range of sound (20 Hz-20 kHz), by means of mechanical impulses at a point of the structure. The pulse velocity is related in an elastic, homogeneous and isotropic solid to the modulus of elasticity, density and Poisson coefficient. The relationship is independent on the frequency of the vibrations. In the case of masonry, due to its heterogeneity, the pulse velocity can be qualitatively connected to the characteristics of the masonry.

According to J. Shull and B. R. Tittman, the wave can be defined as a perturbation that propagates without transporting material[159]. This was observed also for waves which propagate in the liquids: waves move on, in the water for instance, but the particles of water passed by a wave limit themselves to oscillate respect to a balance point, without moving with the wave. When a wave propagates in a solid, the material is not subjected to any movement but a propagation of energy is generated from the emission point.

The propagation velocity of the waves in a solid depends on the wave frequency and on the mechanical and physical properties of the material. The nature of the material determines the entity of the attenuation of the waves during their propagation[160]. Experimental tests on different materials showed the following relationships:

a) high propagation velocity and low attenuation in homogeneous solids having high density;
b) low velocity and strong attenuation in porous materials.

The use of sonic tests in diagnostic field is based on the comparison of the results obtained on whole materials with the propagation velocities characterizing the same types of materials which are supposed to be damaged. Knowing the behaviour of a whole material, its sonic velocity can be compared to the one obtained on materials of the same nature, containing cracks, defects or voids. In building field, the presence of structural discontinuities is one of the main information that sonic tests can provide. The presence of lacks (voids which compromise the material continuity of a structure) can be identified thanks to the difference existing between velocities

[159] J. Shull, B. R. *Tittman, Ultasound, in Nondestructive Evaluation*, Dekker, New York, 2002. (Shull, 2002)
[160] G. Pascale, *Diagnostica a ultrasuoni per l'edilizia*, Dario Flaccovio Editore, 2008, Palermo (Pascale, 2008)

measured in solids and fluids means. The main values of sonic velocities measured in different materials are reported in Table 4.3.

category	Material type	Velocity of a sonic wave (m/s)
Solids	iron, steel	5950
	clay rocks	3480
	gum	1550-1850
Liquids (at 25°C)	sea water	1531
	distilled water	1496
	mercury	1450
Gas (at 26°C and 1 atm)	hydrogen	1284
	dry air	342
	carbon dioxide	259

Table 4.3: Propagation velocity of sonic waves measured in different materials.

Considering that the human audibility threshold is about 17000 Hz, methods based on waves propagation can be distinguished in:

a) ultrasonic test, for frequencies higher than 17000 Hz;
b) sonic test, for frequencies lower than 17000 Hz.

Higher frequencies provide more precise results for the identification of defects and discontinuities in the materials. Ultrasonic tests are almost used for the characterization of homogenous and compact materials. The frequencies used to test metals and other compact materials are in the order of MHz, whilst tests on common building materials (rocks and bricks) tests are based on frequencies in the order of KHz.

Ultrasonic tests, based on high frequencies, are characterized by short wavelengths. On the contrary, sonic tests, based on low frequencies, have longer wavelengths. If the tests are carried out on materials or structures presenting strong attenuation, the use of long wavelength is necessary. According to the acoustic, the intensity of the waves propagation in a solid decreases with the increasing of the distance from the origin. Moving away from the origin, the introduced energy distributes on surfaces with increasing extension. This is the case of the geometric attenuation. Moreover, the structural attenuation is defined as dispersion of energy under the form of heat, as an effect of the inelastic deformations, or as diffusion due to the reflections occurring when the waves meet discontinuities (like the passage from one type of material to another one). This characteristics can be found in stony materials, presenting:

- significant dimension of the grains (millimetres or centimetres);
- high porosity;
- interfaces between different materials;
- presence of micro or macro cracks.

In all the above mentioned cases the materials is characterized by several reflecting surfaces which can produce a strong attenuation of the waves propagation. In these cases the test can be significant if the wavelength is higher than the maximum dimension of the particles. For example, doing tests on a concrete beam, knowing that the aggregates have a diameter lower than 5 cm, ultrasonic tests should be carried out assuming a wavelength equal to 5 cm.

In the examples reported in the further paragraphs, the sonic waves are generated by percussion. Wave fronts are assumed to be spherical, according to the scheme in Figure 4.27.

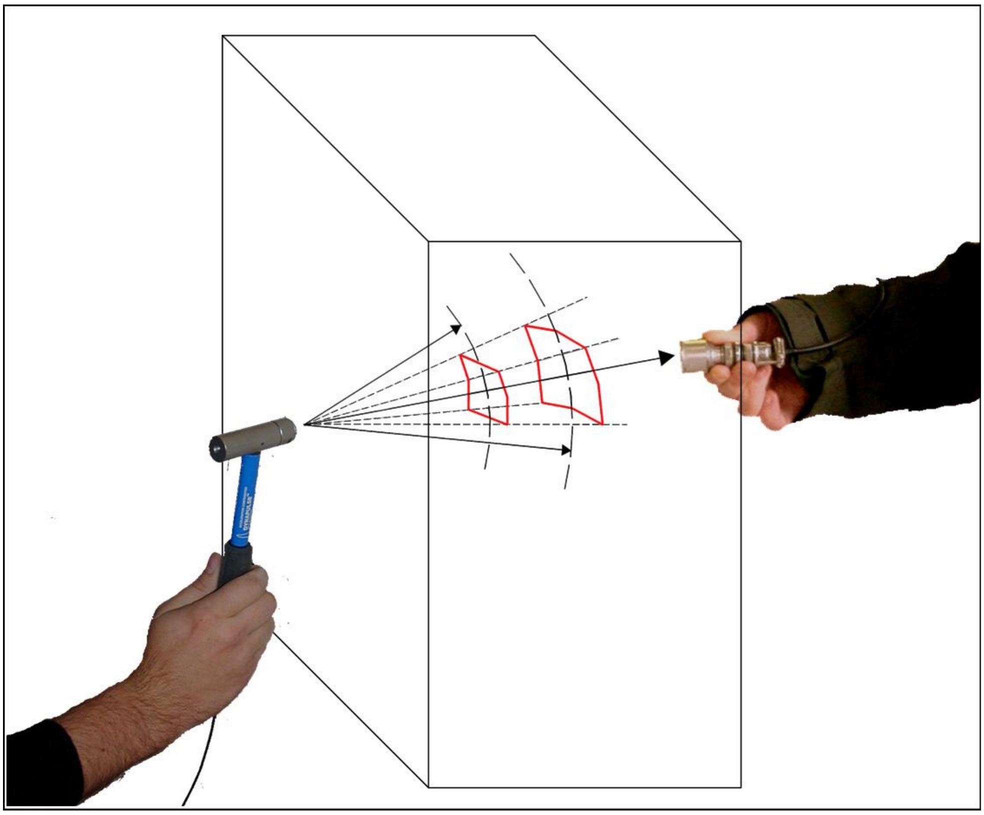


Figure 4.27: Increasing spherical fronts of the waves generated by an impact in a solid mean (scheme by the author).

Waves can have different characteristics. Two main types of waves are generated by percussion:

a) longitudinal waves (P waves). These are compressive waves. They corresponds to compressions and rarefactions of the mean in which they are travelling. During their passage, the particles oscillate in the direction of the propagation. They produce linear dilation and no angular sliding (Figure 4.28).

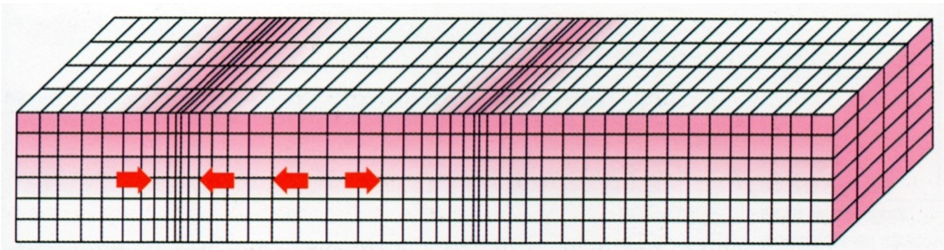


Figure 4.28: Representation of longitudinal waves propagation in a solid (taken from G. Pascale, "Diagnostica a ultrasuoni per l'edilizia", 2008, p. 23).

b) transversal waves (S waves). In this case, during their passage, the particles of the mean oscillate along a direction that is orthogonal to the direction of wave propagation. The deformation of the material produces only angular sliding (Figure 4.29).

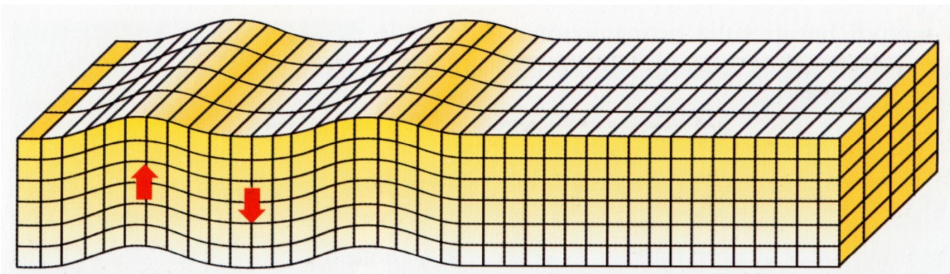


Figure 4.29: Representation of transversal waves propagation in a solid (taken from G. Pascale, "Diagnostica a ultrasuoni per l'edilizia", 2008, p. 24).

P waves have a higher velocity then the S waves and for this reason sonic tests are able to measure easily the compressive waves. There are different types of superficial waves which propagates only in the in the external layers of the solids. Rayleigh waves, for example, are generated by the reflection of the S waves on the surface of the material: they cause the movement of the particles along elliptical orbits, perpendicular to the external surface of the solid.

Their velocity is lower than the S waves velocity. Rayleigh waves will be taken into account for a part of the research that will be described in a further paragraph.

4.3.2 Technical specifications for sonic tests

Instead of their large use on historical buildings, sonic tests are not completely normalized. Standards and guidelines were set expressly for the application of ultrasonic tests to concrete structures. In these cases, simplifying concrete material to a fairly homogeneous, isotropic and elastic material, the test can be used to access some mechanical characteristics of the structure. The main standards are:

- RILEM recommendation, Les assais sur béton par la methode de l’auscultation dynamique, 1973; (RILEM, 1973)
- UNI 9524:1989, Calcestruzzo indurito – Rilievi microsismici mediante impulsi d’onde vibrazionali ad alta frequenza, in campioni o strutture di calcestruzzo semplice, armato e precompresso, settembre 1989; (UNI9524:1989, 1989)
- RILEM Recommendation TC 127-MS, MS.D.1 - Measurement of mechanical pulse velocity for masonry, in *Materials and Structures*, n. 30, 1997, pp. 463-466. (RILEM-TC 127-MS, 1997)
- ASTM C 597-02, Standard Test Method for Pulse Velocity Through Concrete, 2002; (ASTM-C597-02, 2002)
- EN 14579:2005, Metodi di prova per pietre naturali: determinazione della velocità di propagazione del suono; (EN-14579:2005, 2005)
- EN 12504:2005, Prove sul calcestruzzo nelle strutture – Parte 4: determinazione della velocità di propagazione degli impulsi ultrasonici, gennaio 2005; (EN-12504:2005, 2005)
- EN 13791:2007, Assessment of in-situ compressive strength in structures and precast concrete components (EN-13791:2007, 2007).

These standards are based on some relationships which bond the propagation velocity of the elastic waves through a material mean to its elastic properties. For an elastic, homogeneous and isotropic material, the velocity (*V*) of the elastic waves is directly correlated with the mechanical and physical characteristics of the material, according to the following relationship:

$$V = \sqrt{\frac{K \cdot E_d}{\rho}} \qquad (4.1)$$

where:

ρ = density of the material
E_d = Elastic Dynamic Modulus
And

$$K = \frac{(1-\nu)}{(1+\nu)\cdot(1-2\nu)} \qquad (4.2)$$

with ν = Dynamic Poisson Coefficient

According to ASTM C 597-02, the pulse velocity, *V*, of longitudinal stress waves in a concrete mass is related to its elastic properties and density as indicated in the following relationship:

$$V = \sqrt{\frac{E_d(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \qquad (4.3)$$

where:

E_d = dynamic modulus of elasticity,
ν = dynamic Poisson's ratio,
ρ = density.

Through the relationship reported in (4.3) and knowing the velocity of the longitudinal waves (V_l) and the transversal waves (V_t), the dynamic modulus of elasticity (E_d) can be calculated, as reported in (4.4):

$$E_d = V_l^2 \times \rho \times \frac{(1+\nu)\times(1-2\nu)}{(1-\nu)} \qquad (4.4)$$

where:

$$\nu = \frac{(r^2/2)-1}{(r^2-1)} \qquad (4.5)$$

with $r = V_l/V_t$

Experimental tests demonstrated that the difference between the Young Modulus (E) and the elastic dynamic modulus (E_d) increases in relation with the inhomogeneity of the studied material.

In a material with linear behaviour, like steel, the correspondence between E and E_d is really good. Considering the results obtained on concrete specimens, E_d is higher than E in a percentage comprises between 5% and 15%[161].

Sonic and ultrasonic tests are dealing with mechanical quantities. The acquisition of the data is based on the conversion of those mechanical quantities into electric signals. The devices used for the tests are equipped with piezoelectric sensors which are able to convert a mechanical impulse into an electric magnitude[162].

4.3.3 Description of sonic test configuration

As already mention in chapter no. 3 of the thesis, a signal is generated by percussion with an instrumented hammer or by an electrodynamics or pneumatic device (transmitter) and is received by means of an accelerometer (receiver), which can be placed in various positions. The resulting signals can be stored by a waveform analyser coupled with a computer or, thanks to the new virtual machines, stored into a personal computer connected with a digital acquisition module (Figure 4.30).

Figure 4.30: Devices used for sonic tests: a) instrumented hammer; b) accelerometer; c) computer (author's pictures).

[161] J. H. Bungey, *The testing of concrete in structures*, London; Surrey University Press, 1982. (Bungey, 1982)

[162] Emitter and receiver are usually formed by an instrumented hammer and an accelerometer for the execution of sonic tests. These devices works like load cells: they host a piezoelectric sensor that is able to take advantage of the properties of the crystalline organization of some materials, where the mechanical deformations are bonded to the displacement of the electric charges in the material. More information about the main sensors used for sonic and ultrasonic tests are available in G. Pascale, *cit*., 2008, *Chapter 5*, p. 51. (Pascale, 2008)

The data processing consists in measuring the transit time (T) between the transmitter and the receiver and in calculating the pulse velocity dividing the distance (d) between the devices by the transit time. According to the previous mentioned standards, velocity (*V*) is determined according to the following relationship:

$$V = \frac{d}{T} \qquad (4.6)$$

Where:

d = distance between the origin of the impact and the receiver

T = travel time of the sonic impulse.

The travel time of the generate pack of waves is related to the density of the medium in which it propagates (*Figure 4.31*).

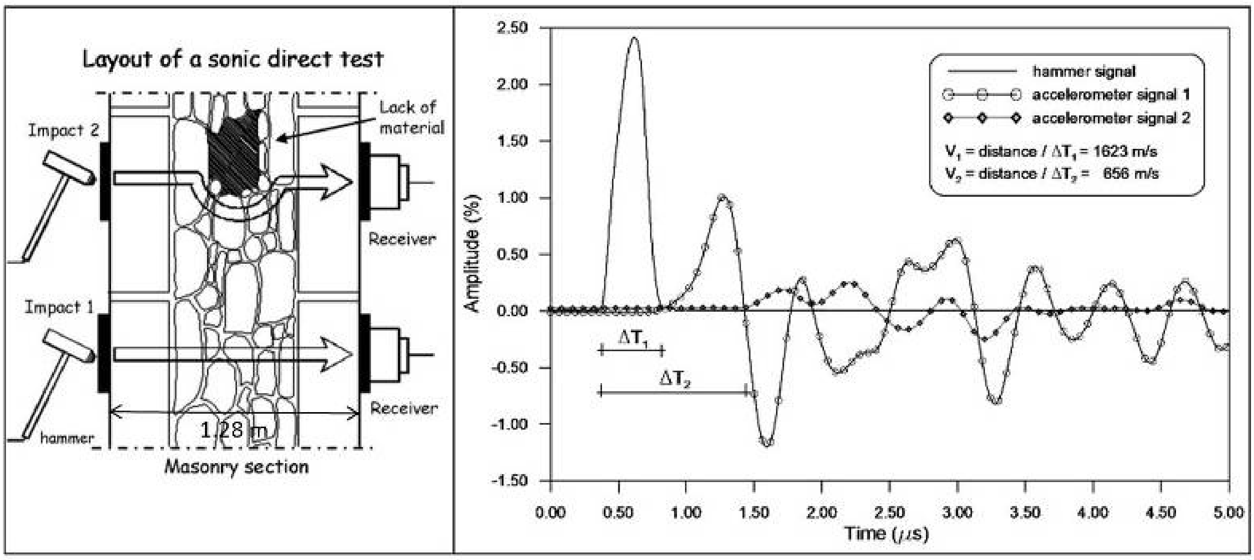


Figure 4.31: Example of data processing for the signals obtained on a masonry characterised by a lack of material inside the section (drawing and diagram by the author).

The main configurations of the test are based on the position of the emitter and the receiver (*Figure 4.32*). Three types of tests can be carried out:

1) *direct* (or through-wall) tests in which hammer and accelerometers are placed in line on opposite sides of the masonry element;
2) *semi-direct* tests in which hammer and accelerometers are placed at a certain angle to each other, and
3) *indirect* tests in which hammer and accelerometer are both located on the same face of the wall in a vertical or horizontal line.

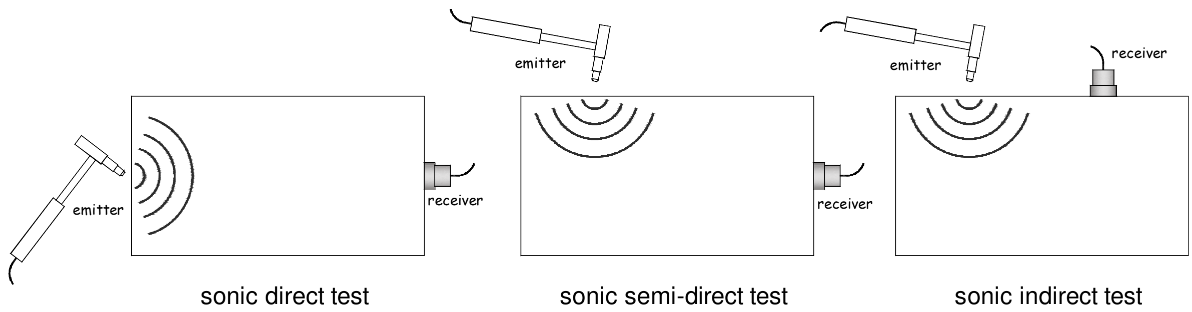


Figure 4.32: Three main configuration of the sonic test (drawings by the author).

According to the above described methodology, the result of the test can be referred to the single points where emitter and receiver are placed. Generally, for sonic direct tests, a grid of acquisition points is drawn on the opposite sides of the structure (*Figure 4.33*), having care to place them at the same height from the floor, so as to have an hypothetical straight line between the opposite points that is perfectly perpendicular to the faces of the structure. The closer is the distance between the points of the grid, the more precisely the single results can be representative of the areas between those points.

Figure 4.33: Example of grid of acquisition points used for sonic direct tests.

The aims of the test are: qualification of the masonry morphology; detection of the presence of voids and flaws and of crack and damage patterns; control of the effectiveness of repair by injection technique.

Commercial software provided with the device for Pulse Velocity Test are usually set for the main analysis of the signals obtained by hammer and accelerometer.

4.3.4 Calibration and validation of sonic tests

4.3.4.1 Strategy for calibration and validation

Results obtained by Pulse Sonic tests are strictly connected to the adequacy of the equipment and the conditions of the surface of the walls. The main problems are connected to:

- noise from partially damaged connections of cables;
- lack of adhesion between plaster (if present) and masonry;
- correct displacement of the accelerometer on rough surfaces: voids between the receiver and the external surface can contrast the correct acquisition of the waves arrival (*Figure 4.34*);
- scattering of the results (repeating the test for several times in the same position, it does not permit to obtain the same value for the sonic velocity).

Figure 4.34: Example of bad contact between the receivers and the rough surface of a stone

Accessibility: direct sonic tests provide the most complete information about the characteristics of the masonry section. If one side of the structure is not accessible, the correct configuration for direct sonic tests cannot be applied.

By the complementary use of other conventional techniques, the results achieved by Pulse Sonic Tests can be controlled. GPR are useful to identify the morphology of the masonry sections, whilst double flat jack tests can provide indications on the deformation properties of the external areas of the structure. Boroscopy or videoboroscopy are recommended to detect the presence of large voids (or cavity) identified by previous direct sonic tests.

4.3.4.2 Previous and on-going calibration and validation works

Usually the velocity obtained by Sonic Tests are calculated by taking into account the first arrival of the signal provided by the receiver. An on-going work is focusing on the interpretation of the signals in order to distinguish the different component of the sonic waves: the first arrival is supposed to represent the P-waves, but for Sonic Surface Tests also R-waves can be detectable. The correct interpretation of these components could improve the use of Sonic Surface tests on structure that cannot be accessed on both sides of the masonry.

An on-going research took into account the simultaneous use of three accelerometers to carry out sonic direct and surface tests (*Figure 4.35*). This layout allows to compare the waveforms acquired by the accelerometers and, as a consequence, the interpretation of the signals is safer.

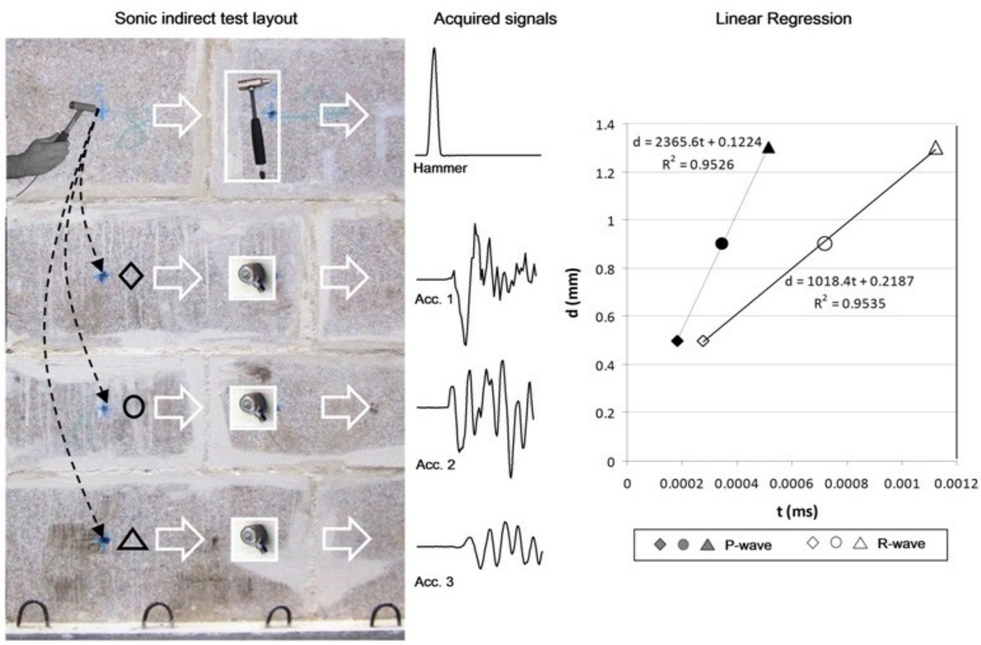


Figure 4.35: Layout, procedure and analysis of results.

A secure interpretation of the signals is particularly important for the application of sonic surface tests: the characteristics of the surface; the presence of joints, the distance between the emitter and the receivers are the main variables influencing the waveform. By a correct interpretation of the waveform obtained performing sonic indirect (or surface) tests, according to the theoretical background, P-waves and R-waves are detectable. The on-going research is focusing on the potentialities provided by the Rayleigh waves. Tests have been carried out on different samples in laboratory, measuring the propagation of sonic waves along vertical trajectories (Figure 4.35). The aim of the test is to estimate the mechanical properties of the investigated structure. The comparison between the modulus of elasticity estimated by compressive test is usually not comparable with the dynamic modulus of elasticity obtained by direct or indirect tests. Usually the velocity is determined considering the very first arrival of the signals provided by the emitter (V_p). A new approach can be represented by the use of the velocity estimated by R-waves (V_r). The research has started by applying the tests on few samples and for this reason the results are not enough to validate the effectiveness of this method, but the first elaborations are well promising (Figure 4.36) and new tests on laboratory samples and on site are scheduled.

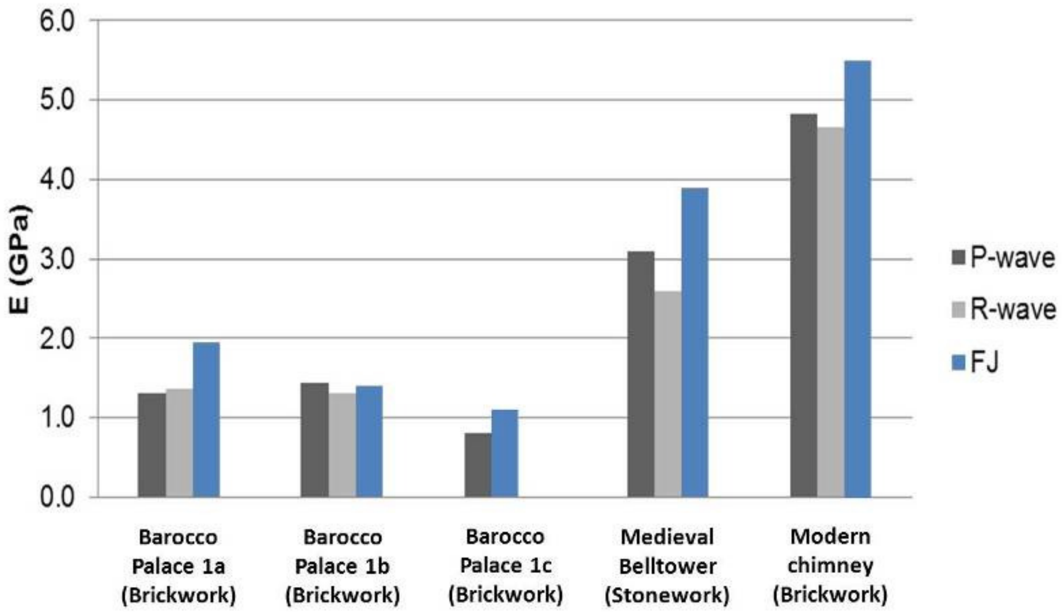


Figure 4.36: Comparison between Moduli of Elasticity obtained by double flat jack tests, P-wave and R-wave velocity

4.3.5 Application of sonic tests on masonry structures

4.3.5.1 Application to laboratory inspection

In general, Sonic Tests are mainly a non-destructive technique issued for characterizing qualitatively a masonry: since ten years it was also proposed to use them in order to control some repairing and strengthening processes. In laboratory, they can provide information about the state of damage of large samples (masonry prisms).

Sonic Tests are indicated to characterize masonry samples before and after injections. The choice of the most suitable mixture for injection require several calibrations: in laboratory samples can be injected by using different grouts and sonic tests can show a general and uniform increasing of the sonic velocity in those samples injected by a proper mixture and using a correct method.

4.3.5.2 Application to in-situ inspection

Sonic Tests can provide significant information concerning the morphology of masonry structures. Before performing other non-destructive (like GPR) or minor destructive tests (like single and double flat jack tests) on traditional structures, a preliminary overview of the state of conservation of the studied structures can be obtained by direct sonic tests. Figure 4.37 shows the result of sonic test carried out along the borders of a masonry mediaeval tower in Castelleone (near Cremona, Italy). The building had to be studied through radar and flat jack tests and a preliminary overview of the main discontinuities of the masonry sections was observed by applying direct sonic tests on two lines of points with a regular distance of 20 cm, placed along each side of the tower. The mean velocity is around 1500 m/s, indicating a good connection between the components of the masonry. This value increases in the edges of the tower, demonstrating a certain care in the building technology used for the tower. Low velocities, closed to the propagation velocity of sonic waves in the air (according to Table 4.3), were found in a large area of east side of the basement of the tower. This extended discontinuity could be put in relation with previous transformation of the structures of the building (historical maps indicates that other ancient buildings were built along this side of the tower and later demolished) and its presence could influence the mechanical behaviour of the tower (a concentration of stresses is expected in the near load bearing walls).

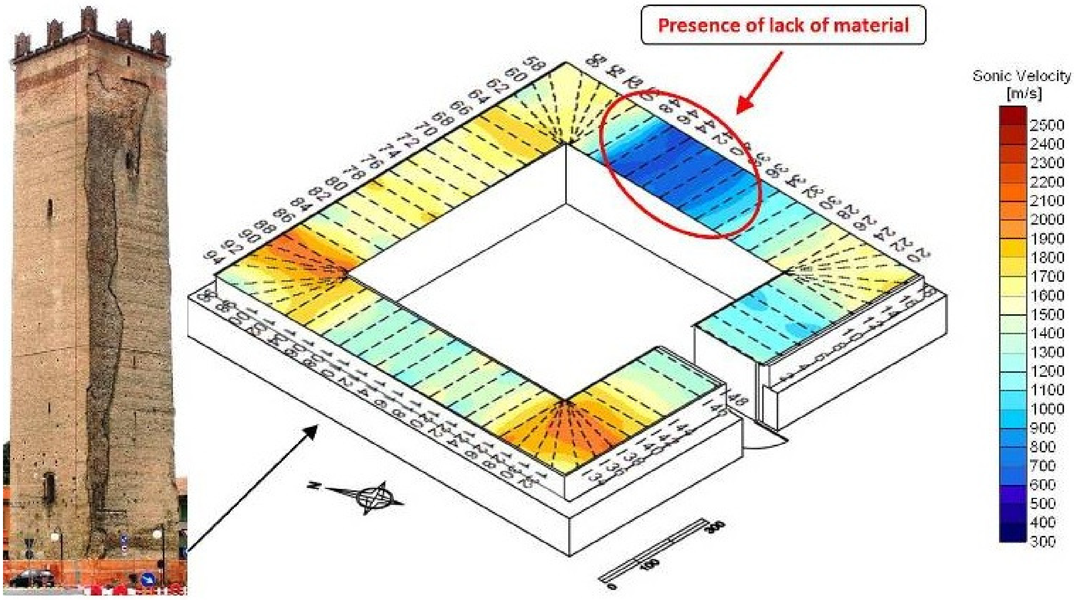
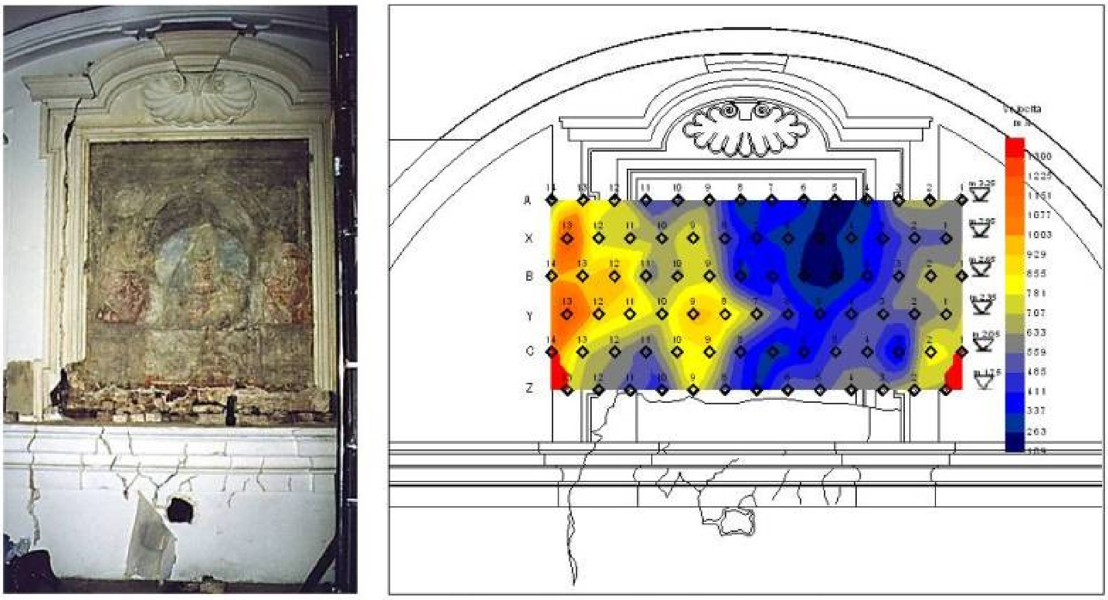


Figure 4.37: Distribution of the sonic velocities along the borders of the basement of a mediaeval tower

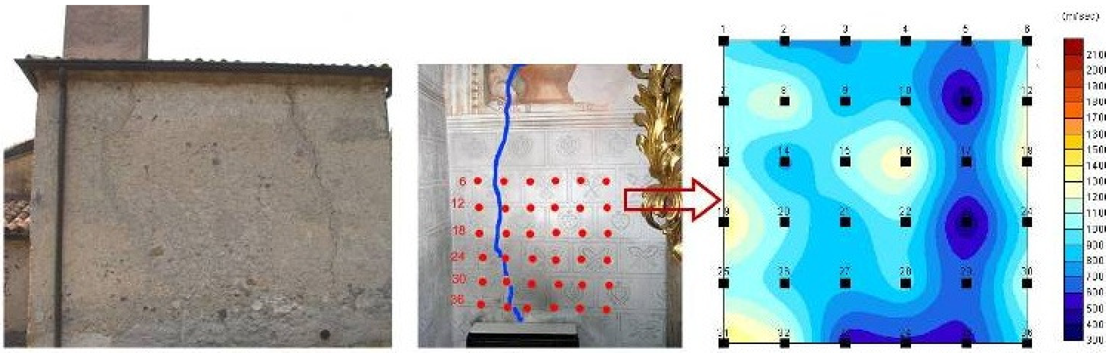
A first detection of the presence of faults and voids in the structure can be obtained by direct sonic tests. Knowing that the velocity of waves in the air is close to 348 m/s, this technique can identify the presence of discontinuities in large massive structures. This principle is useful to detect:

- hidden chimney, inserted in the body of the walls (Figure 4.38);
- discontinuities in the connections between the elements forming the section of the masonry (Figure 4.39);
- the presence of peculiar building characteristics, such as the use of infill between the external leaf of the structure or the periodical use of transversal elements crossing the masonry section and connecting the separated leaves of the wall (Figure 4.40).



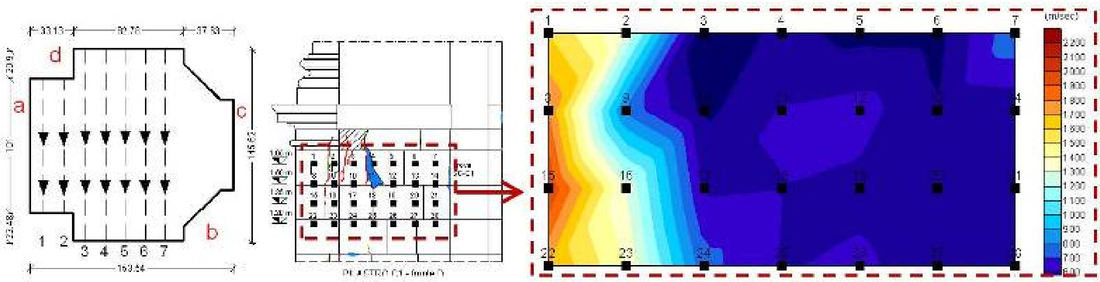
View of the investigated wall *Map of the velocities obtained by direct sonic tests*

Figure 4.38: Detection of a hidden chimney in a historical masonry wall (picture, drawing and graph by the author).



External and internal side of a damaged apse of a church *Map of the distribution of sonic velocity*

Figure 4.39: Detection of discontinuities in the connections between the elements forming the structure (pictures and drawing are a courtesy of A. Saisi).



Plan and lateral side of a damaged pillar with the test points *Map of the distribution of sonic velocity*

Figure 4.40: Detection of an internal infill in a pillar characterized by weak connections (drawing and graph by the author).

4.3.5.3 Identification of macroscopic discontinuities

The example reported in *Figure 4.38* is referred to an application of a sonic direct test on a wall of the Brera Palace in Milan. The wall is located in a room of the Academy of Fine Arts. Here one of the wall presents a decoration under the barrel-vault: it is a *sinopia* of a fresco (removed in the 20th century) realized in the 15th century by G. Foppa[163] (Figure 4.41). The traces of the fresco was restored in 1998, but the materials applied by the restorer had problems of adhesion with the support. In order to detect the morphology of the wall, a direct sonic test was requested.

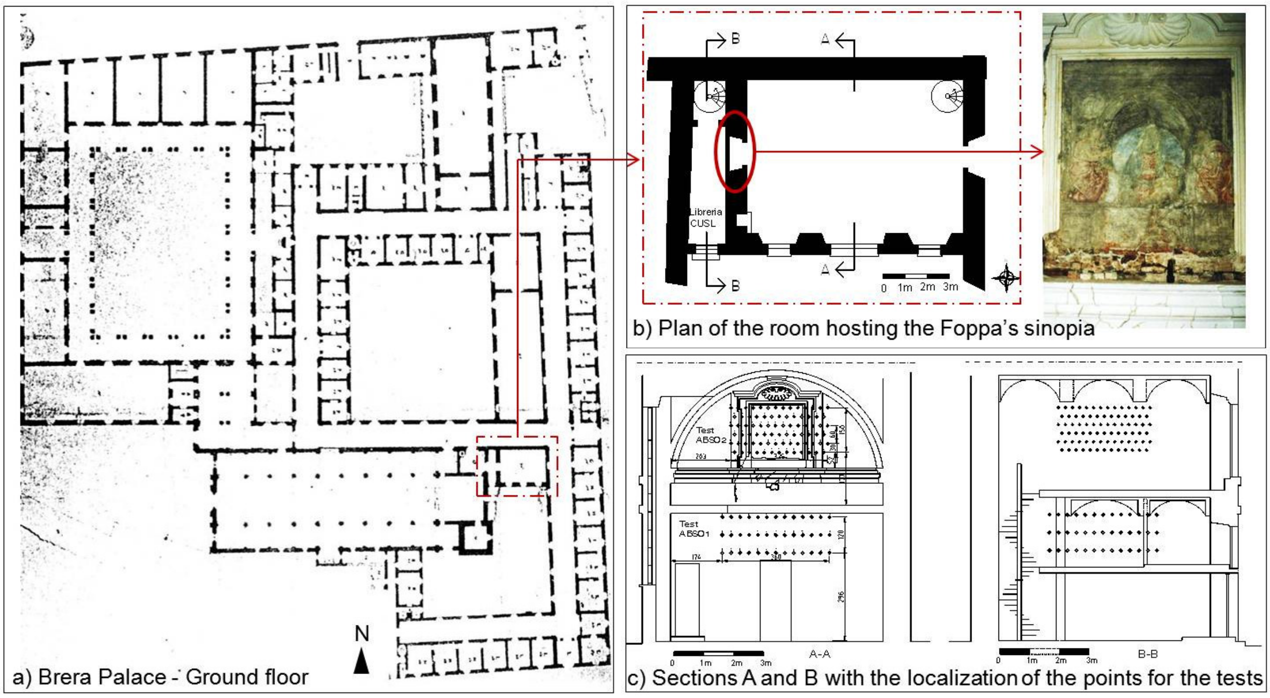


Figure 4.41: Localization of the sonic tests carried out in Brera Palace: a) Plan of the palace (plan taken from A. A. V. V., Progetto Brera, 1985, p. 106); b) the room hosting the Foppa's Sinopia (drawing and picture by the author); c) sections A and B of the room with the sinopia (drawing by the author).

The Superintendence enabled to carry out the test placing the accelerometer on the *sinopia* and the using the hammer on the opposite side of the wall, on a surface that had no decoration. The grid-points were indicated by placing a string-net on the *sinopia*. The results, compared to the

[163] More information about the history of the palace and this specific direct sonic test application are available in L. Cantini, *L'indagine sonica per la diagnostic delle strutture murarie: interpretazione dei risultati per alcuni casi di studio*, graduation work, Faculty of Architecture, Politecnico di Milano, 1998-1999.

geometry of the wall, showed high velocities in the points located near right and left borders of the grid. Over the moulding that frames the sinopia the velocities are lower. The points placed on the area of the sinopia the velocities are close to 348 m/s, the value associated to sonic waves traveling in the air. This result suggested that a cavity could be present behind the *sinopia* and for this reason a new direct sonic test was carried out in the lower part of the wall. The test showed again an area characterized by very low values of sonic velocity. Thank to these results an observation by an endoscope was carried out to confirm the information obtained by the direct sonic tests (see Figure 4.42). An ancient chimney was found and the cause of the problems observed by the restorers was identified: the presence of the chimney caused a fast hardening of the mixtures used on the sinopia, due to the circulation of air that accelerated the drying process.

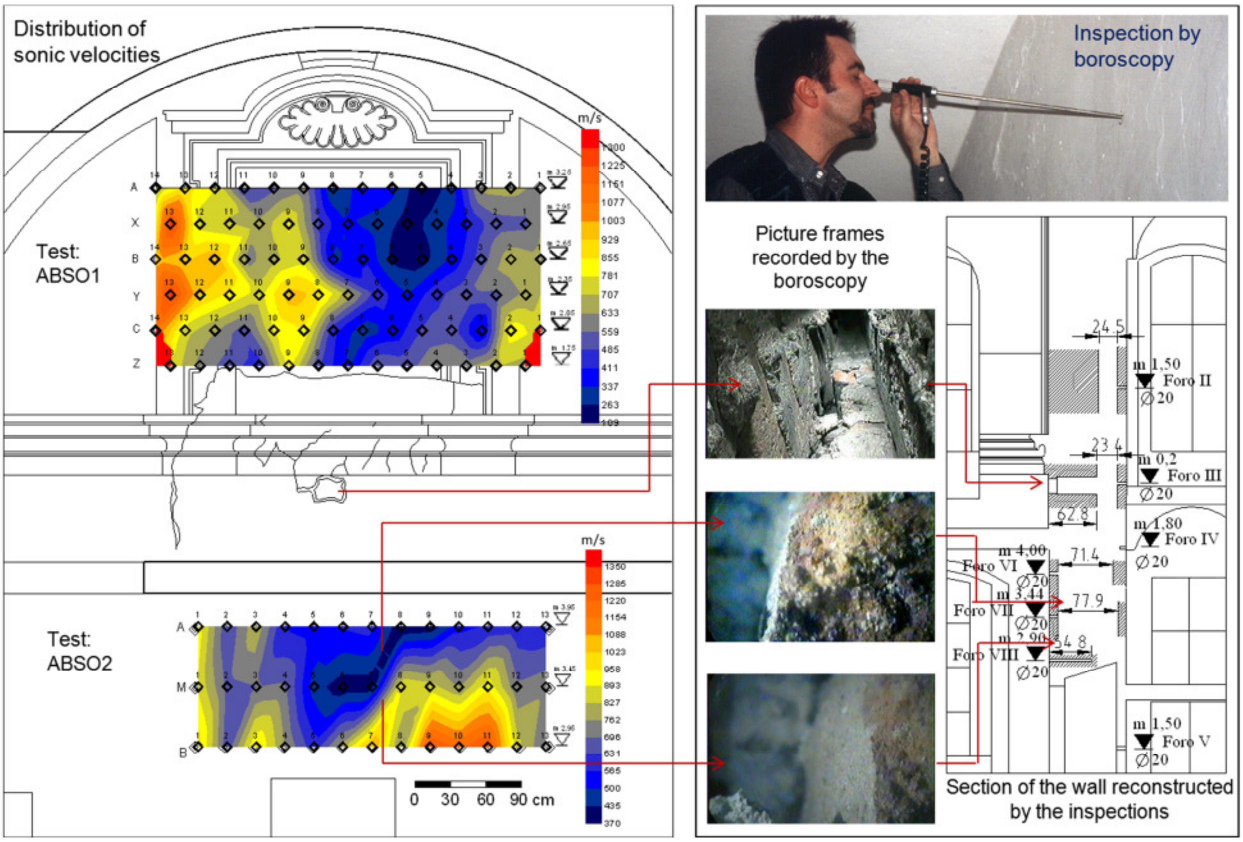


Figure 4.42: Results of direct sonic tests carried out in Brera Palace (Milan) and reconstruction of the section of the wall through the inspections carried out by boroscopy.

The presence of a large discontinuity in the masonry structure, such as a chimney, is detectable through direct sonic tests, according to the short distance between the points of the geometric grid used for the acquisition of the data: the paths of the sonic waves become longer when the discontinuity is placed between the emission point and the receiver.

4.3.5.4 Interpretation of the masonry morphology

Irregularities of lower dimension can be recognised by the same configuration of the test presented above, as shown in Figure 4.39. That case refers to the control of the connections of the walls of an apse in a church stroke by a seismic event near Garda lake (north Italy), in 2005. The church was characterized by several cracks on the vertical walls (Figure 4.43) and different direct sonic tests were carried out in order to evaluate the masonry morphology and the extension of the damage.

Figure 4.43: Views of the main cracks in a church damaged by the earthquake in the Garda Lake area (pictures by the author)

Compering the map of the velocities obtained in 5 different positions (Figure 4.44), the church seems to be characterized by a façade presenting a very different morphology of the masonry section, if compared to the other walls. Also test number 1, performed near an opening, showed results that are not similar with tests number 2, 3, 5. These differences can be connected to different building phases of the church. The distribution of the velocities for tests 2, 3 and 5 presents a common feature: some points with high velocity can reveal the presence of stone elements connecting the internal with the external layer of the wall.

Considering the results obtained by test number 5, the column of points presenting low velocity can be associated to the vertical crack near the edge of the apse: a deep crack can influence the propagation of the sonic waves during the test: here the east wall of the apse present a weak connection with the perpendicular walls: the test revealed a vulnerability of this part of the building.

The interpretation of the masonry morphology is here based on the qualitatively association of a range of velocities to the density of a composite structure.

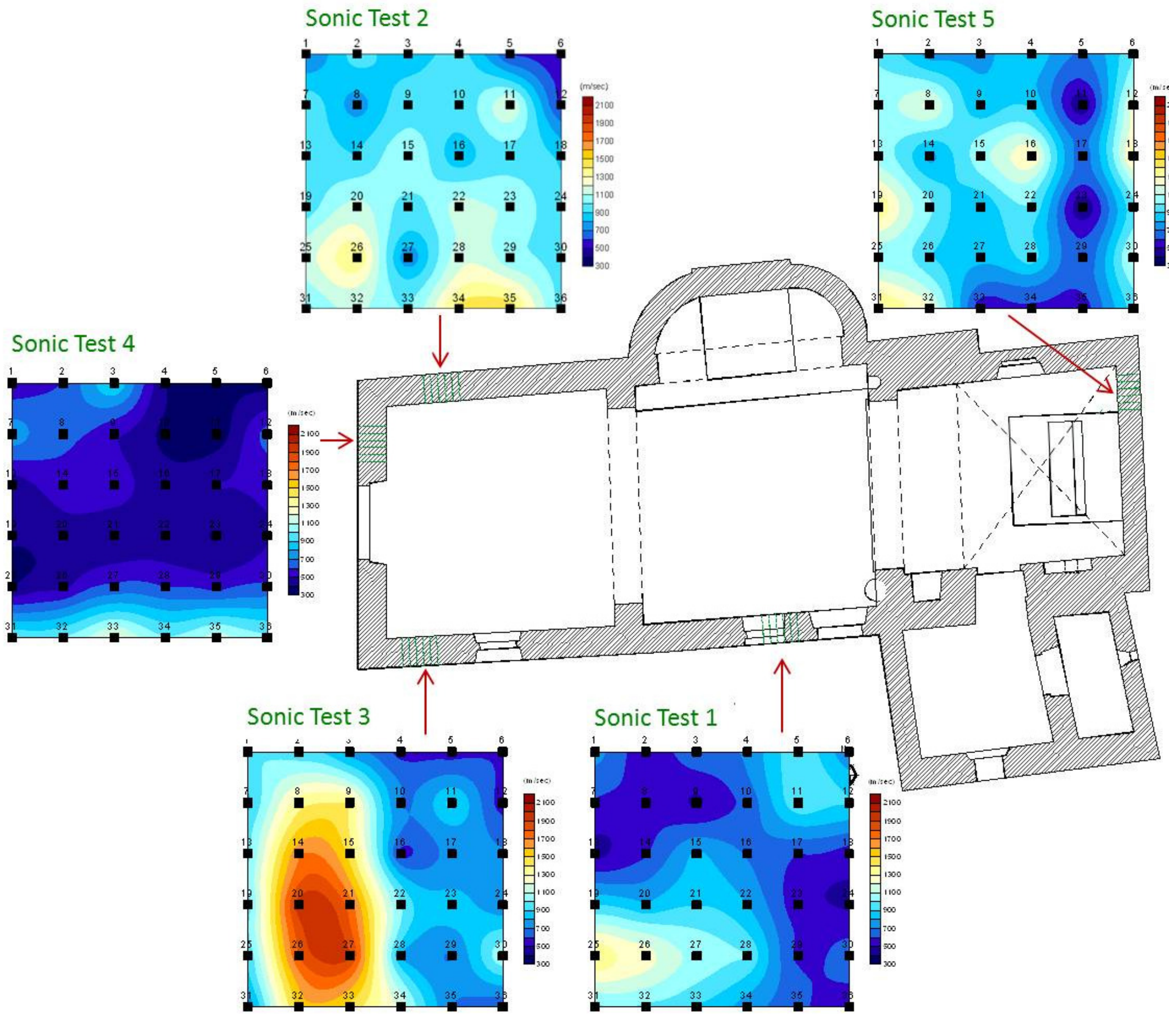


Figure 4.44: Distribution of the velocities obtained in 5 tests carried out on the different walls of a church near Garda Lake (layout by the author).

4.3.5.5 Application of sonic tests to control the strengthening interventions

On site, direct sonic tests can be used to qualify the injected area of damaged structures: performing the test before and after the injections, by the comparison of the results obtained in the two different conditions, the distribution of the mixture and its effectiveness can be estimated. Figure 4.45 shows a synthesis of the results obtained through the execution of a direct sonic test on a pilaster of the collapsed Noto Cathedral (in Sicily), before and after the injection of a strengthening mortar. The bar-chart reported in Figure 4.45b contains the comparison between the velocities measured in the two conditions: before (blue colour) and after (red colour) injecting. Each bar-chart represents a line of the geometric grid used for the test. Through the distribution of the velocities by the colour maps reported in Figure 4.45c, the high increasing of the velocities right part of the grid area is evident. After the injection the whole studied area showed an increasing of the velocities (from a mean value of 1189 m/s to 1566 m/s, but the concentration of the strengthening mixture in the right part of the grid indicates a discontinuity, whilst the injecting procedure should provide a more uniform distribution of the mixture inside the structure. This study is useful for the identification of the right injecting procedure, able to guarantee a more homogeneous distribution of the injected mixture in the wall.

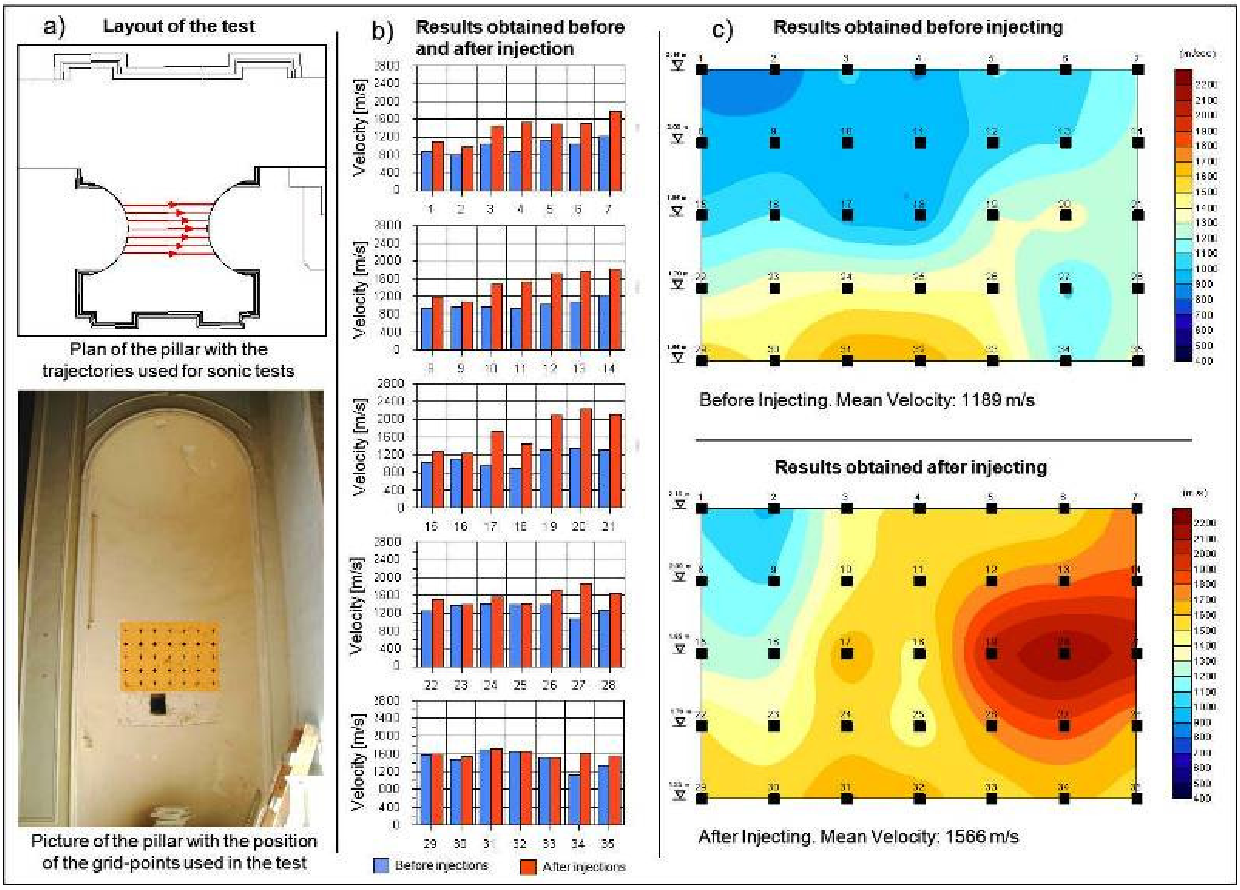


Figure 4.45: sonic direct tests carried out on a damaged pillar before and after injections.

4.3.6 Application to assessment of intervention strategies

Pulse sonic tests are a useful non-destructive technique to address the study on traditional masonry structures. The distribution of sonic velocities is a valid parameter to identify the areas of the structure characterised by extended discontinuities, damages or large voids: positions that cannot be properly used by other tests, such as single and double flat jack tests. Moreover the detection of areas affected by irregularities and inhomogeneities can be indicated for further investigations, using more refine techniques, like GPR or minor destructive techniques like boroscopy.

Recent applications of sonic and ultrasonic tests were carried out on buildings presenting damaged structures. The control of the extension of the damage, if present, is one of the main goals of this research. In the next examples, the depth of the cracks on monolithic structures and the variation of the density of the materials in masonry sections will be presented.

4.3.6.1 Estimation of the depth of cracks in monolithic stone elements

This ultrasonic test is carried out through the traditional ultrasonic device, composed by two transducers, one emitting the impulse and one for receiving it, and an acquisition unit. The test was developed to detect the depth of cracks in concrete structures. According to the theoretical background[164], well documented for this kind of application, the test is based on some relationships between the sonic velocity of the material in its undamaged condition, the distance between the transducers and the velocity measured leaving the crack between the transducers, as shown in Figure 4.46.

Maintaining the transmitter and receiver transducers at a constant distance over a crack and knowing the characteristic sonic velocity of the stone, the depth of the crack can be detected by a defined relationship between the distance of the transducers (*2x*), the travel time measured by the test (T_c) and the given sonic velocity of the undamaged material (T_s).

[164] J. H. Bungey, *The testing of concrete in structures*, London : Surrey University Press, 1982. (Bungey, 1982)

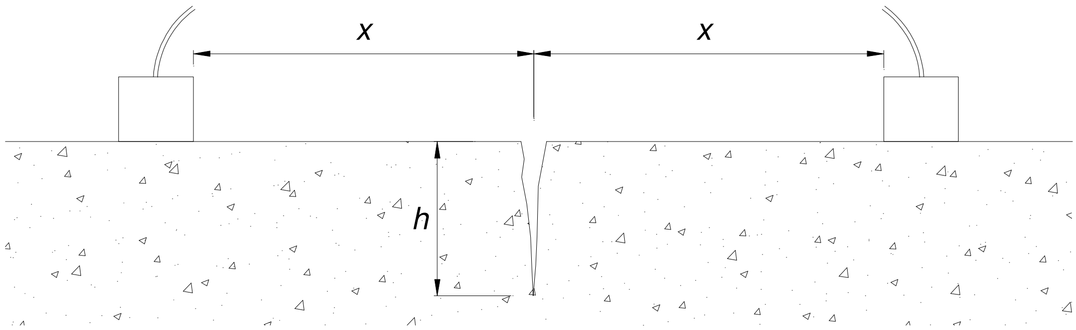


Figure 4.46: Configuration of the position of the transducers for the detection of the crack depth by ultrasonic test (layout by the author).

The depth of the crack (*h*) is determined through the following relationship:

$$h = x \cdot \sqrt{\left(\frac{T_c^2}{T_s^2} - 1\right)} \qquad (4.7)$$

Where

T_s is the surface travel time of the wave in the undamaged condition of the material (with the distance between the transducers equal to *2x*), according to the following

$$T_s = \frac{2x}{V} \qquad (4.8)$$

T_C is the surface travel time of the wave with the presence of the crack (with the distance between the transducers equal to $2\sqrt{x^2 + h^2}$), according to the following:

$$T_c = \frac{2\sqrt{x^2 + h^2}}{V} \qquad (4.9)$$

This kind of application was used to control the state of damage of a stone column (Figure 4.47) in a church struck by an earthquake in the area of the Garda Lake. The column presented a diffused crack pattern formed by several vertical cracks. The test was carried out on the main vertical cracks, reporting test points along them with a constant distance of 10 cm. The indirect ultrasonic test was previously carried out on a column made by the same material, without cracks, in order to obtain the travel time in an undamaged condition of the material. Then the test was carried out following the vertical development of the main cracks. According to the relationship reported in (4.7), the depth of the cracks was calculated for each tested point. The results were represented graphically as shown in Figure 4.48.

Figure 4.47: View of the damaged column, presenting a diffused crack pattern and application of the transducers for the ultrasonic test (author's pictures).

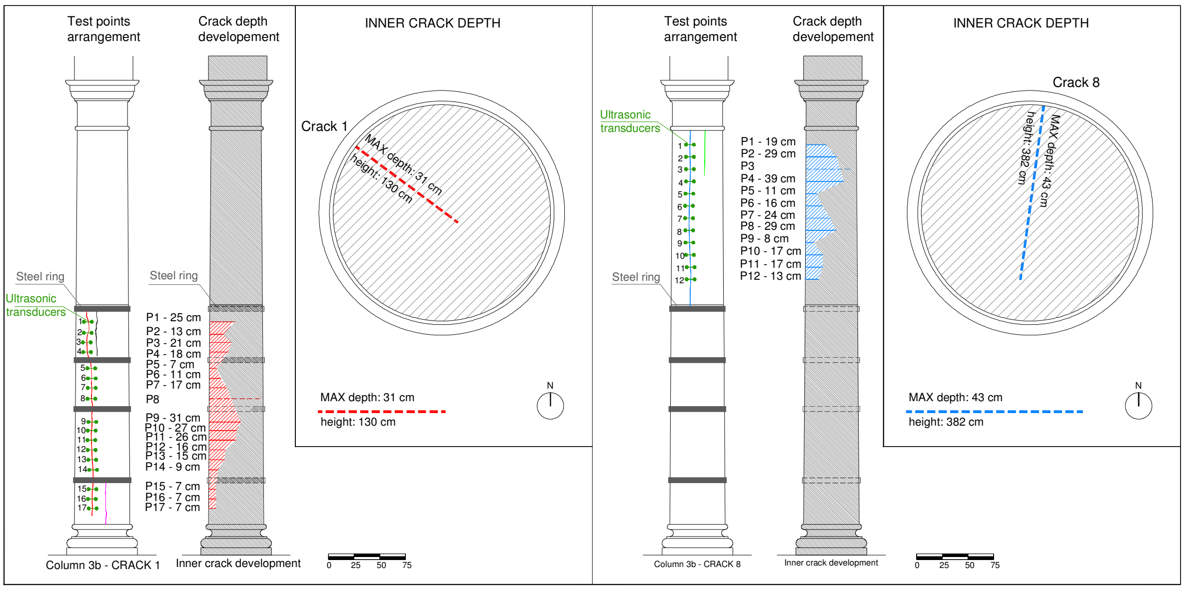


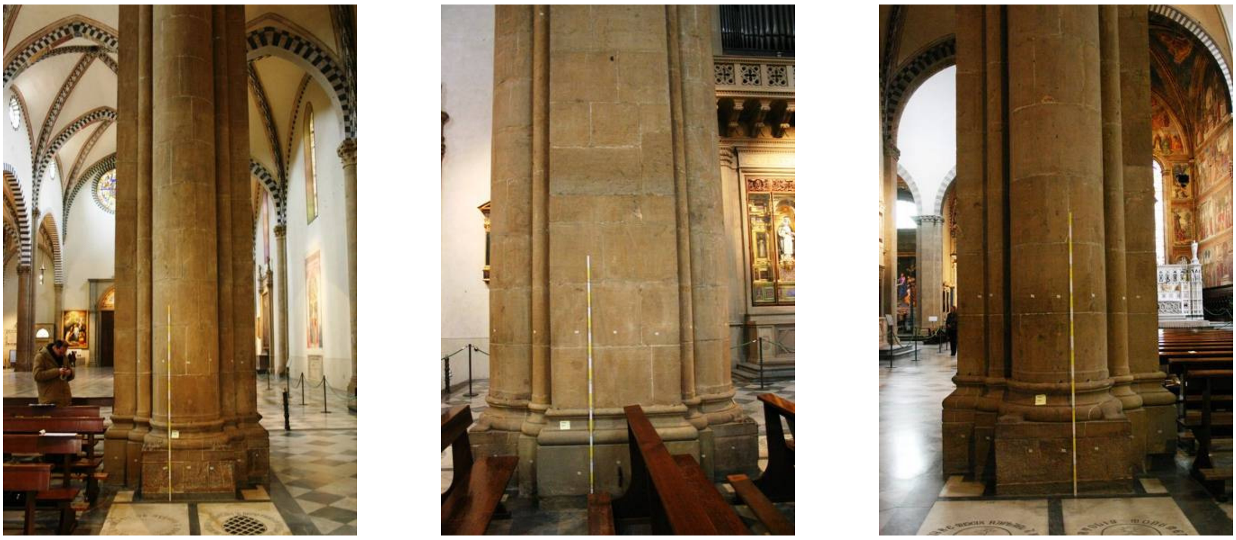
Figure 4.48: Representation of the depth of the cracks estimated trough the application of indirect ultrasonic tests (laypout by the author).

The results were useful to justify the maintenance of the iron rings along the shaft of the column. In some points the depth estimated by the ultrasonic tests was higher than the radius of the column, condition that indicates a serious damage for this structural element.

4.3.6.2 Qualitative evaluation of the extension of the damage in masonry structures.

Direct sonic tests can be used to have a qualitative idea of the masonry morphology along the vertical development of the structures.

In Santa Maria Novella, one of the main mediaeval churches in Florence, the differences between the basement of a pilaster and its shaft was evaluated through a grid of points, displayed horizontally (one for the basement level and one for the shaft), along the borders of the structure. The aim of the test was to control the building technique used for the pillar: it is supposed that this kind of structures present a base realized by a monolithic element or few compact blocks, whilst the shaft is characterized by the presence of different layers, formed by compact and shaped stones for the external part and more incoherent materials for the internal one.



a) north side of pillar P3w b) east side of pillar P3w c) south side of pillar P3w

Figure 4.49: Partial views of 3 sides of the pilaster in Santa Maria Novella characterised by direct sonic tests on the basement and on the shaft (author's pictures).

A grid of 28 points was used for the basement, whilst 20 points were used for the upper level on the shaft of the pilaster. Direct sonic tests were carried out along the trajectories indicated in Figure 4.50. The velocities were calculated for each trajectory connecting the points on opposite sides. These data were then used to determine the mean value between each crossing point of the net formed by the intersection of the trajectories. A mean value was obtained and associated to each point of intersection of the net. These data were elaborated by a software that is able to calculate the mean values between the velocities associated to the points of intersection, in order to obtain a colour map of the velocities. The result is a map showing the distribution of the velocities in the horizontal section of the structure.

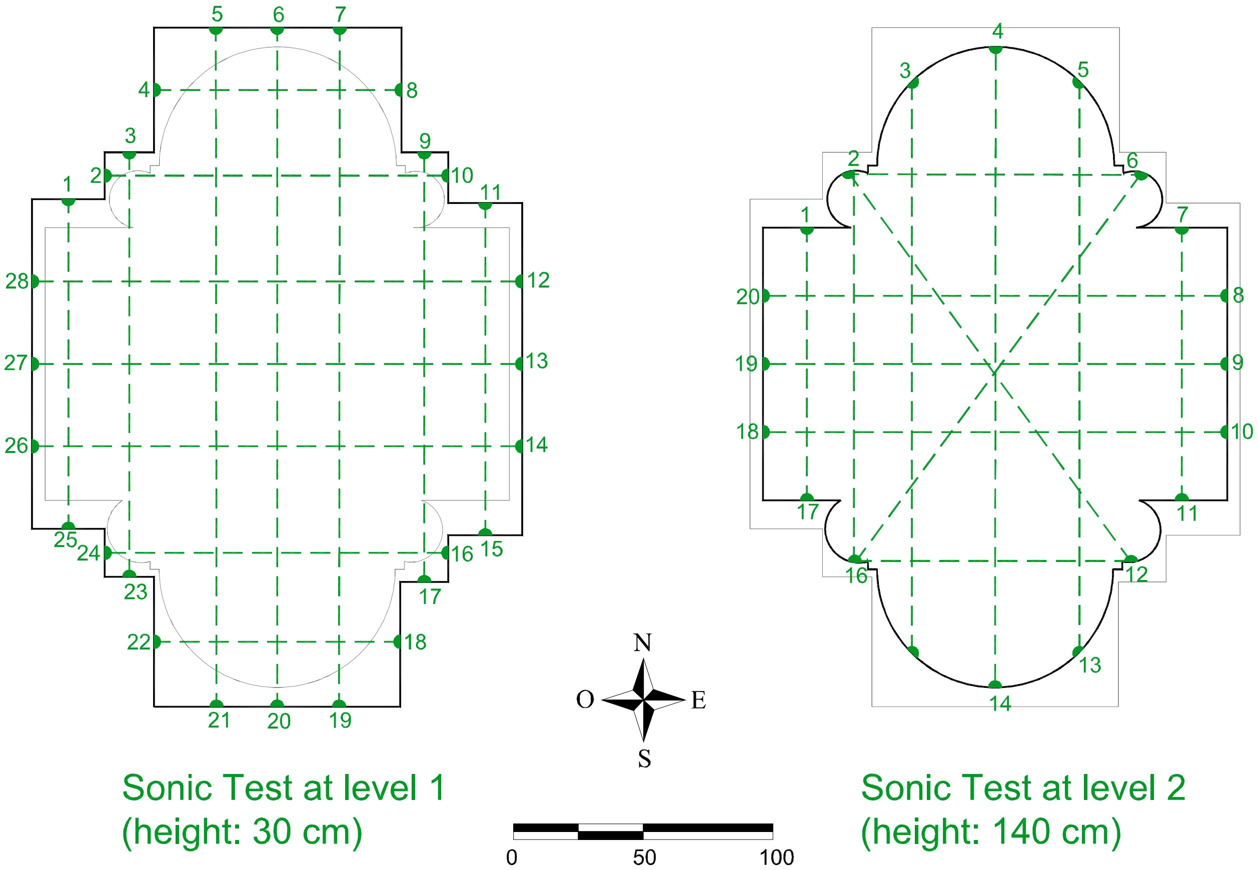


Figure 4.50: Layout of the tests carried out on the pilaster (laypout by the author).

The results of the tests show two levels of the same structure presenting different characteristics (Figure 4.51). Both levels are characterized by fairly uniform sonic velocities, with values which do not indicate the presence of internal discontinuities. The velocities in the basement are anyway higher than the value found in the upper level, indicating that the shaft was realized with different layers. The mean velocity in the basement is around 2700 m/s, whilst the mean value in the shaft is around 1700 m/s.

The idea of a qualitative representation of the distribution of the velocities in a horizontal section was used to study other massive structures. This application requires the accessibility on each side of the structure for the acquisition of a large number of tests, but is not complicated as a sonic tomography (see chapter no. 3) and allow to obtain a significant representation of the morphology of the masonry structure.

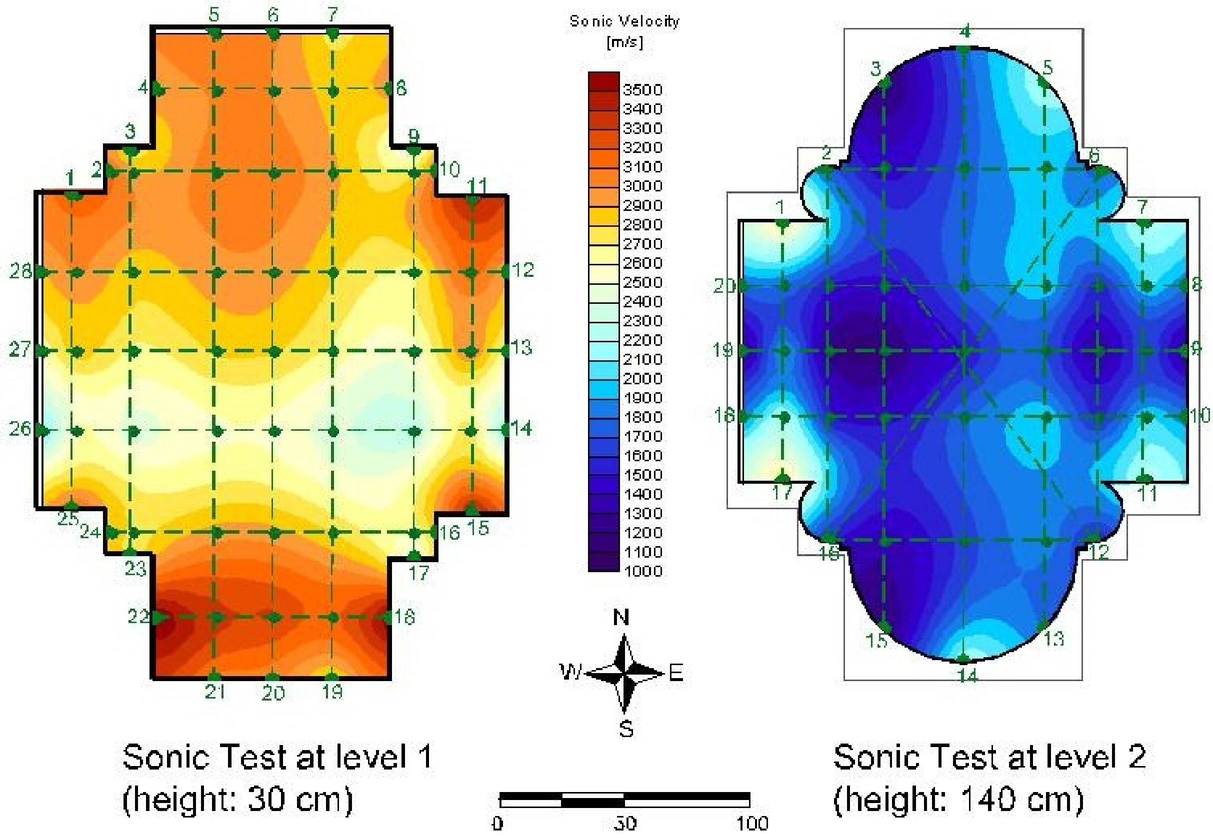
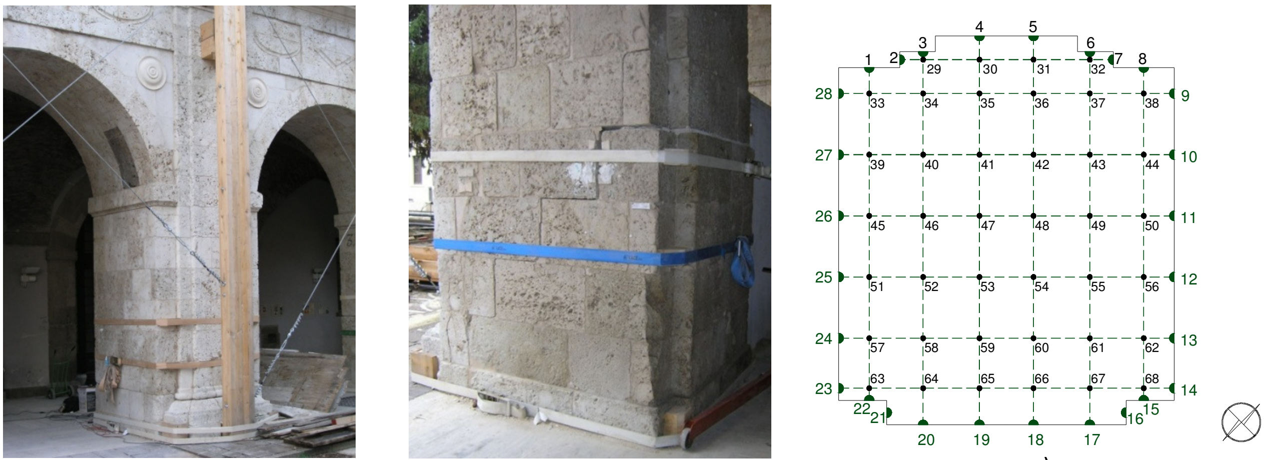


Figure 4.51: Distribution of the velocities in the horyzontal sections of the pilaster, at two different levels (layout by the author).

In the next case, a similar configuration of the test was used on two different pillars of the courtyard of the Spanish Fortress in L'Aquila (Figure 4.52). The Building was struck by the 2009 6th April earthquake. Diagonal cracks were visible on the pilasters and sonic tests had the aim to evaluate the extension of the damage in the internal part of the structure.

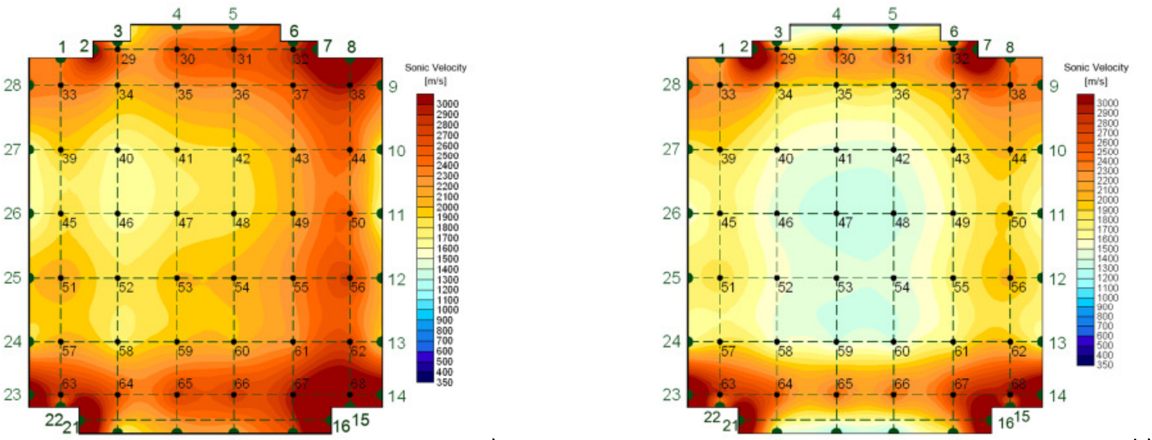
The two pillars taken into account had the same geometry but one (pillar no. 4) did not present any crack pattern, whilst the other one (pillar no 6) had important diagonal cracks (Figure 4.53a and b). On pillars no. 4 and no. 6 direct sonic tests were performed reporting 28 points around the borders (Figure 4.53c)of the structure at a height of about 126 cm from the floor. After computing the average value obtained for each intersection between the main trajectories, a plan-map of the distribution of the velocity was created (Figure 4.54). Pillar no. 4 reviled an homogeneous distribution of the sonic velocities. The results on pillar no. 6 (widely damaged by the earthquake) showed a structure characterized by some discontinuities in the internal masonry layers.

Figure 4.52: Views of the pilasters of the courtyard of the Spanish Fortress in L'Aquila (author's pictures).



a) b) c)

Figure 4.53: a) Pillar no 4; b) pillar no. 6; c) test layout reported on a horizontal section of the pillar (pictures and layout by the author).



a) b)

Figure 4.54: comparison between the morphology of the horizontal section of pillar no. 4 and no. 6, obtained by direct sonic tests (graphic layout by the author).

The accuracy of the results is confirmed by the sonic tomography carried out on the same pillars. These tests, very time consuming and based on the implementation of special algorithms, were executed by a research unit from the Dept. of Structural Engineering and Transportation of the University of Padua[165].

Tomographies are based on a combination of sonic acquisitions over several directions in the same section. For both pillars (no. 4 and no. 6) a grid of six points for each side of the structure was used. The trajectories used for the acquisition are reported in Figure 4.55 Each impact generated on one side of the pillar was simultaneously acquired by six receivers placed on the opposite side.

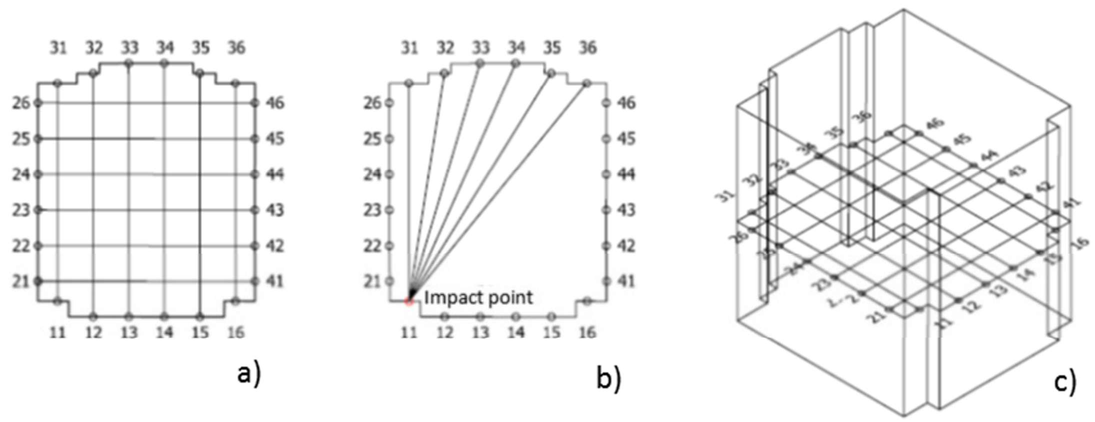


Figure 4.55: Test layout used for sonic tomographies applied on pillar no. 4 and no. 6 of the courtyard.

The results show that pillar no. 4 maintain higher velocities than pillar no. 6 (Figure 4.56). Even though the differences between the results obtained by direct sonic tests and sonic thomographies, both techniques indicated the different morphology of the two pillars. The interpretation of the data is based on the comparison between the supposed undamaged structure with the one presenting the crack pattern. In both tests the presence of the cracks in pillar no. 6 influenced the correct wave propagation in the masonry structures. The extension of the damage is not clearly detectable in both cases, but the differences between the sonic

[165] Detailed descriptions about this test campaign are available in L. Binda, C. Modena, F. Casarin, F. Lorenzoni, L. Cantini, S. Munda, *Emergency actions and investigation on Cultural Heritage after the l'Aquila earthquake: the case of the Spanish Fortress*, in *"Bulletin of Earthquake Engineering"*, Special Issue: *L'Aquila 2009*, 2010. (Binda L. M., 2010)

velocities found in the two conditions (damaged and undamaged) are proving the decreasing of the mechanical performance of the damaged pillar.

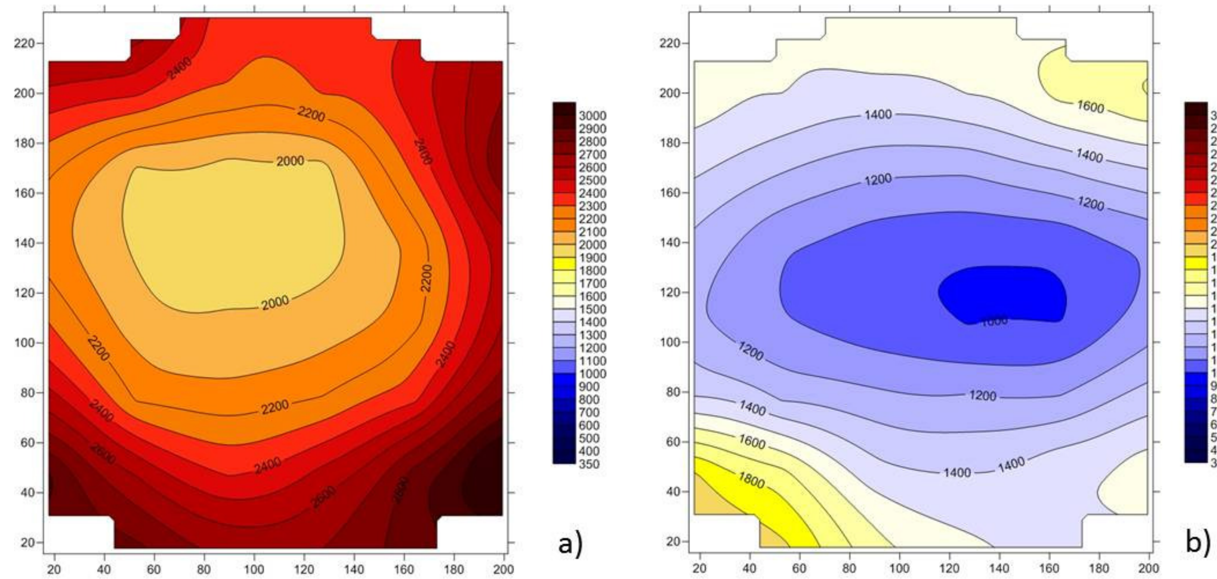


Figure 4.56: Results of the sonic tomographies carried out on a) pillar no. 4 and b) no. 6 (courtesy of professor C. Modena).

Sonic thomography and direct sonic tests trough crossing trajectories supported the investigation on two load bearing structures, showing that one of them reported an extended damage after the earthquake. Comparing the results reported in Figure 4.55b and Figure 4.56b, the distribution of the results appear to be very different. The mean values obtained by direct sonic tests along crossing trajectories maintain a distribution with lower velocity near the visible cracks and showing a significant decrease of velocities in the central area of the horizontal section of the pillar. The result obtained by sonic tomography reveal a large decrease of the velocity for a large part of the pillar, from the external layers near the cracks to the central part.

4.4 Example of the complementary use of thermovision and sonic tests to qualify masonry structures

The well promising results obtained through the application of direct sonic tests along crossing trajectories was used to qualify the pillars of the St. Biagio Church in the historical centre of L’Aquila, seriously damaged during the 6th April earthquake in 2009. The church presented a diffused crack pattern and a partial collapse of the upper part of the façade (Figure 4.57). Nevertheless, the building faced the seismic event without reporting other collapses. The problem for the designer was to study the state of conservation of the survived structures of the church, in order to identify the extension of the damages and the eventual vulnerable elements.


Figure 4.57: External and internal view of the St. Biagio Church in L'Aquila

As mentioned in paragraph 4.2.7.2, thermographic tests were applied to the main structures of the church (pillar A, D. G, H) to study the masonry texture. In a second time, direct sonic tests were carried out on each pillar of the church (see Figure 4.58).

After heating the surfaces of the main structures for 2 hours, the IR camera was able to observe a distribution of the temperatures, during the cooling phase, that allowed to recognize clearly the regular stone blocks which formed the masonry texture of the pillars. The same study was carried out by applying RADAR tests. Thanks to the different conductivity of electromagnetic waves, between stones, bricks and mortar joints, also radar tests were able to show the texture hidden by the plaster (see Figure 4.59).

The results presented in Figure 4.59 show that the efficacy of the thermovision is validated by the RADAR technique. Moreover the thermographic tests were significant thanks to the uniform heating provided by the heater (a convector): the whole area of the pillar, recorded in different frames by the IR camera, was later merged together by mosaicking the single thermograms. Compared to this procedure, the application of RADAR tests was more time-consuming (the antenna had to be moved along vertical paths on the surface, using a scaffolding) and the data elaboration requires long periods for processing the acquired signals.

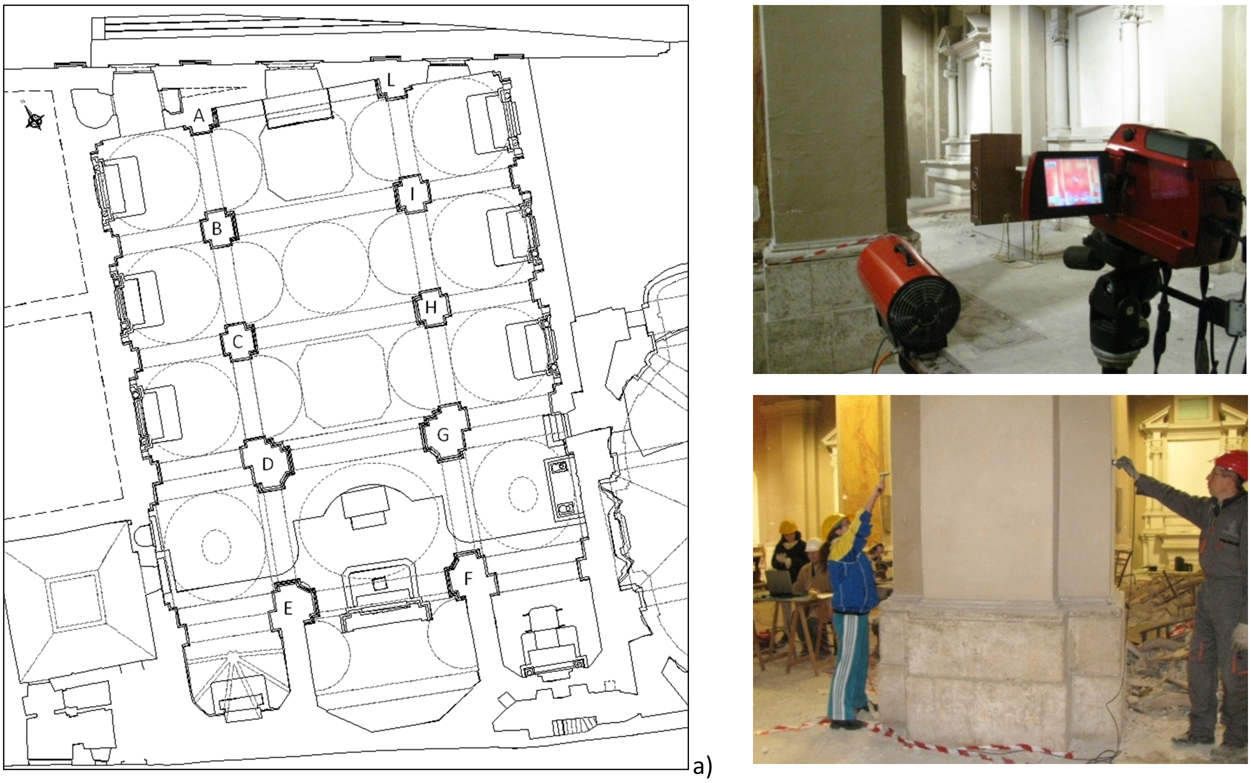


Figure 4.58: a) plan of the church of St. Biagio; b) execution of a thermographic test; b) execution of a direct sonic test.

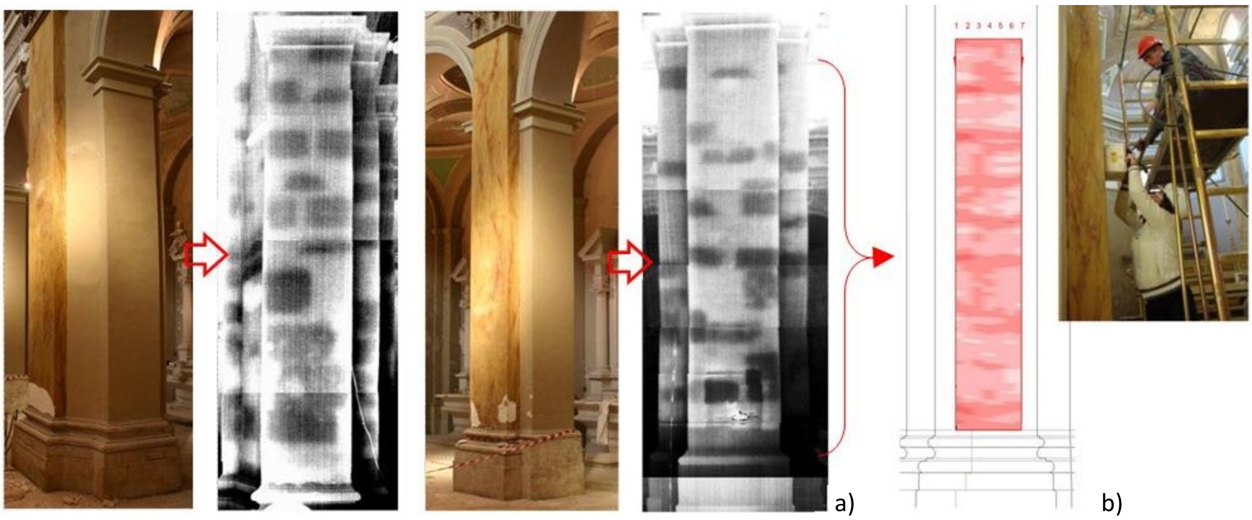


Figure 4.59: Results of the a) thermographic tests and comparison with the result obtained by b) RADAR test: in both cases the masonry texture was identified.

The masonry texture of the pillars was the first step for a complete knowledge of the building characteristics of the pillars. In the same time, the crack pattern survey of the structural elements of the church was carried on. The pillars presented, in some cases, vertical and diagonal cracks near the basement. In this case the request of the designer focused on the identification of extended damages inside the pillars. Sonic tests, along horizontal crossing trajectories, repeated vertically for 6 levels on the pillars (taking into account the basement and the first part of the shaft), were carried out (Figure 4.60). The aim of this configuration of the test was the identification of large discontinuities in the horizontal section detectable for each tested level.

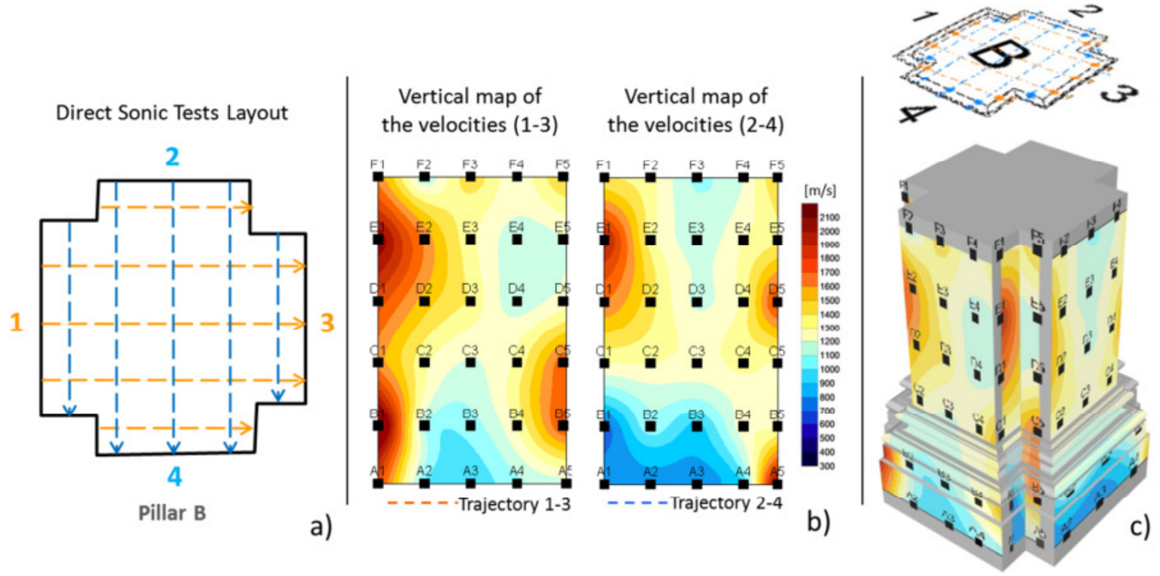


Figure 4.60: Example of the layout used to carry out direct sonic tests on pillar B: a) layout of the crossing trajectories; b) map of the velocities obtained for each tested path; c) 3D representation of the velocity maps (layout by the authors with the supports of the students C. Gervasoni and N. Ortolan).

The common representation of the results, through the colour map of the velocities, was here really complicated. The inhomogeneous distribution of the values could have different interpretations. The presence of stone slabs on the basement (with a thickness of 4 cm and in some cases presenting evident detachments); the cross shape of the pillars; the presence of mouldings in the basement. These characteristics could be associated to the low sonic velocity found in same area of the pillar, as shown in Figure 4.60c.

In order to provide more detailed results, the data acquired by direct sonic tests were used to estimate the mean value of the velocity in each point of intersection between the crossing trajectories. The result was a map of the velocities for each vertical level of the test: two horizontal levels corresponding to the basement and four levels in the shaft. The horizontal velocity maps presented in Figure 4.61 describe the morphology of the horizontal section of the pillars, in 5 different levels. These results were not obtained by tomographic tests, but the simple combination of the two perpendicular paths used for each direct sonic test allow to achieve a suitable result with significant information. By comparing the pillars presenting few cracks and high, uniform velocities with the pillars characterized by areas with low velocity, the identification of the damaged structures was possible. According to the information presented in Figure 4.61, pillar I shows the best condition (high and fairly uniform velocities), whilst pillar D presents a progressive decrease of velocities from the beginning of the shaft to the last level (from 3rd to 6th level).

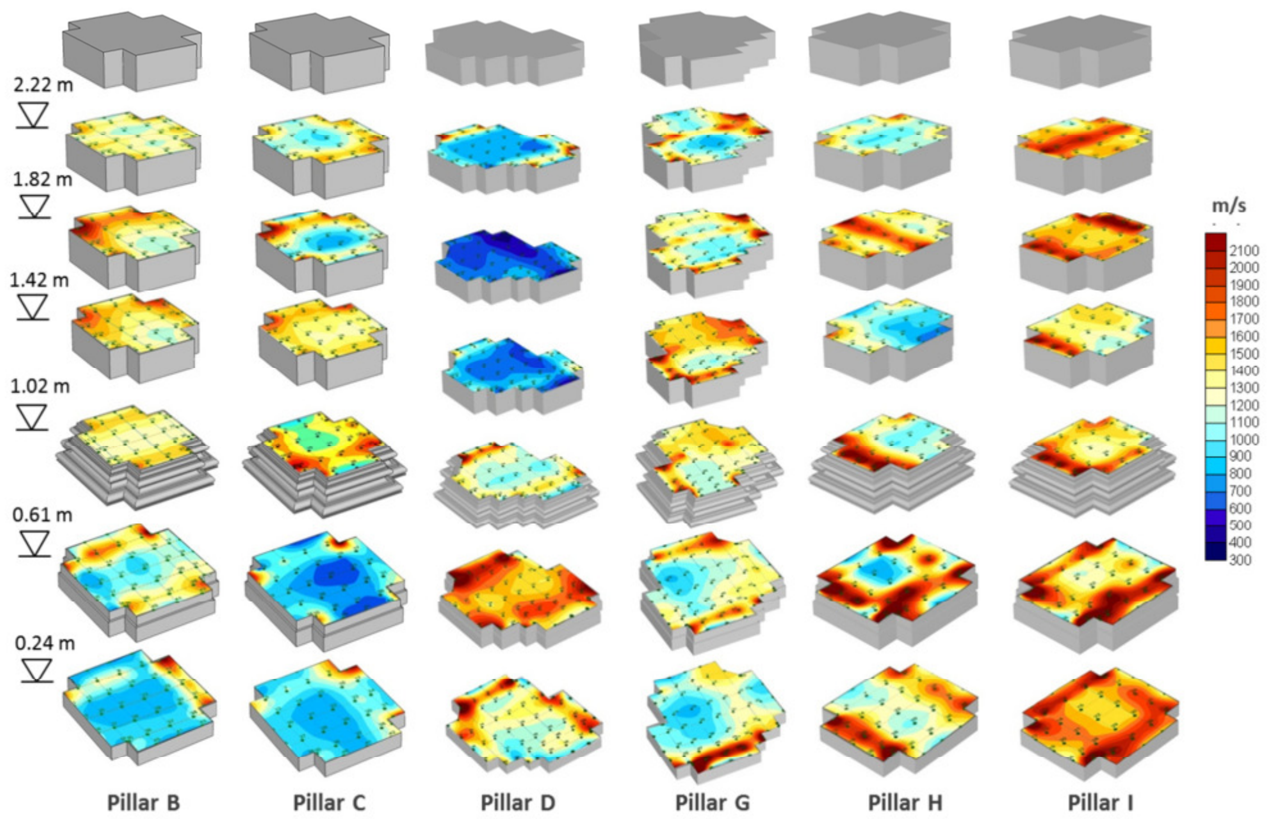


Figure 4.61: Results of the sonic tests carried out by crossing trajectories on 5 levels for each pillar of the church.

This kind of characterization allow to study in depth the discontinuities affecting the load bearing structures and provide the detailed position of the damaged areas. For this reason the repairing intervention can be limited to those damaged areas and not extended also to those structures which do not present significant damages. In this way, the visual inspection for the control of the results can be localized in the most critical parts of the structures. Moreover this kind of diagnostic approach supports the sostainability of the intervention, defining the specific areas in which the intervention should be carried on.

4.5 Development of sonic tests: reliability of sonic impact method

4.5.1 Introduction to the research: the methodology of study

The application of sonic and ultrasonic tests has been well developed for some building materials: ultrasonic tests are considered very useful to characterize concrete structures and impact echo tests are applied to modern standardized masonry. Both methodologies can provide quantitative results: the hardness process of concrete structures can be evaluated by ultrasonic tests; the depth of cracks in homogenous materials can be identified by a peculiar configuration of ultrasonic tests (as shown in paragraph 4.3.6.1); the presence of defects in regular masonry wall (i. e., brickworks) can be controlled by applying impact echo tests.

The use of direct sonic tests on historical masonry structures provides qualitative results. An attempt to refine the results and connect the velocity with other mechanical parameters was performed by prof. L. Binda[166]. Her research, in 2004, focuses on the comparison between velocities obtained by measuring the travel time of compression waves (P-waves) in different traditional masonry typologies with the elastic moduli estimated by double flat jack tests. This idea was suggested first by a study of G. Riva[167], who noticed a tendency between the two parameters: high performance masonry structures presented high values of sonic velocity and elastic modulus: a real correspondence was not determined and the further study promoted by prof. Binda tried to support this promising intuition.

Recently, the research group led by Joao Guedes (University of Porto) started a very complete test campaign in order to estimate the use of indirect sonic tests for the characterization of traditional masonry structures. The research, realized largely by Eng. Luis Miranda[168], introduced the evaluation of the velocity estimated by measuring the so called Rayleigh waves (R-waves), in addition to the compression waves (P-waves). According to the theory of the propagation of

[166] L. Binda, L. Cantini, G. Cardani, A. Saisi, C. Tiraboschi *Use of Flat-Jack and Sonic Tests for the Qualification of Historic Masonry*, in. *10th Tenth North American Masonry Conference (10NAMC)*, Missouri, 2007. (Binda L. C., 2007)

[167] G. Riva, *Messa a punto di tecniche non distruttive (Italia settentrionale)*, contained in "Atti convenzione tra il Ministero dei Beni Culturale e Ambientali e IUAV", 1997. (Riva, 1997)

[168] L. Miranda, J. Guedes., et al., *Propagation of Elastic Waves on Stone Masonry Walls*, in "8th International Masonry Conference 2010", Dresden, I.M. Society. (Miranda L. G., 2010)

seismic waves, elastic waves can have different characteristics[169]. As mentioned in the description of the theoretical background, pack of waves can be distinguished in:

a) primary waves or compression waves (P waves): the effect of their propagation is the variation of the volume of the material along the direction of the propagation;
b) secondary waves or shear waves (S waves): during their propagation the particles of the medium realize oscillations perpendicular to the direction of propagation;
c) Rayleigh waves (R waves): they took the name from the mathematician John Strutt, better known as Lord Rayleigh, who evaluated their presence during his research on the propagation of waves in an elastic medium. Their propagation produce movement of the particles along elliptical orbit, on a plane perpendicular to the surface along the direction of propagation.

Rayleigh waves are considered to be the result of the effects produced by the combination of P and S waves (Figure 4.62). It is known that P and S waves are characterized by different velocities and that P waves can be propagated across solid and fluid medium, whilst S waves are not able to be propagated in fluids. Being faster in their propagations, P waves present higher velocities respect to S waves. For this reason the measure of wave propagation can detect easier the velocity of P waves than the velocity of S waves. Being so hard to distinguish the S-velocity, R waves are considered to be a parameter that can be representative for the velocity of S waves.

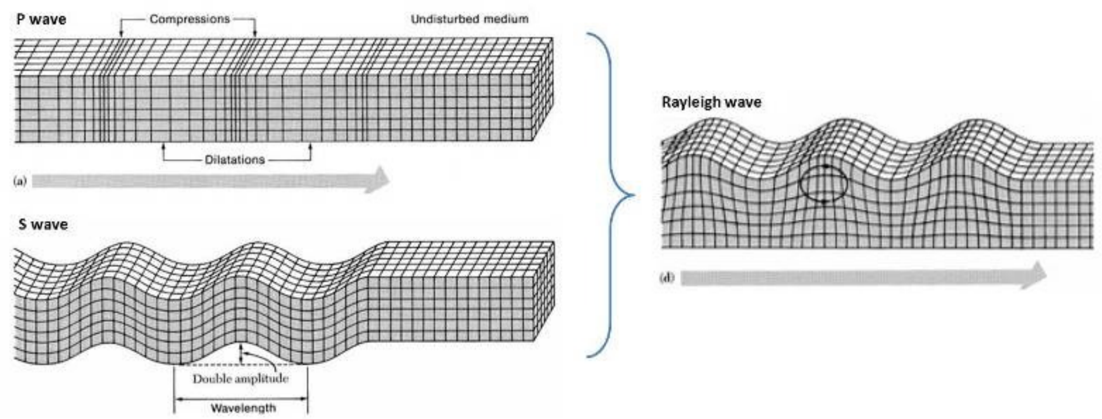


Figure 4.62: Representation of P, S and R waves

[169] G. Pascale, *Diagnostica a ultrasuoni per l'edilizia*, Flaccovio Editore, 2008. (Pascale, 2008)

4.5.2 Reliability of Indirect sonic impact method

Although non-destructive acoustical techniques applied to masonry elements provide mainly qualitative data, recent studies have shown the potential of acoustic tests to estimate the mechanical properties of stone walls. The modulus of deformability of 12 one-leaf stone masonry panels was estimated using a procedure referred to as Indirect Sonic Impact Method (ISIM) that consists on applying series of indirect configurations to measure P and R-wave propagation velocities. The results were analysed taking into account the masonry texture and the characteristics of the stones obtained through direct sonic tests, and were compared to the mechanical properties obtained by mechanical tests carried out, by other authors, using masonry structures with similar characteristics.

The sonic tests can be applied using a simple configuration that corresponds to a single measure with emitter and receiver placed on opposite sides of a structural element, or using complex configurations with several receivers, placed according to a prearranged criterion to provide a more complete analysis. Sonic tomography is an example of such a complex configuration. Trials to obtain complementary information have been made using impact-echo technique[170], or other more complex analyses to characterize more in depth masonry samples[171]. Nevertheless, the results provided by sonic tests on masonry structural elements give only qualitative information on their mechanical properties[172].

A new procedure, called Indirect Sonic Impact Method (ISIM), was used to estimate the modulus of deformation of different types of stone masonry specimens (6 irregular and 6 regular wall panels) made by granite stone blocks and lime mortar, and constructed at the Laboratory of Earthquake and Structural Engineering (LESE) of the Faculty of Engineering of the University of Porto (FEUP). This procedure is based on the application of sonic indirect tests and on the analysis

[170] A. Sadri Application of Impact-Echo technique in diagnoses and repair of stone masonry structures. NDT&E international: Science Direct; 2003. p. 195-202. (Sadri, 2003)

[171] G. Cascante, H. Najjaran, P. Crespi. Novel Methodology for Nondestructive Evaluation of Brick Walls: Fuzzy Logic Analysis of MASW tests. Journal of Infrastructure Systems. 2008. (Cascante G., 2008)

[172] L. Binda, A. Saisi, L. Zanzi Sonic Tomography and Flat Jack Tests as Complementary Investigation Procedures for the Stone Pillars of the Temple of S.Nicolo' L'Arena (Italy). NDT & Evaluation Int Journal. 2003;36/4:215-27. (Binda L., 2003)

of P and R-waves velocities. During the research it was studied the way sonic velocity changes according to the type of stones (shape, mechanical properties, finishing) and joints. The results of the 12 stone masonry panels are compared to the mechanical properties obtained through mechanical testes on regular and irregular stone masonry prisms with similar characteristics.

The specimens used in this study consisted in 12 one leaf stone masonry panels constructed at FEUP and presented in Figure 4.63, with a volume of 1.20x1.79x0.28m^3. The masonry panels present two different typologies:

- 6 perfectly regular wall panels, with regularly sawn stone blocks and joints made by a lime based mortar;
- 6 irregular wall panels, with irregular stone blocks and irregular joints made of small stones and lime based mortar.

a) b)

Figure 4.63 – Tested walls: a) regular stones wall panels and b) irregular stones wall panels (pictures by the author).

The sonic indirect tests were carried out using a 0.32kg hammer with a range of frequencies of 0 to 1kHz (flat response). In operational conditions, the hammer can send a pack of frequencies until 6kHz, a value that is much lower than the hammer resonance frequency that is greater than 22kHz. As receivers, a set of three unidirectional miniature accelerometers with a flat response up to 10kHz were used (Figure 4.65). The accelerometers were coupled to the stone surfaces with grease to promote a better wave transmission[173 174].

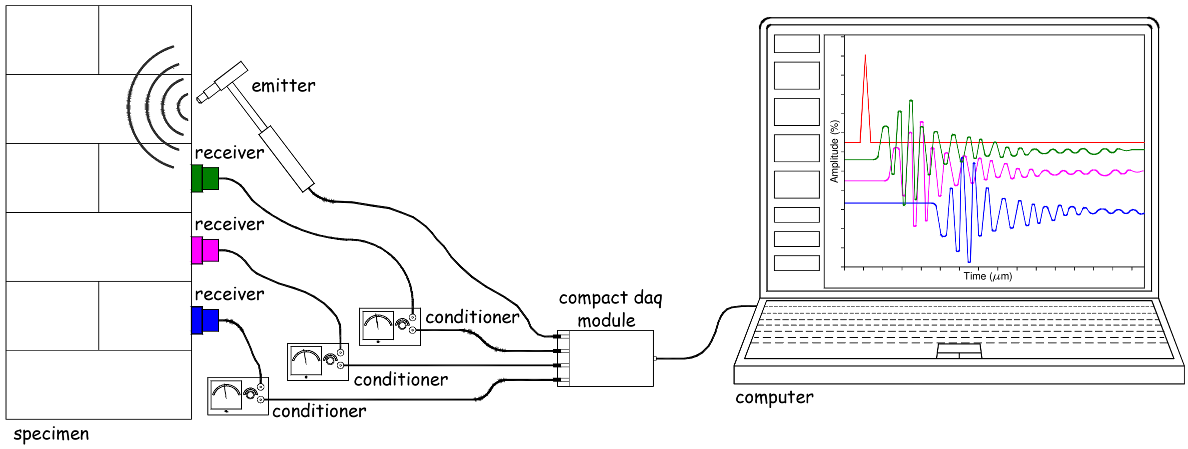


Figure 4.64: Layout to carry out sonic tests by using three accelerometers (layout by the author).

The data acquisition system is a NI-9233 compact module with a resolution of 24bits and a maximum sampling rate of 50kHz. The signal processing consists on measuring waves travel time. A LabView application developed in LESE of FEUP enables the visualization of the transmitted and received signals on time domain. The first arrival of the wave package is obtained using an automatic algorithm and then it is checked and corrected by the operator through visual reading. The distinction between P and R-waves is achieved through a series of procedures settled within the ISIM method.

Sonic direct tests applied to a masonry wall through its thickness (direct test) enable to assess the wall transversal characteristics. However, to predict the behaviour of masonry subjected to vertical loads it is important to study the propagation of waves along the vertical direction, i.e. emitter and receiver placed on the top and bottom of the wall[175]. Because these areas are not accessible in reality (on top there may be the roof or a floor and on bottom the foundation) and

[173] Carino NJ. Handbook on Nondestructive Testing of Concrete. In: Malhotra VM, Carino NJ, editors. *Stress wave Propagation Methods*. 2nd Edition ed. Barr Harbor Drive: ASTM - International CRC Press LLC; 2004. (Carino, 2004)

174 ASTM. *Standard Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock*. D 2845 - 00. USA: ASTM; 2000. (ASTM, 2000)

[175] L. Binda, V. Bosiljkov, L. Zanzi, M Tomazevic, *Guidelines for diagnostic investigation of historic buildings*, in 7th International Masonry Conference, 30/10-1/11/2006, London, CD-Rom, 1-8, 2006. (Binda L. B., 2006)

because a signal may not have the sufficient energy to travel along the whole height of a real wall, the idea was here to access the characteristics of the specimens along the vertical direction performing tests on the surface using the ISIM technique.

According to this technique, and because 3 accelerometers were used simultaneously, the tests were performed in 4 points placed on different stones along the same surface (indirect tests) and following a vertical alignment (also called columns, ahead).

As shown in Figure 4.65, these 4 points (which define a column, i.e. a vertical alignment) were marked on the main surfaces and the acquisition was carried out according to two different setups: i) impact on the highest point of the column and reception along the 3 underneath points, where the accelerometers were placed, and ii) impact on the lowest point of the column and reception along the 3 upper points. Thus, two impact points were used on each column, i.e. two ISIM tests were performed on each column. Using three accelerometers to acquire each single impact, three results were obtained for each vertical alignment. Furthermore, in order to verify the response of the applied testing technique in different positions, four columns per panel (2 per faces) were considered, i.e. 8 ISIM tests per panel that corresponds to a total of 24 indirect tests per panel. Thus, each wall typology (regular and irregular) provided 288 results (144 for P waves and 144 for R waves readings).

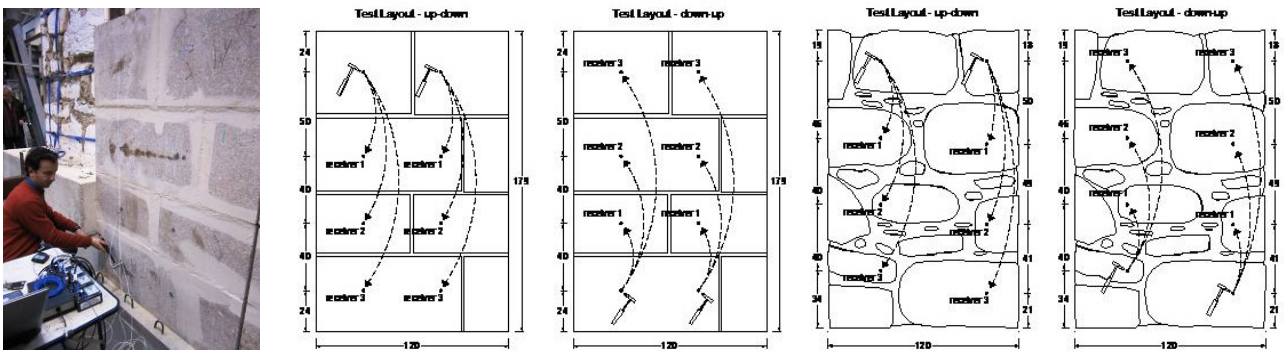


Figure 4.65 – Test layout on the regular and irregular wall panels

AS already described in paragraph 4.3.3, sonic tests can be performed using different setups, according to the proposed objectives: direct, semi-direct and indirect or surface configurations, according to the relative position between hammer (emitter) and accelerometer (Figure 4.66):

- Direct test – hammer and accelerometer placed on opposite faces;
- Semi-direct test – hammer and accelerometer placed on adjacent faces;
- Indirect test – hammer and accelerometer placed on the same face.

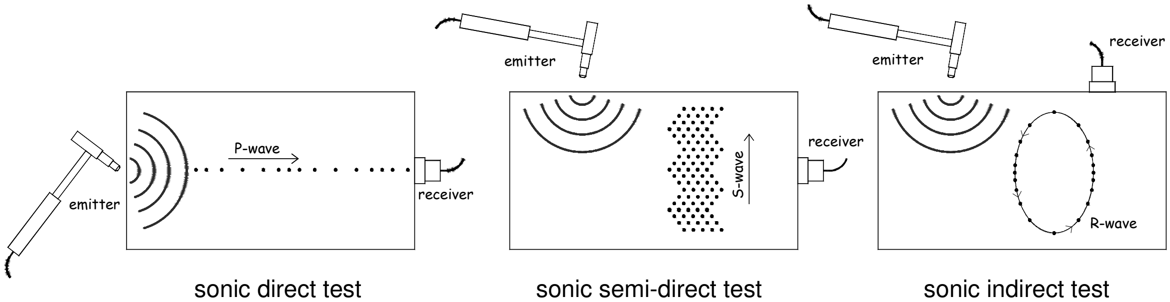


Figure 4.66 – Sonic test configurations (layout by the author).

It is important to outline that the configuration of the test and the acquisition setup are two fundamental steps for the identification of the main parameters[176]. In fact, the identification of P waves and R waves is based on the interpretation of the acquired signals. Noise or other negative effects in the acquisition of the resulting signals from emitter and accelerometers can compromise the correct interpretation of the requested parameters.

The direct configuration is advisable to access P-wave velocities, because P-waves propagate mainly along the direction of the impact, i.e. the main surface movements caused by this wave are measured on the opposite face of the impact. The semi-direct configuration is used to access the S-wave velocities, since S-waves cause movements mainly on the surface perpendicular to the impact. The indirect tests are more used to access the R-wave velocities, because this type of waves diffuses along the impact surface. Nevertheless, different waves can be detected in a same configuration and the operator should be able to distinguish them. For instance, on an indirect test the receiver will also detect the P-waves that propagate along the impact surface[177] [178]. However, in this case, and apart from being faster, P-waves contain less energy than R-waves, 7%

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[176] BSI. Testing Concrete - Part 203: Recommendations for measurement of velocity of ultrasonic pulses in concrete. BSI; 1986. (BSI, 2003)

[177] Cascante G, Najjaran H, P.Crespi. Novel Methodology for Nondestructive Evaluation of Brick Walls: Fuzzy Logic Analysis of MASW tests. Journal of Infrastructure Systems. 2008. (Cascante G., 2008)

[178] Qixian L, Bungey JH. Using compression wave ultrasonic transducers to measure the velocity of surface waves and hence determine dynamic modulus of elasticity for concrete. Construction and Building Materials. 1996;10:237-42. (Qixian L, 1996)

against 67% of the total energy[179], and, therefore, these two different waves may be distinguished by the operator. P-waves arrive first, but with much lower energy than R-waves, making them more difficult to detect than R-waves[180].

In the study only P and R-waves are considered and, thus, only these two types of waves will be referred to. As it was mentioned, besides having different energy, P and R-waves have different propagation velocities, V_P and V_R, respectively, which depend on the mechanical properties of the material they cross. Equations 4.10 and 4.11 present the velocities for both waves on a homogeneous, elastic and semi-infinite media with a Young modulus E, a Poisson ratio ν and density ρ:

$$V_P = \sqrt{\frac{E(1-\nu)}{\rho(1-2\nu)(1+\nu)}} \tag{4.10}$$

$$V_R = \frac{0.87+1.12\nu}{1+\nu} \cdot \sqrt{\frac{E}{\rho} \cdot \frac{1}{2(1+\nu)}} \tag{4.11}$$

According to these expressions, the ratio between velocities of P and R-waves in such a media depends only on the Poisson ratio as it is presented in Equation 10[181]. It is known that for Poisson ratios of about 0.25, the relation between the velocity of P and R-waves is about $V_R/V_P=0.5$[182]. For concrete with a Poisson ratio of 0.2, Carino[183] verified that the ratio on concrete samples was $V_R/V_P=0.56$.

$$\frac{V_P}{V_R} = \sqrt{\frac{2(1-\nu)}{(1-2\nu)} \cdot \frac{(1+\nu)^2}{(0.87+1.12\nu)^2}} \tag{4.12}$$

[179] Richart FEJ, Hall JRJ, Woods RD. Vibrations of soils and foundations. Englewood Cliffsm, NJ.: Prentice-Hall, Inc.; 1970. (Richart, 1970)

[180] Lamb H. On the propagation of tremors over the surface of an elastic solid. Philosophical Transactions of the Royal Society. 1904;203:1-42. (Lamb, 1904)

[181] See reference (Richart, 1970)

[182] See reference (Richart, 1970)

[183] See reference (Carino, 2004).

The mechanical properties obtained using the mentioned equations are called dynamic properties because they are based on small deformations and fast load rates and their values are frequently higher than the static ones. It is well known that for concrete and masonry specimens, it has been proved that the strength depends on the rate of application of stress[184] [185]. According to the standard, the ratio between the static and the dynamic Young modulus varies from 0.5 to 0.9, increasing with the increase of the Young modulus. On granite samples, tests show that although the value of the dynamic Young modulus tends to be higher than the static one, the difference between them is usually much smaller than the one on concrete[186]. However, there are results where the static Young modulus is smaller than the dynamic one[187]. These different results may also reflect the natural characteristics of granite, which present a large variability on the mechanical properties.

The above expressions were deduced for homogeneous, elastic and non-infinite media. However, since no other mathematical relations are available, in the research work these expressions were applied to masonry, as if masonry could be considered to be a homogenised material with the masonry global mechanical characteristics. It must be remarked that this consideration is extremely limitative for the most diffused historical wall typologies, characterized by multiple leaves.

The Indirect Sonic Impact Method allows measuring the surface wave velocities through indirect configurations, i.e. hammer and accelerometer placed on the same side of the wall. Moreover, the relative position of the hammer and of the accelerometer should be so that the signal follows the direction under analysis. Since the work aims analysing the axial behaviour of the walls, all the ISIM tests within this study were performed along vertical trajectories.

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[184] BSI. *Testing Concrete - Part 203: Recommendations for measurement of velocity of ultrasonic pulses in concrete*. BSI; 1986. (BSI, 2003)

[185] Neville AM. *Properties of concrete. 4th edition*. Harlow: Addison Wesley Longman Limited; 1995. (Neville)

[186] Christaras B, Auger F, Mosse E. *Determination of the moduli of elasticity of rocks. Comparison of the ultrasonic velocity and mechanical resonance frequency methods with direct static methods*. In Materials and Structures. 1994;27:222-8. (Christaras, 1994)

[187] Vasconcelos GdFMd. Experimental investigations on the mechanics of stone masonry: Characterization of granites and behaviour of ancient masonry shear walls. Guimarães: Universidade do Minho; 2005. (Vasconcelos, 2005)

The ISIM involves the determination of both velocities of P and R-waves propagating along the surface. As it was already mentioned, in this condition P-waves are more difficult to distinguish because of their low energy content, especially when compared to R-waves. Sometimes, the identification of the wave arrival using receivers positioned closer to the impact point helps eliminating uncertainties concerning the same identification at points positioned at longer distances due to the loss of energy in between.

The P-wave arrival identification is linked to an objective criterion: P-wave is the first to arrive, i.e. is the fastest one. However, due to its low energy content, sometimes its arrival is not recognizable and the first arrival being detected may correspond to the R-wave. However, and in spite of their higher energy content, R-waves are not always easily detectable neither, since the acquired signal is the result of different contributions (P-waves, S-waves), which may disguise the R-waves arrival. Nevertheless, R-waves arrival is, in general, more evident[188] and the results based on its detection are usually more accurate than those based on the P-waves arrival. Nevertheless, the knowledge that P-wave is the first to arrive and that P and R-wave velocities are related by equation 10 can give quite useful information to the analysis. For the research, and taking into account the material involved (granite), values V_R/V_P in the range of [0.4 – 0.6] were assumed.

Therefore, and to help identifying the arrival time step of R-waves a simple criterion was settled: it corresponds to the time step on the signal with amplitude zero before a major increase on the signal amplitude. Following this procedure on the different receiver points (accelerometers) for the same impact point, the operator can "follow" the R-wave arrival time step and, thus, obtain the R-wave propagation velocity.

In order to obtain the tendency of the velocity, which is known to decrease with the number of crossed joints[189], linear regression time vs. distance curves were settled according to the British

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[188] Qixian L, Bungey JH. *Using compression wave ultrasonic transducers to measure the velocity of surface waves and hence determine dynamic modulus of elasticity for concrete*. In "Construction and Building Materials". 1996;10:237-42. (Qixian, 1996)

[189] Abbaneo MP, Binda L, Fatticcioni A., *Non Destructive Evaluation of bricks-masonry Structures: Calibration of Sonic wave propagation procedures*. In Int Symposium "Non-Destructive Testing in Civil Engineering". Berlin,1995. p. 253-260. (Abbaneo M. P., 1995)

Standard on the Determination of Sound Speed Propagation[190]. This mathematical operation describes the P and R-wave velocities with the effects of the crossing of the joints included. Figure 4.67 presents the layout of the ISIM and the mentioned data treatment.

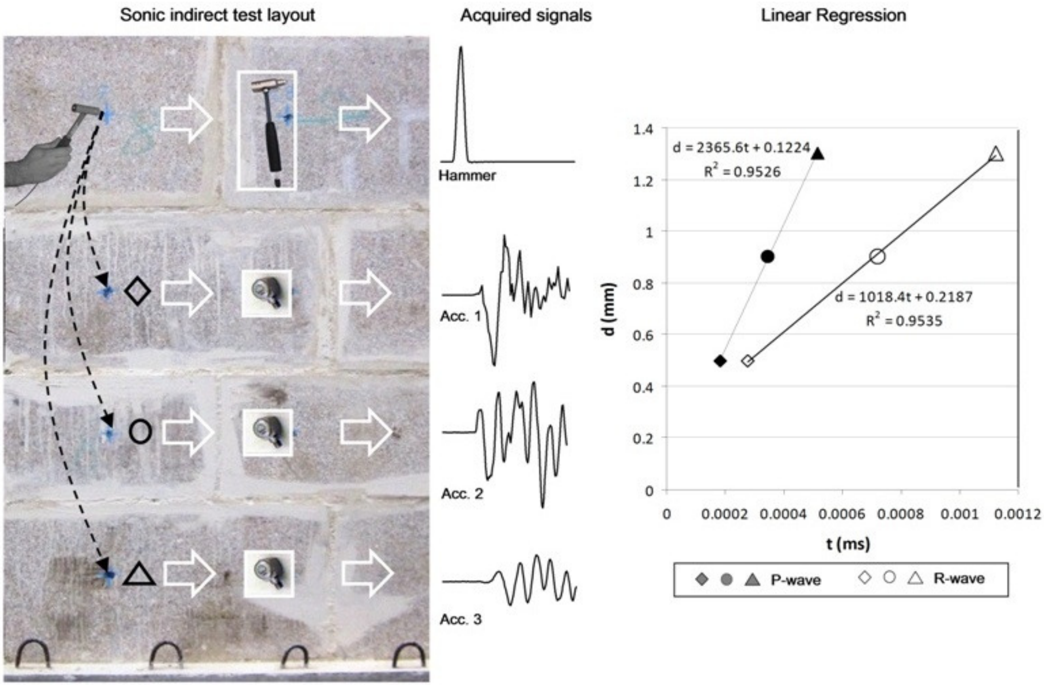


Figure 4.67 – Indirect sonic tests: procedure and analysis of results (layout by he author)..

This procedure is also useful to reduce the errors caused by an incorrect interpretation of the signals acquired in the tests. Even if the initial time steps of the signals (from hammer and accelerometers) are not all perfectly recognizable, the linear regression provides an estimation of the tendency for all the travel time vs. distance points of the curves, helping in the interpretation of the signals, since the determination of the waves travel time is not always an easy task. Figure 4.68 shows two indirect sonic results which express two paradigmatic situations: on the left, the slow development of the impact curve and some noise in the first part of the accelerometer curve produce ambiguity in the identification of the travel time; on the right, both signals are clearly identifiable.

[190] BSI. Natural Stone Test methods - Determination of Sound Speed Propagation. British Standard; 2004. (BSI, 2004)

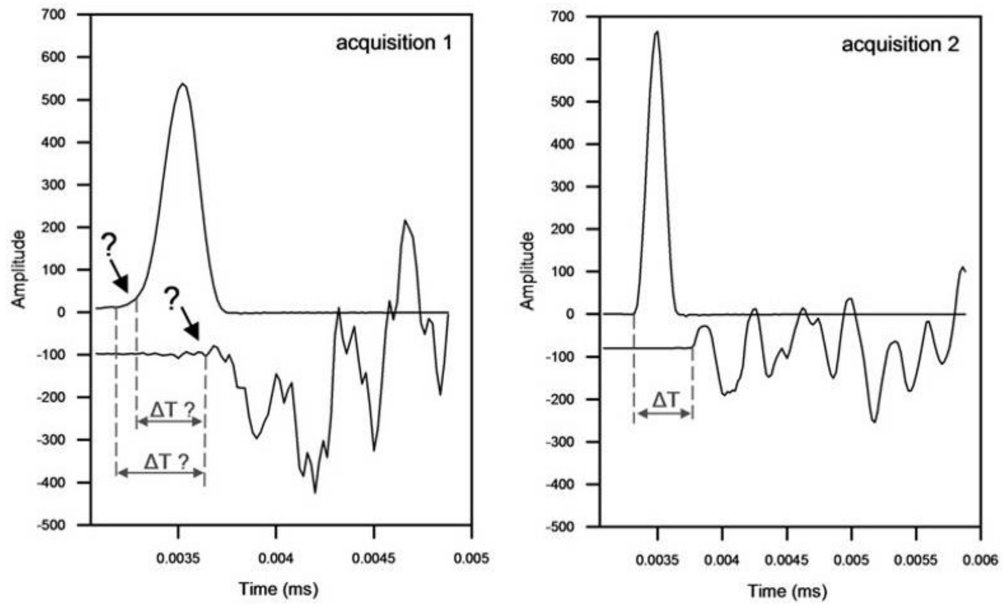


Figure 4.68 – Two paradigmatic cases concerning the identification of the waves travel time. Acquisition 1 shows the receiver signal characterized by noise, whilst acquisition 2 presents the case of more precise acquisition, where the interpretation of the arrival time is more certain (diagrams by the author).

Thus, the ISIM is based on the determination of the linear regression between the P and R-waves travel time from the same impact point to points at increasing distances along a straight line. As final result, it gives the tendency of the P and R-wave velocities crossing the composite material (stones and joints) and it provides the global velocity of those waves propagating along the wall surface. In the next section the ISIM will be applied in the identification of the already presented 12 stone one leaf masonry panels.

4.5.2.1 Results of the laboratory experimentation

The P-wave velocity of the stones belonging to the two categories of tested wall panels was measured using a direct configuration. The following average values were obtained: 4200m/s and 3000m/s for the stones of the panels with regular and irregular texture, respectively, with correspondent standard deviations of 668m/s and 722m/s, using a total of 72 direct sonic tests per panel type. Thus the stones from the panels with irregular texture present an average propagation velocity that is 30% lower than that from the regular ones (Figure 4.69). This difference can be related to the provenience of the stones (they come from different sites): they represent two different classes or qualities.

a) Masonry specimen with regular texture — b) Masonry specimen with irregular texture

Average sonic velocity obtained by P-waves: 4200 m/s — Average sonic velocity obtained by P-waves: 3000 m/s

Figure 4.69: Comparison between the results obtained by considering P-waves (pictures by the author).

Table 4.4 presents the results for the 6 specimens with regular texture plus 6 specimens with irregular texture in terms of the maximum and minimum P-wave velocities, gathered by the direct tests, and the corresponding deformation moduli computed using equation 8 and considering current values for the density and Poisson Ratio, 2600kg/m^3 and 0.3, respectively.

		Regular panels stones	Irregular panels stones
Velocity (m/s)	maximum	5036	4762
	minimum	2820	1071
	average	4181	2981
Deformation modulus (GPa)	maximum	49.0	43.8
	minimum	15.4	2.2
	average	33.8	17.2

Table 4.4 – Results of P-wave velocities on stones and estimated deformation moduli.

A quite uniform average P-wave velocity measured on the stones of the 6 regular and 6 irregular stones panels was attained, as it is illustrated in Figure 4.70.

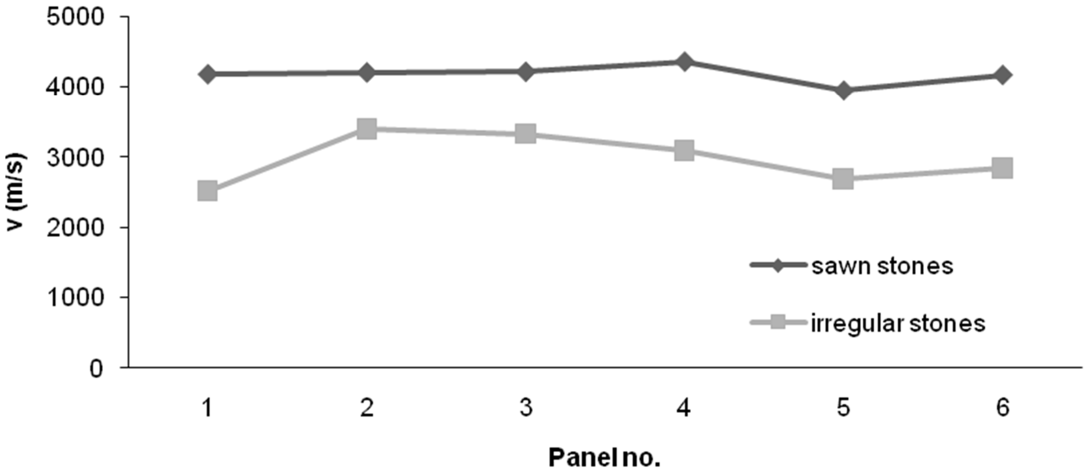


Figure 4.70 – Average velocities of the stones of panels with regular and irregular texture.

After the characterization of the stones, the global behaviour of the wall panels was analysed using the ISIM along the vertical direction of the wall. The results pointed out a decrease in the measured velocity according to the number of joints crossed by both P and R-waves. However, this is mainly noticed on tests where the impact was applied on top, i.e. this tendency was not so evident when the impact occurred at the lower part of the specimens. Figure 4.71 presents the results obtained by sonic indirect tests carried out on one of the faces of the 6 regular panels, considering an up to bottom layout, i.e. impact on the upper point and receptions on the lower points along the vertical direction, applied in 12 columns (2 per panel). Both results for P and R-waves are presented.

Figure 4.72 presents the linear correlation coefficient for the P and R-waves using the ISIM at both regular and irregular wall panels (the tendency is given here by the whole amount of the acquired data). The coefficient was, in most of the cases, very close to 1, denoting the presence of a trend. Nevertheless, it must be remarked that some values, especially on the irregular wall panels, denote the influence that the joints, the quality of the stones and their shape and finishing can have on the results.

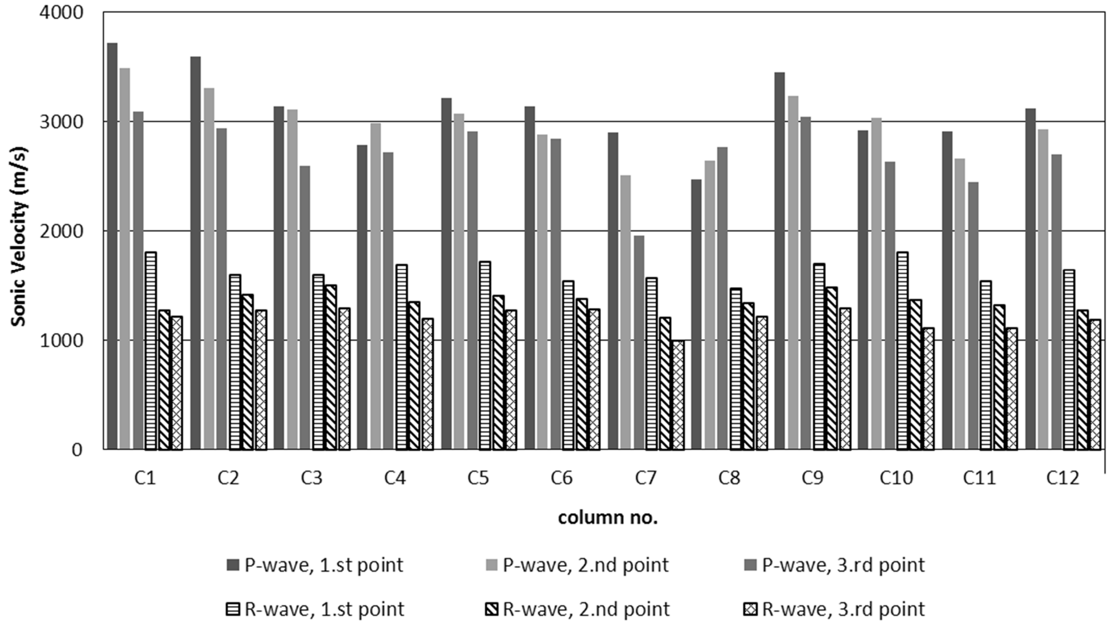


Figure 4.71 – Results for P and R-waves measured in one of the main faces of the 6 regular panels (2 columns for each panel).

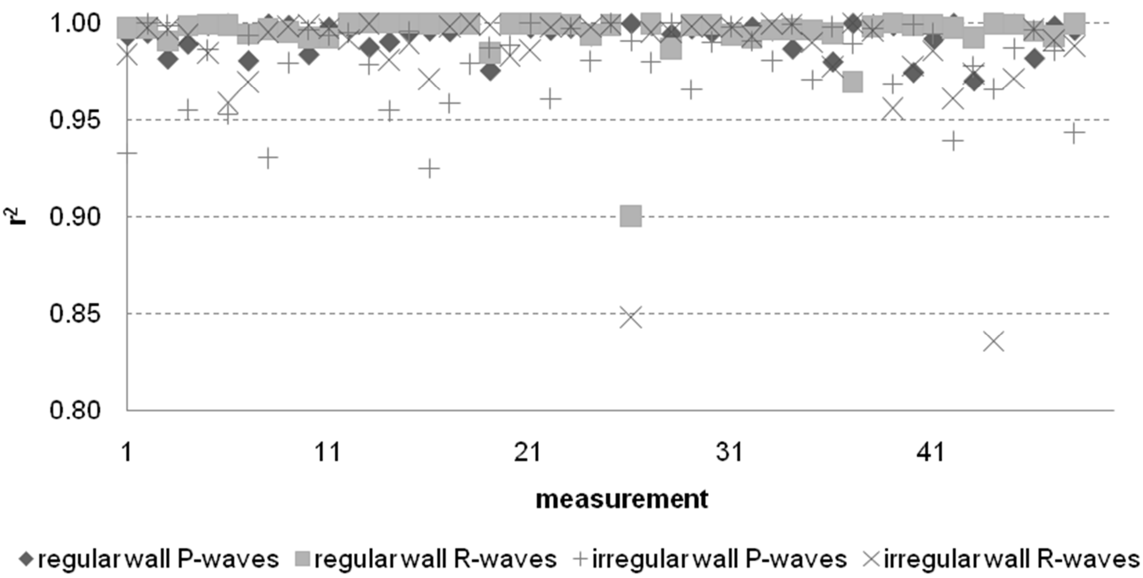


Figure 4.72 – Linear correlation coefficient for each ISIM test performed on both types of wall.

The tests carried out considering the propagation of the waves from top to bottom and vice-versa on both tested faces of the regular wall panels presented fairly different, but consistent results (see Figure 4.73 – 2 columns per panel, per face, meaning 48 P and 48 R-waves velocities). For instance, column 7 (panel 4) presented, in all the four tests, the lowest P-wave velocity; on the contrary, column 9 (panel 5) has the highest P-wave velocity. Nevertheless, it is clear that the scattering of P-wave velocities (i.e. the obtained velocity with the different methods) is considerably higher than those of R-wave velocities that, in general, were more regular.

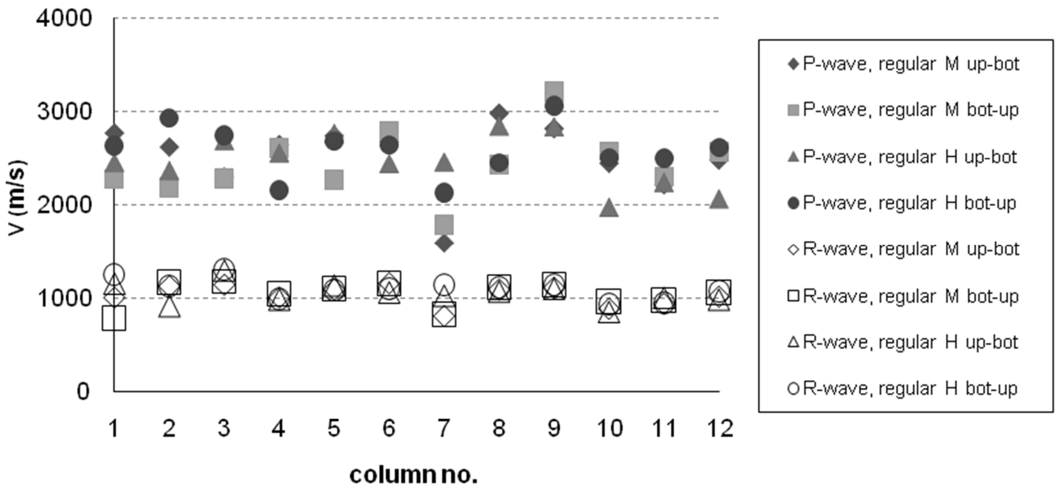


Figure 4.73 – P and R-wave velocities on regular wall panels using different facades and testing orientations.

Thanks to their particular characteristics, R-waves were more clearly recognizeble during the interpretation of the acquired signals (their evaluation was based on very clear acquired signals). This was also noticed on the irregular masonry wall panels, as the results presented in Figure 4.74 obtained with the ISIM confirm. Thus, the results using R-waves can be considered more reliable and produce more consistent values than those using P-waves.

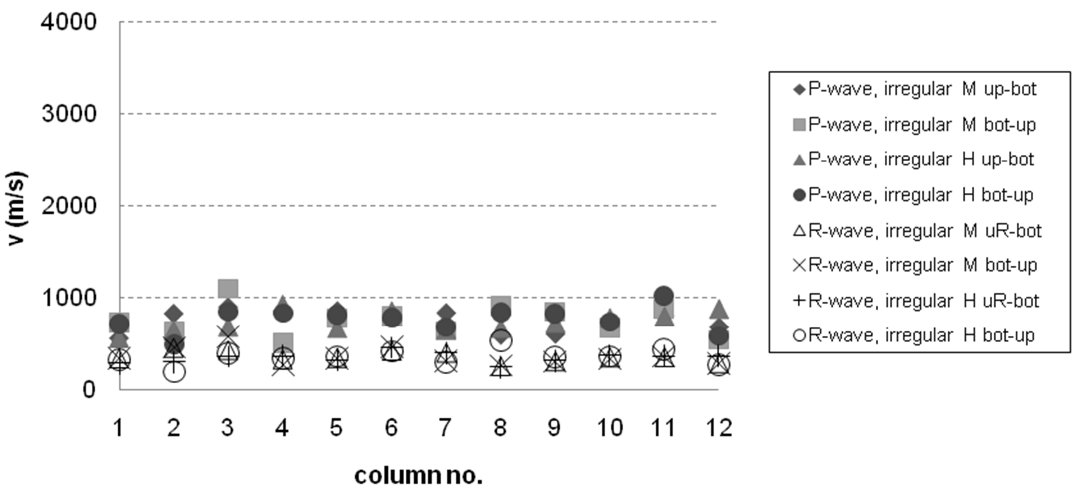


Figure 4.74 – P and R-wave velocities on the irregular wall panels using different facades and orientations.

According to sonic indirect tests, the two groups of panels, regular and irregular, responded with similar properties. Table 4.5 summarizes the values obtained by indirect sonic tests and the corresponding moduli of deformation computed by Equations 8 and 9 and considering a density of 2400kg/m^3 and a Poisson ratio of 0.3.

	Value	Regular wall		Irregular wall	
		P-wave	R-wave	P-wave	R-wave
Velocity (m/s)	maximum	3216	1305	1097	579
	minimum	1591	787	493	197
	average	2508 (13%)	1056 (11%)	751 (17%)	357 (21%)
Deformation modulus (GPa)	maximum	20.7	12.1	2.4	2.4
	minimum	5.1	4.4	0.5	0.3
	average	12.6 (23%)	7.9 (21%)	1.1 (35%)	0.9 (45%)

Table 4.5: Summary of the obtained velocities and the corresponding estimated deformation modula (between parentheses it is presented the coefficient of variation in %).

The results show that the scattering is important. Nevertheless, the estimated moduli, in particular the average values considering R-waves are considered to represent a more relieble estimation of the deformation moduli of the tested walls. Moreover, the results show that a much higher modulus is expected for the regular walls when compared to the irregular walls, in this case 8 times higher. Notice that these are average values and that the limits for the mechanical properties in terms of design strength and stiffness are established using statistical analysis and acceptable probabilities of failure, which are determined by the codes of each country.

Considering only the stones, it is interesting to notice that the velocity of P-waves on the stones of the regular wall panels was 30% higher (on average) than the velocity on the stones of the irregular panels. However, looking at the average values of the panels, the regular walls presented a P-wave velocity about 70% higher than that of the irregular walls. This means that other parameters beyond the stones quality influence the final results. The irregular shape of the stones and of the mortar joints should be among the most important causes for this reduction. The tendency revealed by these results are in agreement with Vasconcelos ones. Moreover, the results in Table 4.4 show that the final ratios between the average deformation moduli of the wall panels and the stones (E_w/E_s) are equal to those found by that author for the regular wall panels, i.e.

E_w/E_s=23%, and similar for the irregular wall panels, meaning E_w/E_s =5%, close to the value of 6% found by Vasconcelos.

4.5.2.2 Observations on the proposed test methodology

This research presents a series of sonic tests performed on 12 one-leaf stone masonry wall panels constructed at FEUP: 6 with regular joints and stones and 6 with irregular joints and irregular stones; it was used the same mortar in both cases. The stones from the regular wall panels presented an average P-wave velocity 1.4 times higher than that of the stones from the irregular wall panels. However, the P-wave velocity measured on the regular wall panels was, on average, 3.3 times the P-wave velocity measured on the irregular wall panels. This result underlines the importance of the geometry of the joints and stones, which have a high influence on the walls mechanical characteristics.

Moreover, the ratio between the deformation modulus of the wall and of the stones for the regular wall panels was 23%, much higher than the same ratio computed for the irregular wall panels that was about 5%. These results are comparable to the results obtained on a large campaign of compression tests using prisms made of stones and mortar joints with different geometrical and mechanical characteristics.

Finally, the ISIM, like other in-situ non-destructive or slightly-destructive techniques, should be applied to the structures together with other techniques and both results should be confronted. In spite of the very promising results obtained with this technique, more laboratory and in situ campaigns are still needed to give more consistency to this newly proposed assessing methodology. It should be remarked that in the case of multi-leaf masonry walls, the ISIM technique only allows assessing the mechanical properties of the external layers. Therefore, in this case it doesn´t give the global mechanical characteristics of the masonry wall.

Chapter 5. Orientations for the conservation design

5.1 From final design to its realization through the diagnostic process

The diagnostic techniques described in depth in chapter 4 are a limited aspect of the design process. Nevertheless, they represent a strategic approach for the description of the state of conservation of existing buildings and afterward for the control of the interventions. Through their implementation and diffusion, measures for the preventive study of alterations and damaging mechanisms can be available to support the activity of the experts involved in the conservative practice. At the same time, thermovision and sonic tests offer a valid solution for the choice and control of the conservative and repairing interventions. Their application, even with the complementary use of other testing techniques, supports the recommended planned maintenance of modern and ancient buildings, according to the most recent indications elaborated in the conservation field. As an example, the periodical application of thermographic tests on the architectural heritage is able to ensure a control of the conditions of the structures, indicating the evolution of alterations appearing in the external layers of the buildings, such as cracks, delaminations and other damages. Sonic tests can be applied for a deeper investigation on structures presenting alterations or signs of decay. Their non-destructive nature assure also a safe use on those structural elements that were improved or repaired, in order to verify the effectiveness of some interventions after their application.

This approach depends on the usefulness provided by the diagnostic techniques. As previously exposed in the third chapter, non-destructive tests provide qualitative results and their interpretation cannot be easily accessible by all the experts involved in the design process. The research illustrated in the fourth chapter had the aim of showing new applications of thermographic and sonic tests, describing the relevant results obtained in on-site and laboratory tests campaign, set for the calibration and the development of their potentialities. This is a path addressed to the review of the outcomes of the diffused *"façadisme"* used by contemporary architecture: the application of differentiated criteria between what is visible (the public view of the building) and what is hidden (the structure of the building or its interiors) is in contrast with the criteria finalized to the respect of the integrity of the entire architectural fabric, presented in the first chapter.

The acceptance promoted by many designers of the replica of the formal style in ancient centres represents a simplification of the problem connected to the cultural heritage recovery. As outlined by R. Pane, the dialectic between present and past has always produced variable relationships between conservation and modification demands. Pane himself, together with P. Gazzola and L. Piccinato, supported the idea of the presence of contemporary architecture in historical centres, adopting specific criteria (like respect for heights and volumes). During the work of the conference "*Gli architetti moderni e l'incontro tra antico e nuovo*" (*Modern architects and the meeting between antique and new*), held in Venice in 1965, Pane's position was in conflict with B. Zevi's opinion. Zevi expressed, supported by other Italian experts like R. de Fusco, C. Valle, L. Benevolo, G. Samonà and C. de Carlo, the thesis of the discontinuity between the architecture of the present and the architecture of the past. Zevi and the others were convinced that new buildings could not be inserted into the historical centres. In this way, they expressed their repudiation for the fake replica of the historical buildings. A congress with the same topic was later proposed in 2004, again in Venice[191]. This time the participants showed new openings towards the possibility of building new architectures into the historical textures of the towns. According to these positions, which also supported the acknowledgement of the diagnostic approach for the realization of the architectural design, the "path to knowledge" represents the common point shared by the different attitudes. In architecture field, many examples showed that the complexity generated by the stratification of the ancient centres can be used as a miilestone of the process for building the future.

The results offered by the *Critic Regionalism* are the answers to the indications given by the "case by case" approach. As outlined by A. Sanna[192], this idea of the "case by case" reminds to the proposal of A. Riegl: due the complexity presented by each architecture of the past, conservation should be set through the identification of the prevalent value between all the values that each specific building is able to collect. The final intervention is then defined applying the suitable strategies to preserve that value. Design and architectural restoration can support the same goal, providing the valorisation of the meaning of pre-existences, increasing their qualities, supporting

[191] The conference Antico e Nuovo. Architettura e Architettura (*Antique and New. Architecture and Architecture*) was held in Venice in 2004.

[192] A. Sanna, Il recupero nel costruito storico, tra conservazione e modificazione, in C. Giannattasio, Antiche ferite e nuovi significati. Permanenze e trasformazioni nella città storica, Gangemi Editore, Roma, 2009, pp. 63-74.

their use and ensuring their availability. Representative of the Critic regionalism[193], like R. Moneo or A. Siza, showed metaphoric references to the comprehension of the *genius loci* of the site hosting their works.

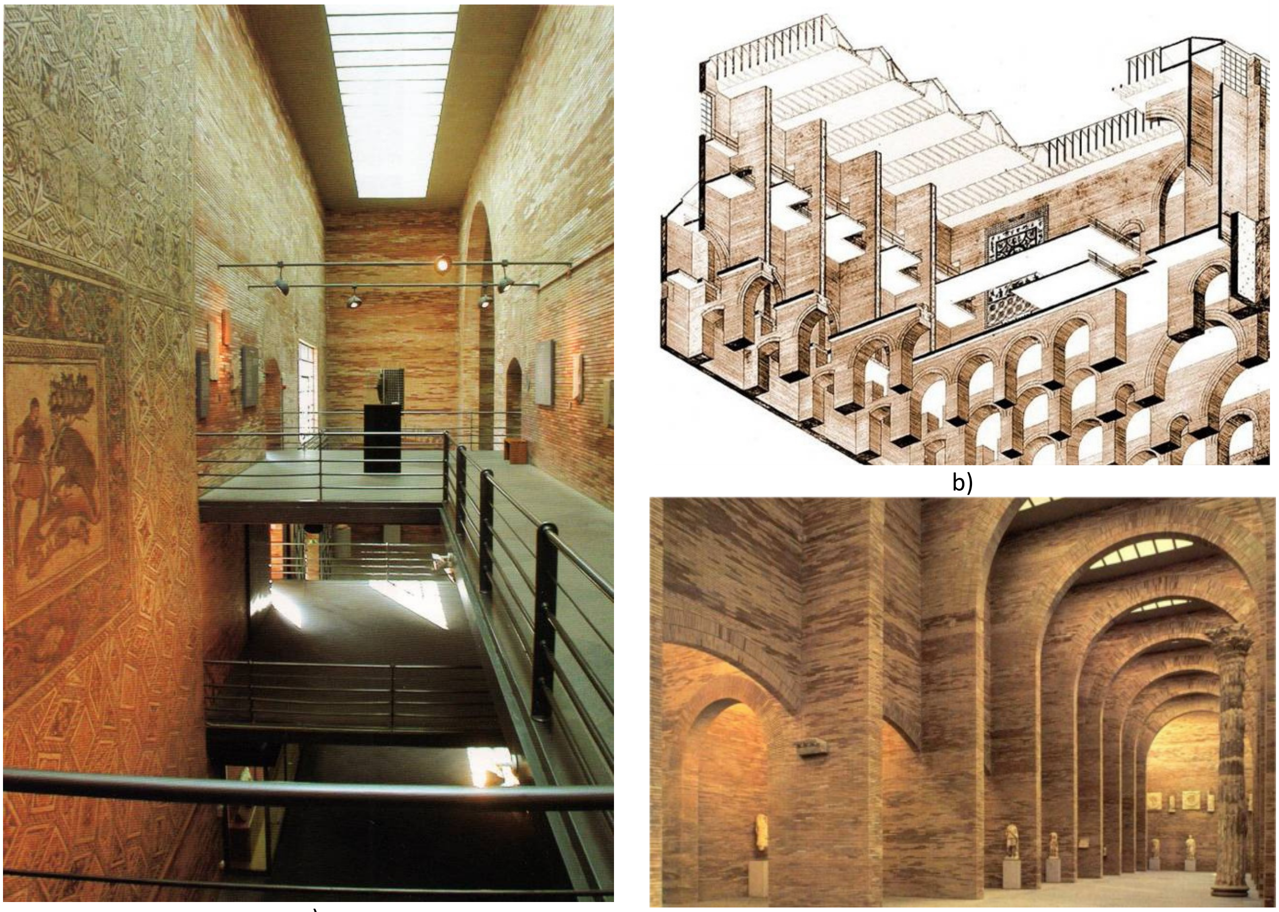
Taking into account Siza's work in the rehabilitation of the Chiado quarter in Lisboa, destroyed by the fire in 1988[194], his attention is clearly addressed to the character of that zone of the town. Through the use of mentions and reminding to peculiar references, Siza studies the typologies characterising the quarter, the spaces and the relationships between them, the material sensation. The result is the interpretation of the place and the interpretation of its spirit. The main peculiarity of the Chiado quarter is expressed by the stonework creating a connection between the existing buildings and the new realizations.

Figure 5.1: Two views of Chiado quarter in Lisboa, after the reconstruction planned by A. Siza (Pictures available in the web: http://www.guiasdearquitectura.com).

[193] R. Moneo, *Inquietudine teorica e strategia progettuale nell'opera di otto architetti contemporanei*, Mondadori Electa, Milano, 2005. (Moneo, 2005)

[194] K. Frampton, *Alvaro Siza, tutte le opere*, Electa, Milano, 2006. (Frampton, 2006)

In the same way, R. Moneo, used the roman structural conception for his Museum of Roman Art in Merida, where the relationship between the new work and the existing ruins is filtered through the material expressivity of the roman building technique. The evocation of the genius loci, in these cases, is not based on the application of specific diagnostic techniques to the surrounding existing buildings, but the knowledge of the historical features of the place is achieved following a part of the same procedures indicated for the conservation design: geometrical survey; materials and technology identification; constructive phases in the development of the buildings. This kind of approach is functional to the preservation of the characteristic of the historical buildings.



a) b) c)

Figure 5.2: Merida, Museum of Roman Art, designe by R. Moneo: a) view of the dialectics between new and old masonry structures and the addition of steel elements (from A. Sanna, "Il recupero nel costruito storico, tra conservazione e modificazione", in C. Giannattasio, "Antiche ferite e nuovi significati. Permanenze e trasformazioni nella città storica", Gangemi Editore, Roma, 2009, p. 66); b) axonometric view of the project (available in the web at http://museoarteromano.mcu.es) ; c) view of the interior in the main nave (available in the web at http://museoarteromano.mcu.es).

Other architects are more open to the dissonance between architectural languages: this is the case of the “Friendly Alien”, like the Kunsthaus designed by P. Cook and C. Fournier in Graz, where the lightness and the informal aspect of the building are in contrast to the solid masonry consistency of the existing surrounding buildings (Figure 5.3). In the same way R. Koolhass shocked the existing context using the metaphoric idea of an asteroid landed in the middle of the city for his Casa da Musica in Porto (Figure 5.4).

Figure 5.3: view of the historical centre of Graz with the Kunsthaus designed by P. Cook and C. Fournier (from A. Sanna, cit, p. 25)

Figure 5.4: view of the Casa da Musica in Porto, designed by R. Koolhaas and realized near the historical centre (author's picture).

This alienation from the context, from the critic knowledge of the various aspects of the problem (mainly regarding the historical techniques) and the attention for geometrical proportions and spatial relationships characterises the design proposed by many architects. A good example of the consequence of a superficial attention to the context is given by the rehabilitation of the House of the Twenty-four in Porto. Here, F. Tàvora, one of the first Portuguese architect who introduced the relationship with the popular traditions in the 60s, proposed the rebuilding of a ruin through the actualized use of the local language with a steel structure (Figure 5.5). The durability of the new architecture is seriously compromised after few years from its construction: a better attention for the use of the materials referred to diagnostic approach could avoid this kind of results.

a)

b)

Figure 5.5: Porto, the House of the Twenty-four, designed by F. Tàvora: a) View of the new tower founded on the ruins of the ancient one after its realization (picture from A. Sanna, cit, p. 73); b) the same view in 2011. The effect of purity given by the new materials of the building is now lost and their decay seems to be faster than the one of the surrounding ancient monuments (author's picture).

The high integration between the landscape and the traces of the history are a common feature of the European culture. This point is skilfully expressed by Goethe in a passage of his trip in Italy[195]. Arrived in the nearest of Spoleto (1786, October 27), he noticed the double identity of the Italian landscape, synthesis of nature and culture (Figure 5.6):

Climbed to Spoleto, I went to the aqueduct that is also working as a bridge between one mountain and the other. The ten arches crossing the valley are quietly standing with their ancient

[195] J. W. Goethe, Viaggio in Italia, Mondadori, Milano, 1983, p. 133. The original translation made by E. Castellani is: *Salito a Spoleto, mi sono recato sull'acquedotto chef a anche da ponte tra una montagna e l'altra. Le dieci arcate che scavalcano la valle se ne stanno tranquille nei loro mattoni secolari, e continuano a portare acqua corrente da un capo ad un altro di Spoleto. Per la terza volta vedo un'opera costruita dagli Antichi, e l'effetto di grandiosità è sempre lo stesso.* (Goethe, 1983)

bricks and are still providing running water from one side to the other of Spoleto. For the third time I see a work built by the Antiques and the effect of magnificence is always the same. A second nature, thought for the public utility: that was the architecture for the Antiques[196].

Figure 5.6: Spoleto, the aqueduct and the castle represent the typical historical Italian landscape (author's picture).

[196] This interpretation of the above mentioned Goethe's passage was added by S. Settis in his *Paesaggio Costituzione Cemento*, Einaudi, Trento, 2010, p. 151. (Settis, Paesaggio Costituzione Cemento, 2010)

The protection of this cultural identity passes through the knowledge of its various aspects: any intervention can produce fatal changings on it and the design activity must be based on a deep investigation of each substantial and cultural component of this issue. Diagnostic techniques, in general, provide an important support for the comprehension of cultural heritage and this thesis-work, limited to a part of the diagnostic field, introduces in the following paragraphs some example showing the definition of conservation and improvement designs according to the diagnostic approach and also to the new philosophy of the Italian seismic code.

5.2 Case-studies: example of conservative designs on complex and diffused buildings

The short description of the following case-studies shows the results obtained by on-site application of the diagnostic tests presented previously. Particular attention will be given to the impact of the diagnostic approach to the preparation of the final architectural design.

5.2.1 The composite convent of St. Paolo d'Argon near Bergamo

The Monastery in San Paolo d'Argon (12 Km far from Bergamo), is a religious complex (Figure 5.7) arranged on four levels (Figure 5.8) with a total extension of about 8145 m^2. Today the building develops around two main cloisters (Figure 5.9) following the slope of the hill.

Figure 5.7: sky-view of the building complex of San Paolo d'Argon near Bergamo (from M. Sigismondi, "L'Abbazia benedettina di San Paolo d'Argon", Flash, 1992, p. 15).

Special concern for the preservation following the new destination of the spaces of the ancient complex was recently shown by religious and civil institutions: the Monastery is going to become a polyvalent building where cultural events and exhibitions will take place into the recovered spaces. The redefinition of the spaces foresees 664 m^2 for meeting rooms (around the cloisters), 591 m^2 dedicated to an exhibition area, 806 m^2 for public catering and 922 m^2 for lodging. This new organization of the spaces was designed taking into account the present distribution of the rooms and the introduction of new functions has been bound to the respect of the existing masonry structures.

Figure 5.8: View of the south and west sides

Figure 5.9: View of the main cloister

The origin of the building is dated around 1092, according to a document concerning the construction of a monastery on a site donated by a noble family of Bergamo to the French Monastery of Cluny. Since that time the religious complex increased its importance and during the XVI century the original construction was extended by the realization of the cloisters: the smallest one in 1513 and the main one in 1536[197]. During the XVII century new buildings were added and the Monastery reached the present proportions.

The development of the structures across different centuries is clearly recognisable observing some features of the building: stratification of layers coming from different ages are visible on the facades (Figure 5.10 and Figure 5.11), by different stylistic elements used for decorations and styles of the vaults inside the building (Figure 5.12 and Figure 5.13).

[197] M. Sigismondi, *L'Abbazia benedettina di San Paolo d'Argon*, Flash, 1992 (Sigismondi, 1992)

Figure 5.10: Different textures appearing from the decayed plasters on the east façade (author's picture)

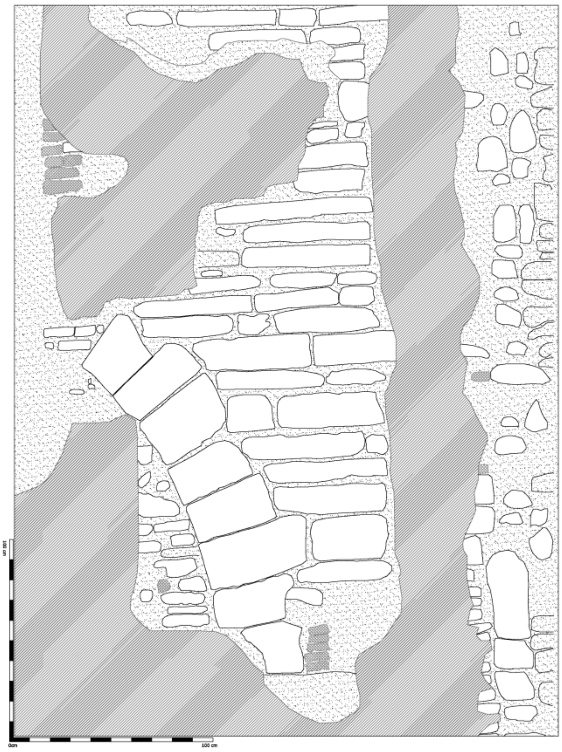


Figure 5.11: sketch of the masonry texture. Detail of the east facade (drawn by arch. Cristina Alberghini)

Figure 5.12: Chapel of the convent, covered by a vault built in a style diffused in XV century (author's picture).

Figure 5.13: Refectory of the convent, covered by a vault built in a style diffused in XVI century (author's picture).

In order to maintain the original characteristics of the building, the state of conservation of the masonry structure was detected by on-site investigations and structural analysis. Geometrical and crack pattern survey were used to increase the knowledge of the organization of the building and the presence of structural problems. The geometrical survey allowed to consider the complexity of the different structural junctions (Figure 5.14, Figure 5.15). The presence of different building technologies was even identified. Existing timber floors are maintained for the minor cloister, whilst other floors have been renewed by modern structures (Figure 5.16).

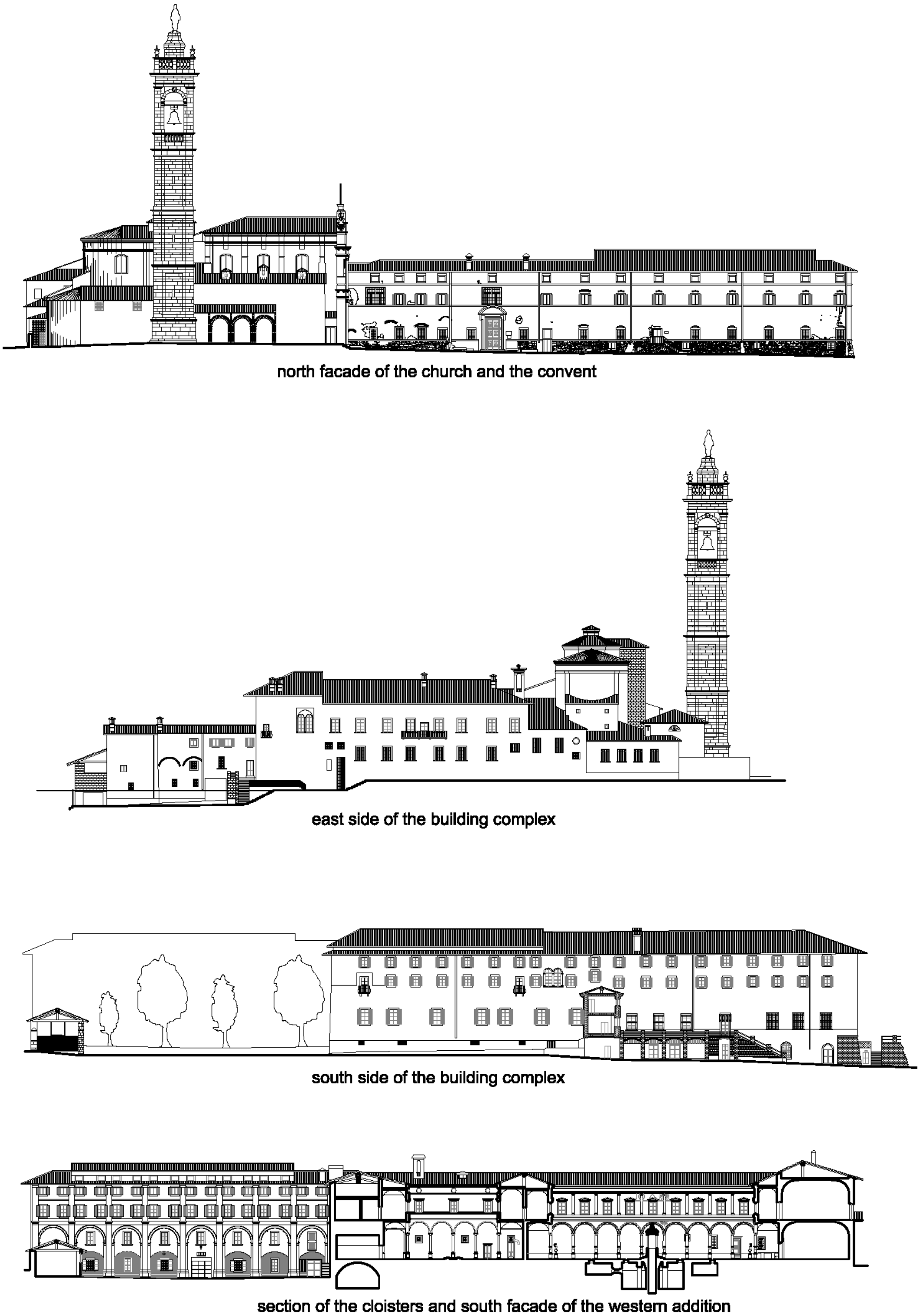


Figure 5.14: Geometrical surveys of the main facades of the building (provided by the designers).

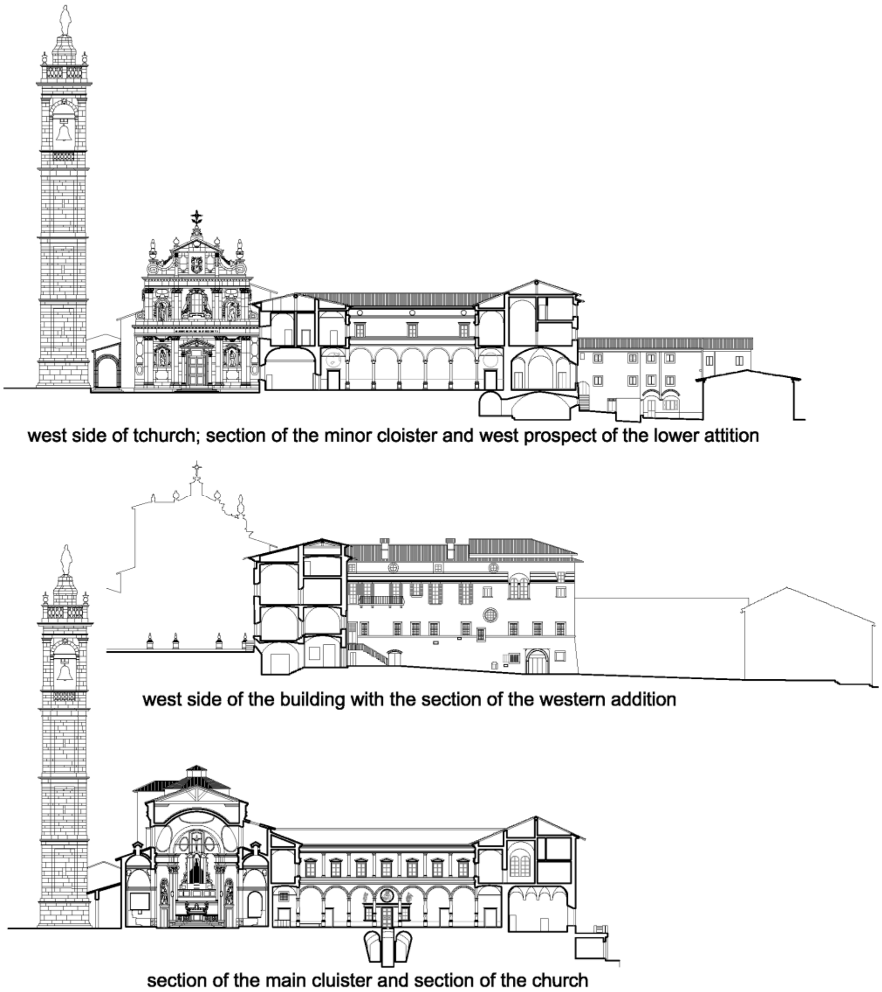


Figure 5.15: Surveys of the main sections of the buildings (provided by the designers)

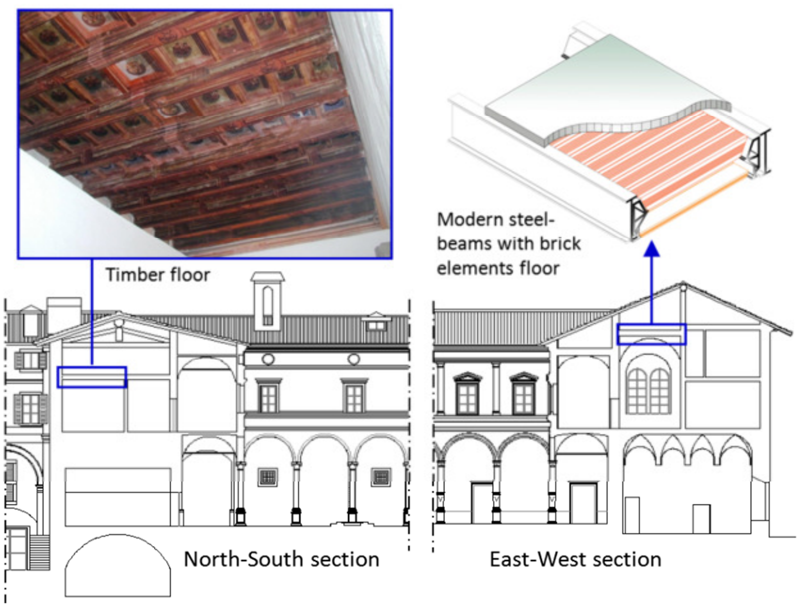


Figure 5.16: Description of the different typologies of floors used in the building: in timber structures in the minor cloister and in modern steel-brick structure in the south part of the complex (layout by the author).

Cracks were present in different areas of the building and through their survey they were put in relation with the mechanical behaviour of the structural elements (arches, vaults, et.). After the survey of the crack pattern a first idea of the damages of the structures was given (Figure 5.17, Figure 5.18). After the individuation of the main dangerous situations, a programme for deeper investigations was proposed.

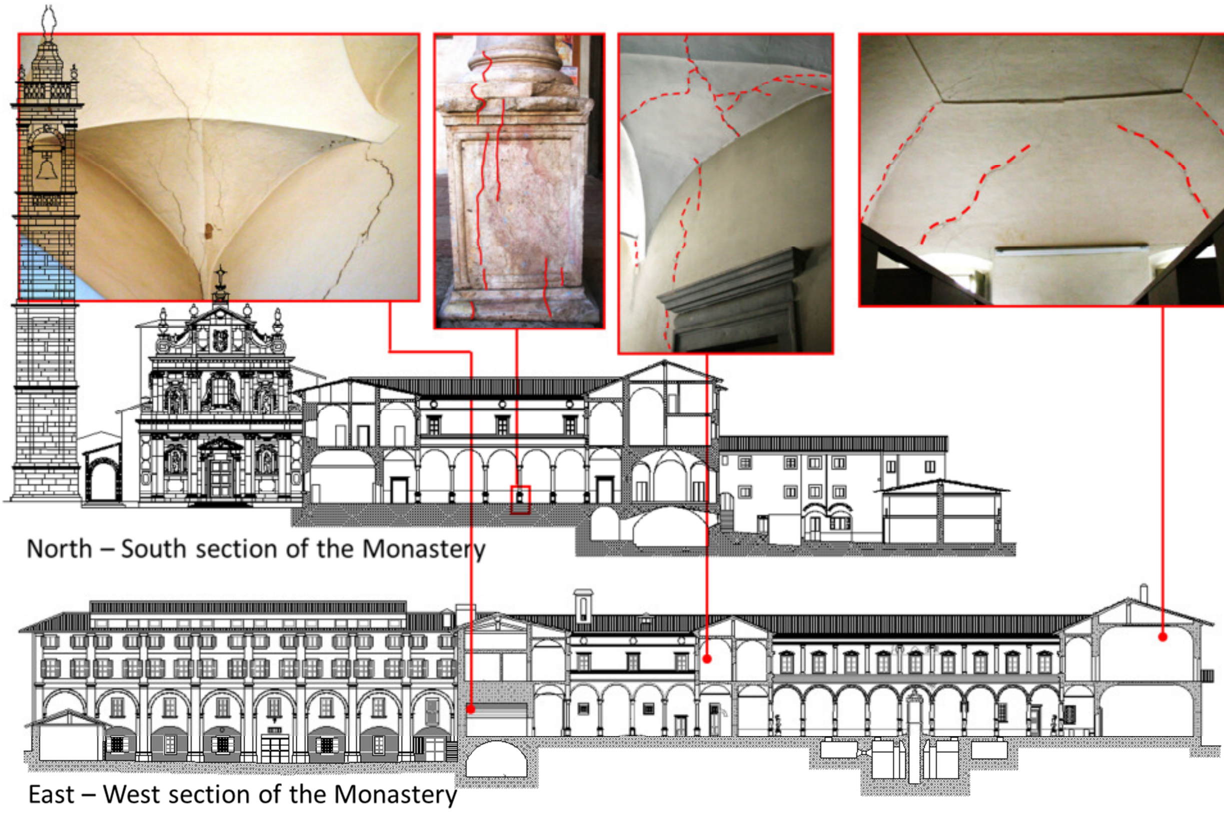


Figure 5.17: Localization of the main crack pattern in the building (layout by the author).

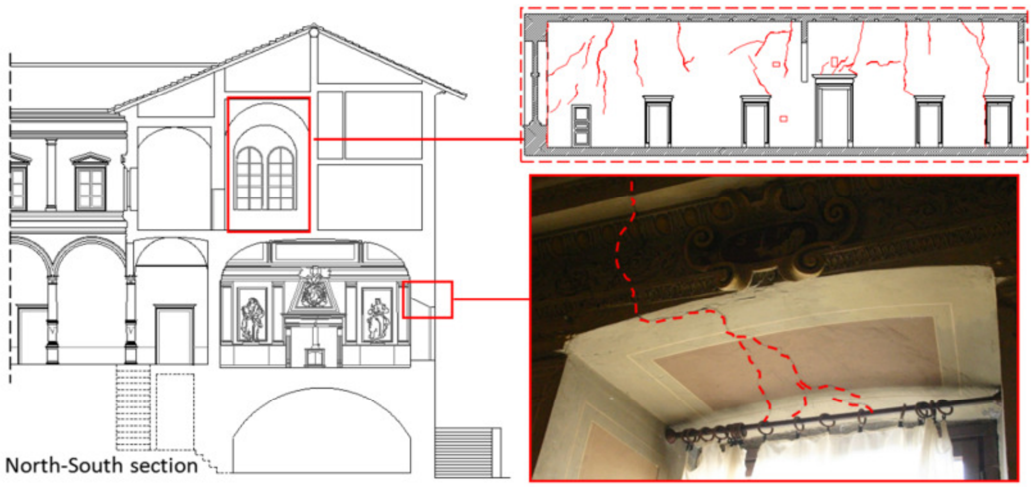


Figure 5.18: Crack pattern in the first floor corridor of the south wing of the building and in the refectory (layout by the author).

After the identification of masonry typologies belonging to different historical phases (Figure 5.19), a design for the application of complementary tests was made including sonic and flat jack tests. Other tests were performed on the stone basements of the columns to detect the depth of the cracks and also the tension in the tie-rods of the vaults was controlled by vibrational tests. Comparing the results of the single flat jack tests some masonry walls were sorted as interesting for the understanding of the structural damages. Out of plane of the walls were controlled by a survey with a total station and the presence of flexural stresses was verified performing some single flat jack tests on both sides of the walls. Also the data coming from the tension measured in tie-rods can be related to some visible out of plumb of the walls and in some points can justify the variation of the stress propagation inside the masonry. These results gave many indications about the state of conservation of the structures. On-site results were integrated with the ones obtained by structural models to improve the knowledge of the building and to confirm the design strategies.

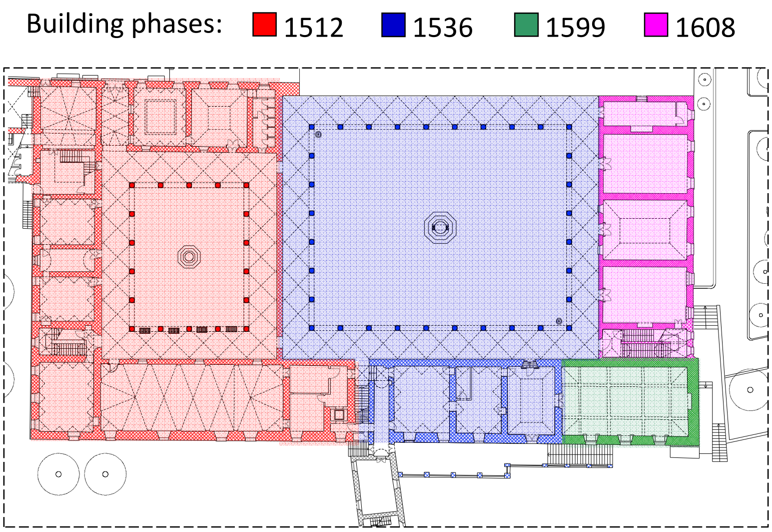


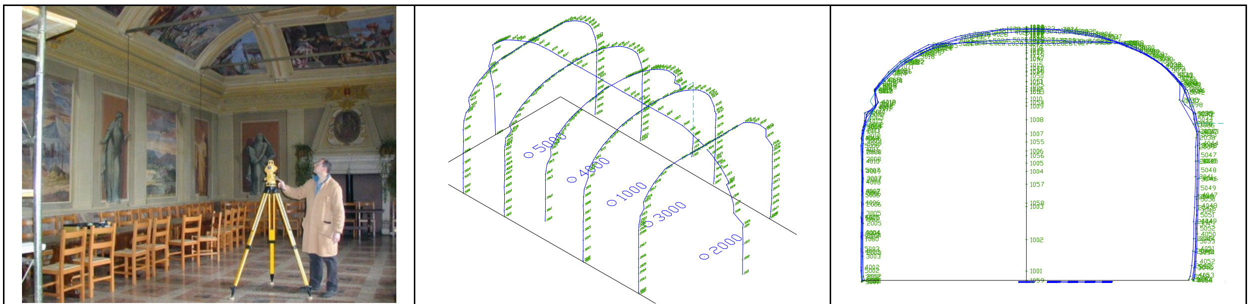
Figure 5.19: The evolution of the main parts of the building, according to the historical sources (layout by the author).

According to the directives of the Regional Office for the Preservation of Historical Buildings, the project provides the conservation of the building and of its superimposed historical layers. The design proposes a new organization of some spaces which were modified during the 60s by adopting a solution which was not compatible with the existing structures. More in detail, the upper levels will be modified for lodging. Other changes will concern: (i) the store-rooms located into the basement floor, which will become the new catering area, (ii) the main rooms at the cloisters level, used for meetings and exhibition activities. The new destinations impose to verify some requirements of this existing structures. Considering that the territory of San Paolo d'Argon is classified as zone 3, according to the new Italian Seismic Zoning Scale, the design took into account the indications contained into the Order of the President of the Italian Council No° 3274/03 and further guidelines for the preservation of monumental and historic buildings in seismic areas. As mentioned in the second chapter, these measures introduce the essential steps to improve the safety of existing structures in seismic dangerous areas and they are considered a strategic support for the designer who has to identify the most appropriate solutions to respect the original properties of the cultural heritage and the addition of new elements for the improvement of the resistance of the masonry structures.

The diagnostic design was developed following the criteria of complementarity: different tests were applied to have a reciprocal validation of the results and to verify the hypothesis on the mechanical behaviour of the structure. The diagnostic intervention will be described in details in the following paragraphs.

5.2.1.1 Survey on deviations from the original geometry

By a survey performed using a total station (Figure 5.20a), different profiles of the vertical development of the external walls were drawn together with several profiles of the development of the vault of the refectory (Figure 5.20 b and c).



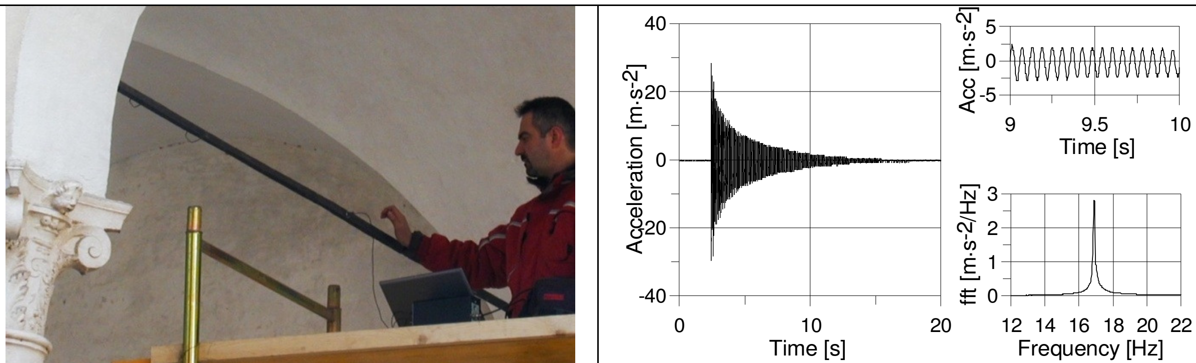
a) Survey by total station | b) 3D view of the surveyed profiles | c) 2D view of the surveyed profiles

Figure 5.20: Survey of the profiles of vertical walls and vaults of the refectory (layout by the author).

As it will be described in a following section, profiles indicating deviations from the original geometry were compared to other results obtained from the tests on the tie rods. Some deformations could be interpreted considering the deviation range from the original verticality and the tensile stresses measured in rods placed near to structural junctions (e.g. the one between walls and vaults).

5.2.1.2 Measurement of the tensile force in tie rods

Following the detected deviation from verticality dynamic tests (Figure 5.21) were used to investigate the supposed relationship between deviations from original geometry and the thrusts confined by the tie rods located under arches and vaults. A free vibration dynamic test allows to identify the tension in the tie rods as a function of the frequency corresponding to the first vibration mode, assuming the tie rods are vibrating cords[198] [199]. The test was performed on different iron tie rods: in the cloisters at the ground and the first floor (25 tested elements), in the chapel (4 elements) and in the refectory (4 elements). Knowing the distribution of tension in the tie rods, a comparison between the most stressed area and its geometrical characteristics was made.



a) Vibrational test on tie rod

b) Example of dynamic wave and frequency diagram for the case of a rod in the major cloister

Figure 5.21: Vibrational tests on tie rods and presentation of the related results (layout by the author).

The results obtained by the dynamic tests were useful to find the state of stress on the vertical structures which are subjected to a non-uniform distribution of stresses. This interpretation was

[198] M. Candela, L. Lanza, F. Laudiero, G. Mezzadri, N. Rullini, *Identificazione dello stato di tensione nelle catene storiche a supporto di due interventi di consolidamento di edifici monumentali*, in the proceedings: *Dalla conoscenza e dalla caratterizzazione dei materiali e degli elementi dell'edilizia storica in muratura ai provvedimenti compatibili di consolidamento*, 16-17/12/2004, DIS – Politecnico di Milano, pp. 225-238.

[199] Anzani A., Binda L., Cantini L. Cardani G., Condoleo P., *Cracking of the apse of S. Lorenzo in Cremona: structural investigation and monitoring*, in the proceedings of the *14th International Brick & Block Masonry Conference (14IBMAC)*, 17-20/2/2008, Manly Pacific Sydney, Australia, 2008.

confirmed by the surveyed vertical profiles of the walls. Some out of plumb could be explained considering the thrust transmitted by arches and vaults. So this behaviour is related to the inhomogeneous distribution of stresses inside the wall (Figure 5.22).

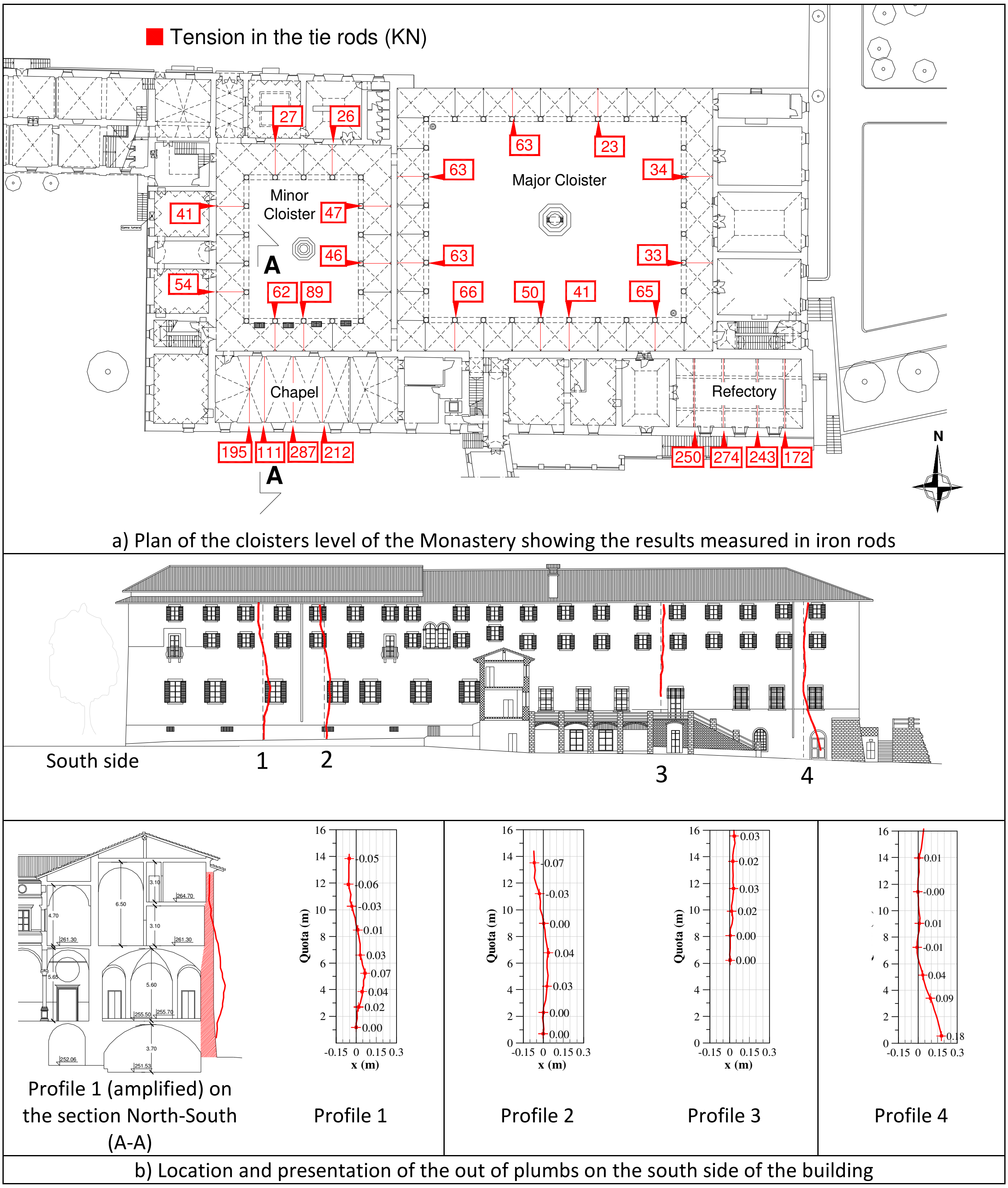


Figure 5.22: Connection between varied tensions in tie rods and out of plumb survey (results provided by M. Cuchi and C. Tiraboschi and rearranged by the author).

The highest values of tension were measured in the tie rods of both Chapel and refectory vaults (Figure 5.22). The 4 tie rods in the refectory, subjected to a tension between 172 and 274 KN (which correspond to a stress in the range of 66÷97 MPa), were able to contrast the horizontal thrust of the vault. In fact the outer wall does not show any out of plumb (profile 3 and 4 of the South side in Figure 5.22).

Non homogeneous distributed of stresses were found in the tie rods of the Chapel, where was also found a broken rod (later repaired by welding the two parts) near the altar. The external wall of the Chapel shows in fact a central bulging at the spring of the vault.

5.2.1.3 Masonry qualification

Direct sonic tests together with single and double flat jack tests were performed on the main structures of the Monastery, at different levels. Direct sonic tests (DST) provide a preliminary detection of masonry characteristics and can suggest the choice of the area for single and double flat jack tests[200]. Single flat jack tests (SJT) were carried out in different positions: this test provides the local state of stress of the masonry and its application in different areas of the complex was useful to estimate the differences in the distribution of the vertical stress in load bearing walls built in different ages. Double flat jack tests were not carried out for each position where single flat jack tests were previously done. The aim of the double flat jack test is to provide the stress strain behaviour of the area of the masonry contained between two parallel horizontal cuts. This technique is slighting invasive and for this reason double flat jack tests (DJT) were limited to one test for each masonry typology at ground and first level. Considering also the inner properties of the investigated masonry element (IMS), flat jack tests can be placed in the area that is supposed to represent better the structure of the wall. For this reason the masonry qualification was obtained by the complementary use of these testing techniques. The type and location of these tests is summarized in Figure 5.23.

[200] L. Binda, L. Cantini, G. Cardani, A. Saisi, C. Tiraboschi; *Use of Flat-Jack and Sonic Tests for the Qualification of Historic Masonry*; in *10th Tenth North American Masonry Conference (10NAMC)*, St. Louis, Missouri, 3-6/06/07, Session 6C, CD-ROM, pp. 791-803, 2007 (Binda L. C., 2007).

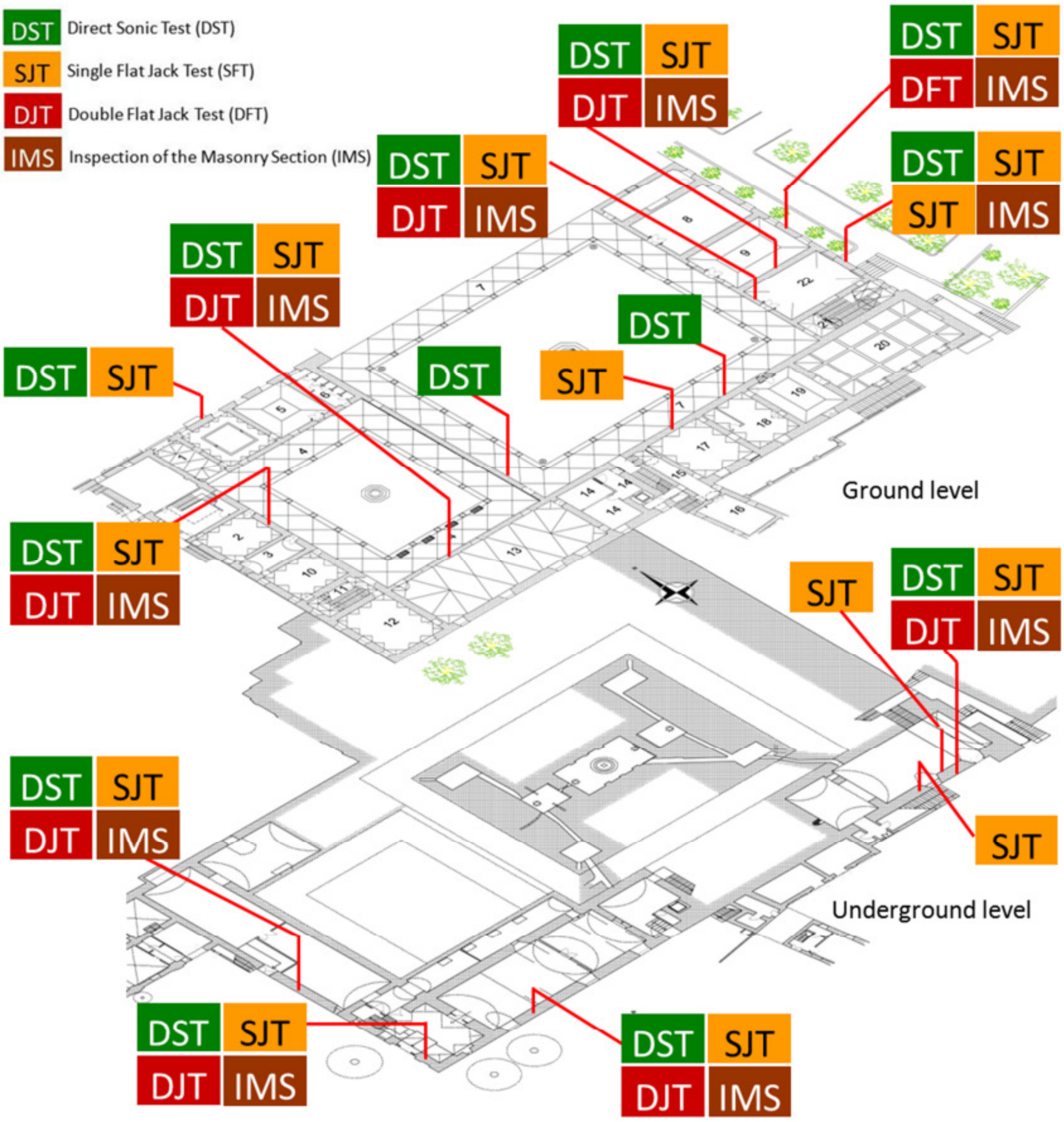


Figure 5.23: Localization of the main tests at ground and first floor (layout by the author).

By performing sonic tests on structures built and repaired in different periods, a first control of the morphology of the masonry was obtained: the propagation of sonic velocity gave indications about the presence of inner discontinuities and voids into the wall-sections. By a geometrical grid of 36 points (6 rows by 6 columns), except for few cases, 15 sonic tests have been performed on three different levels, taking into account outer walls and bearing walls[201].

[201] L. Binda, G. Cardani, L. Cantini, C. Tiraboschi, *On site and laboratory detection of the quality of masonry in historic buildings*, Int. Symp. on Studies on Historical Heritage, 17-21/09/2007, Antalya, Torchy, pp. 667-674, 2007. (Binda L. G., 2007)

The sonic tests revealed an irregular distribution of velocities in the masonry structures. Especially the areas analysed on the east facade present low speed values. Some tested zones are characterized by high velocity values, while in some cases low velocities define rebuilt or damaged areas. From a general point of view sonic tests show that masonry was built with a particular care for the periodical presence of binding elements and stone shaped and cut to work as connection between outer and inner layers (Figure 5.24). In the case a) and d) the velocity was rather high and homogeneously distributed (from 727 to 3138 m/s) while in the cases b) and c) the velocity was rather low (from 375 to 3086 m/s).

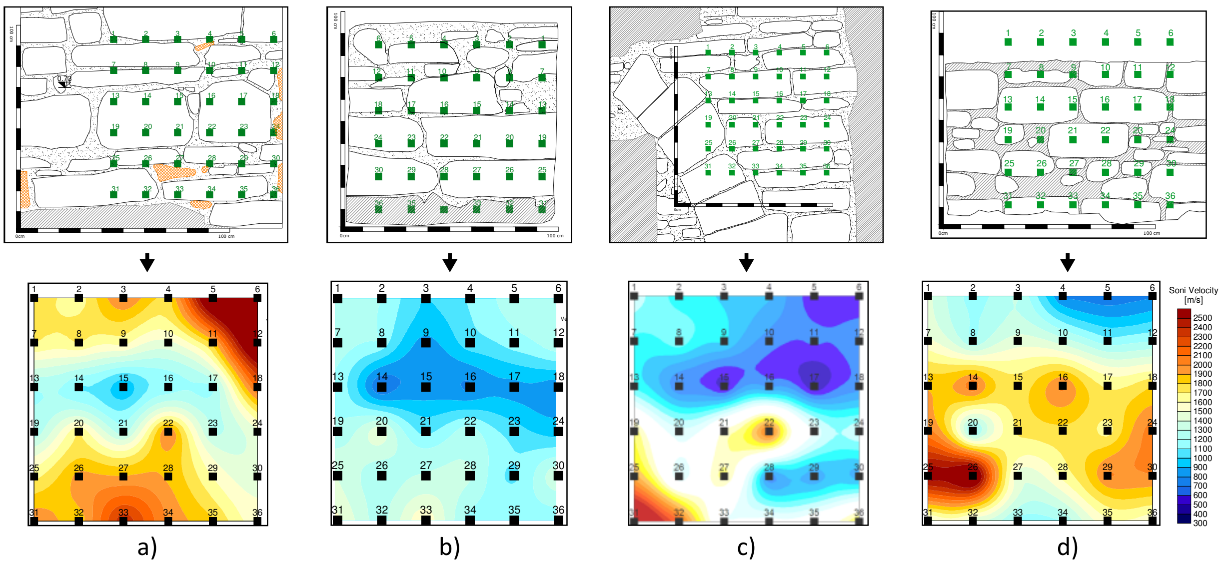


Figure 5.24: Some of the results obtained by sonic tests on different masonry typologies (layout by the author).

Single and double flat jack tests were placed in the areas previously controlled by sonic tests, trying to avoid positions characterized by low sonic velocity, indicating decayed or altered structures. In order to identify the local state of stress of the masonry, single flat jack tests have been performed in 15 positions at the basements of cloister level and at the ground floor of west, south and east facades. In some cases the test was performed on the two sides of the same wall. By single flat jack tests, an inhomogeneous distribution of vertical stresses was found. Problematic situations were identified for concentration of stresses in a basement area and for important differences between the values of stress calculated on both sides of the same wall. In Figure 5.25the distribution of the local state of stress calculated at the ground (blue colour) and at the first floor (red colour) is presented.

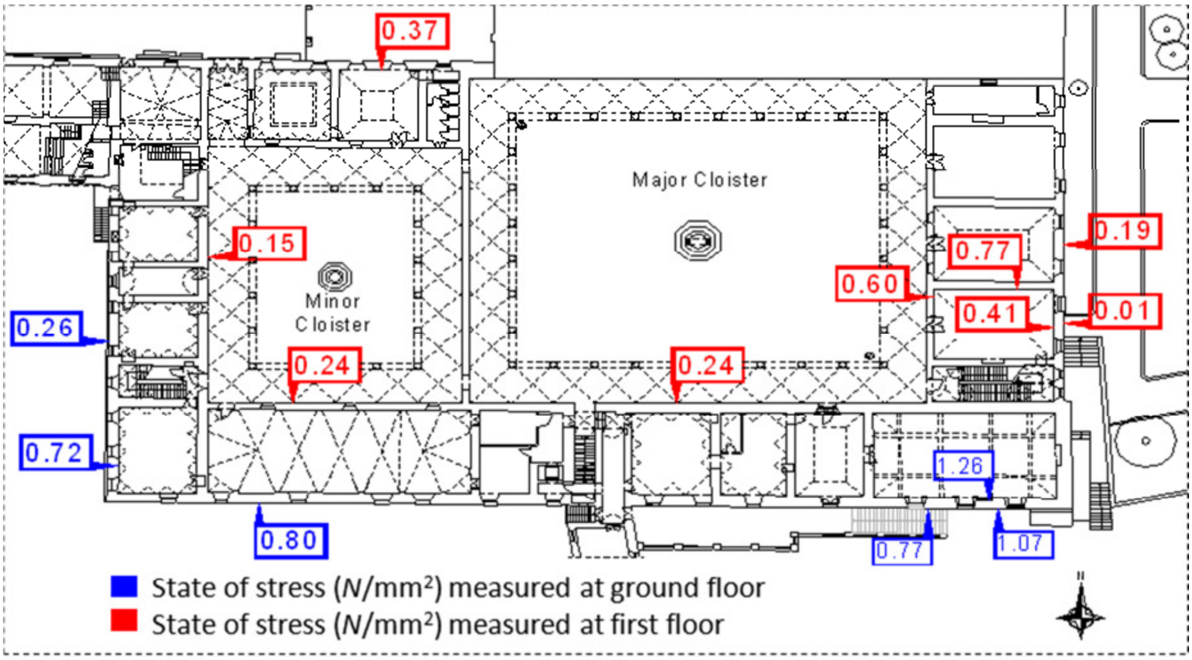


Figure 5.25: Measurement of the local state of stress by single flat jack tests (results are a courtesy of arch. C. Tiraboschi; layout by the author).

Single flat jack tests were even carried out on the opposite side of the same wall in order to detect the presence of eccentricity. This strategy was assumed thanks to different considerations coming from the first characterizations. The deviation from the verticality of some walls and the crack pattern were the principle factors indicating the non-homogenous distribution of the stress in the wall section. Although the minor destructive nature of the test, in this case the identification of a eccentricity state represents an important information for the safety of the building. It indicates a structure subjected to a distribution of stress that is not the one designed by the original builders and the quantification of the state of stress on its opposite sides is a parameter that can refine the mathematical model (Figure 5.26).

The mechanical characteristics of the masonry have been detected by double flat jack tests. This technique was applied in 9 positions, chosen considering the different textures discovered after removing the plaster: the distribution of stone blocks into well ordered cut elements or unshaped ashlars provides various effects to the masonry properties. Double flat jack tests were used to detect the characteristics of masonry deformability on the most representative masonry typologies (Figure 5.27).

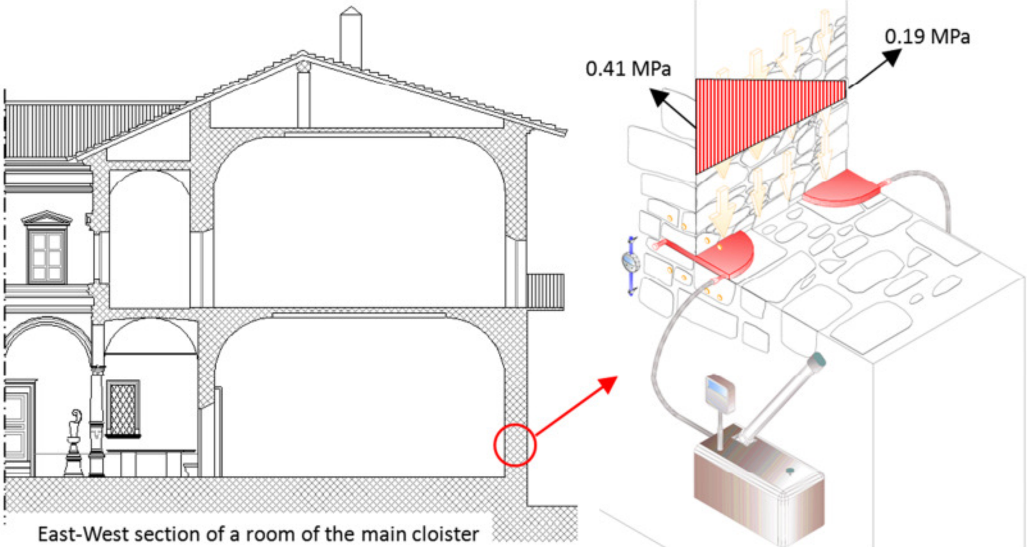
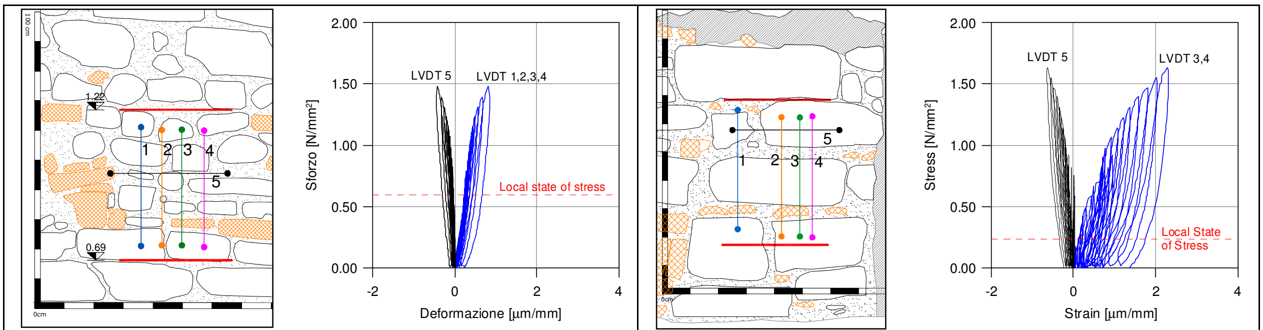


Figure 5.26: Identification of the eccentric distribution of the stress into the wall of the east side of the building through single flat jack tests carried out on the opposite sides of the structure (layout by the author).

From the double flat jack tests, the Modulus of Elasticity of the masonries having different textures was calculated. Also in this case the estimated values are not uniform: from 4000 MPa calculated on a masonry of the base at ground floor, to 814 MPa calculated on a masonry of the minor cloister. Anyway, the previously calculated local state of stress was always contained into the estimated elastic field of each of the different walls (Figure 5.27a, b).

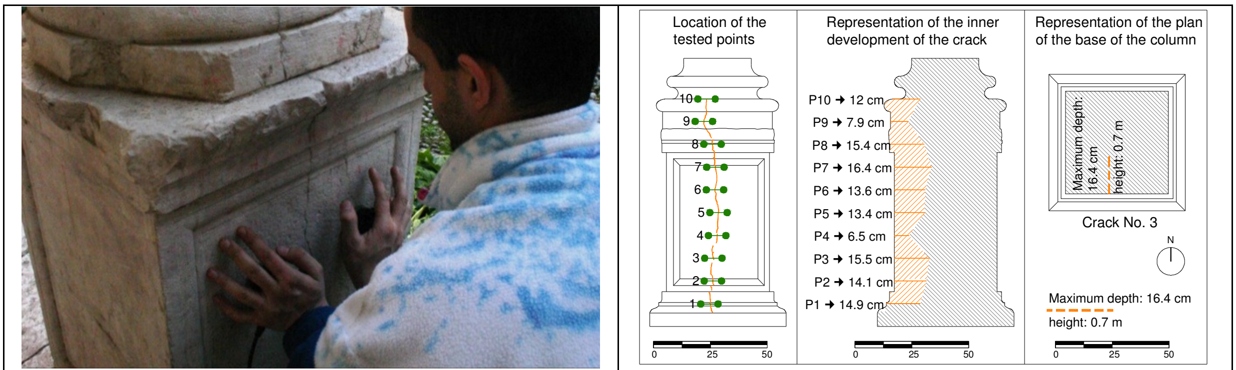


a) Double flat jack test on irregular texture | b) Double flat jack test on large stone blocks

Figure 5.27: Comparison of the stress-strain behaviour of two walls with different textures (layout by the author).

5.2.1.4 Evaluation of the crack depth on monolithic elements

Finally, ultrasonic tests on the bases of the columns of the minor cloister were performed across vertical cracks (Figure 5.28a): maintaining the transmitter and receiver transducers at a constant distance across a vertical crack and knowing the characteristic sonic velocity of the stone, the depth of the crack can be detected by a defined relationship between the distance of the transducers[202], the travel time measured by the test and the given sonic speed of the undamaged material. Results showed that many stone elements are seriously damaged: some vertical crack go deeply inside the material section (Figure 5.28b).



a) Execution of ultrasonic test across a vertical crack
b) Schematic representation of the results

Figure 5.28: Depth of a crack on the base of a column analysed by ultrasonic tests (layout by the author).

The extensive on site investigation, from the general surveys to the local ND tests allowed knowing the global and local behaviour of the complex structure. The work carried out showed the complementarity of the non-destructive tests. Geometrical surveys, change in geometry, sonic and flat jack tests, tie rods control matched very well allowing for a preliminary interpretation of the structural damages. By the results of the on-site investigation, a deep knowledge of various critical points was reached and also FE elastic structural analyses of various part of the building could be optimized in order to understand the characteristics of existing structures. Considering the masonry walls which receive horizontal components of stress from the vaults, the deformation of the vertical structures subjected to thrusts from the vaults was verified: stresses aging into tie rods and stress concentration identified in specific areas were studied with appropriate analytical models. These results were used to set and optimize the final design.

[202] J. H. Bungey, The testing of concrete in structures, London : Surrey University Press, 1982. (Bungey, 1982)

5.2.2 Investigations on four buildings in the historical centre of Sulmona (L'Aquila)

Among the activities supported by the RELUIS project, between 2005 and 2008 the research team led by Professor L. Binda of the Department of Structural Engineering of Politecnico di Milano worked for the programme *Definition and development of databases for the evaluation of the risk and post-intervention scenarios* (*Definizione e sviluppo di archivi di dati per la valutazione del rischio e di scenari post-intervento*). The work continued previous experiences matured on behalf of the GNDT group (*Gruppo Nazionale Difesa Terremoti* – National Group for Earthquacke Prevention), that promoted several studies since 2001 on the evaluation of the quality of masonry buildings and on their vulnerability[203].

In 2008 a diagnostic test campaign was proposed for the historical centre of Sulmona, an ancient town in Abruzzi, a Region that knew in its history many seismic events.

Sulmona was founded by the Romans and preserves in its historical centre the traces of several historical periods: above all, the mediaeval age and the renewal of the town in the baroque period left the main testimonies. According to historical sources, Sulmona was surrounded by defensive walls (still visible in same areas) and organized into different quarters (Figure 5.29), developed in the nearest of the different doors of the town (Figure 5.30). The buildings taken into account for this study are in three different sectors of the centre: Porta Manaresca quarter, Porta Filiababili and Borgo Santa Maria della Tomba.

[203] See reference (GNDT, 2008)

Figure 5.29: Perspective view of a portion of Sulmona (Porta Manaresca quarter), in the beginning of the XVIII century, represented by G. B. Pacichelli, in "Regno di Napoli in prospettiva", Napoli, 1703, Tomo III, f. 14. (Ezio Matiocco, 1978).

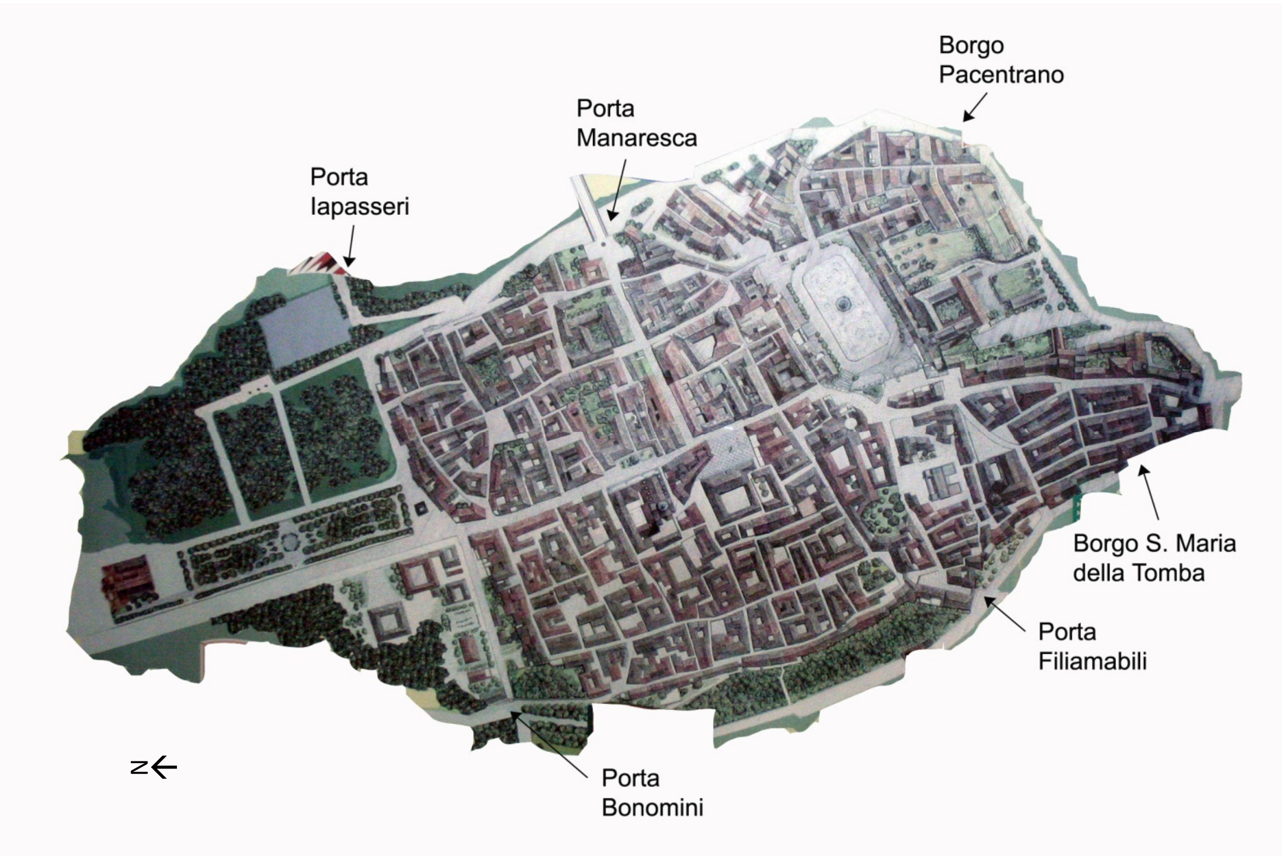


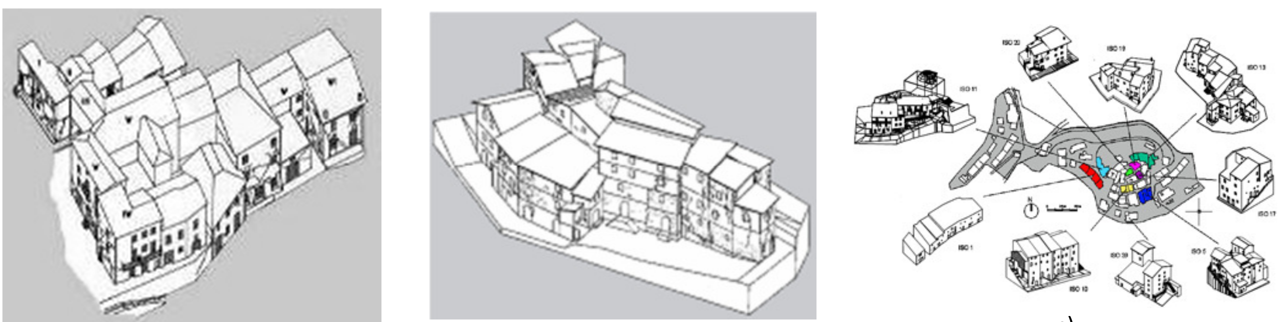
Figure 5.30: Sky view of the historical centre of Sulmona, with the indication of the ancient doors belonging to the defensive walls (Layout modified by the author from Video-grafica-Sulmona).

The aim of the research was to set a sequence of testing techniques for detecting the masonry quality of four different building typologies. The procedure was developed through the following steps:

- a basic historical research, through archive documents, about the evolution of the four buildings taken into account, or concerning the urban areas they belong to;
- the finding of the geometrical surveys (plans of each floor, prospects and sections) for each one of the studied building;
- exam of the masonry typology through visual inspections;
- determination of the masonry quality by applying: observations of the masonry textures characteristics; direct sonic tests; single and double flat jack tests; mortar sampling; partial dismantling of the masonry sections.

5.2.2.1 Description of the building typologies chosen for the research

The buildings used for the research belong to the category of the complex aggregate, a typology very diffused in the town centre, common in the historic centres deriving from a building process which lasts for centuries. The aggregation could be defined as a construction delimited by open spaces. It is formed by Structural Units (S.U.) which could be defined as portions of the aggregation which have a unitary behaviour from a static and seismic point of view (Figure 5.31 gives examples referred to the centre of Castelluccio di Norcia). S.U. are defined thanks to structural criteria (i.e. a rigid floor defines a single S.U. or two parts with a different kind of masonry are two S.U.) and thanks to historical criteria, according to the age of construction of the several parts.



a) b) c)

Figure 5.31: Example of complex aggregates defying the morphology of the town centre (courtesy of architects G. Cardani and A. Saisi).

Also the four buildings chosen for the research work in Sulmona are structurally connected with the adjacent ones in order to form a block. They form a buildings system - also of remarkable dimensions - delimited by public and/or private void spaces. The plan of the town centre was divided into numbered blocks, in order to distinguish the different aggregates. The blocks no. 39, 48, 69 and 92 include the singular structural units (Figure 5.32) used for the research.

The S. U. belonging to the block no. 39 is a 3 storey house (Figure 5.33a) with a very articulated horizontal distribution in plan. According to historical sources, it was built during the expansion of the city occurred during XIX century. The S. U. belonging to the block no. 48 was the Palace of the Sardi family. It preserves a public façade towards a square (Figure 5.33b) and a very complex development on several levels following the steep descent of this part of the centre. Historical maps indicate that a part of the building was constructed on the pre-existing defensive walls of the town. The S. U.s forming the block no. 69 are located in an area along the ancient defensive walls. The building chosen for the research is a two storey house (Figure 5.33c), conserving a wine cellar and a courtyard. The S. U. used to represent the block no. 92 is a Palace organized on three levels. It was deeply changed during the time: in origin it was the palace of the Meliorati Family (Figure 5.33d) and actually is under renewal to host a bank. A comparison between the typologies of the investigated buildings is contained in Figure 5.34.

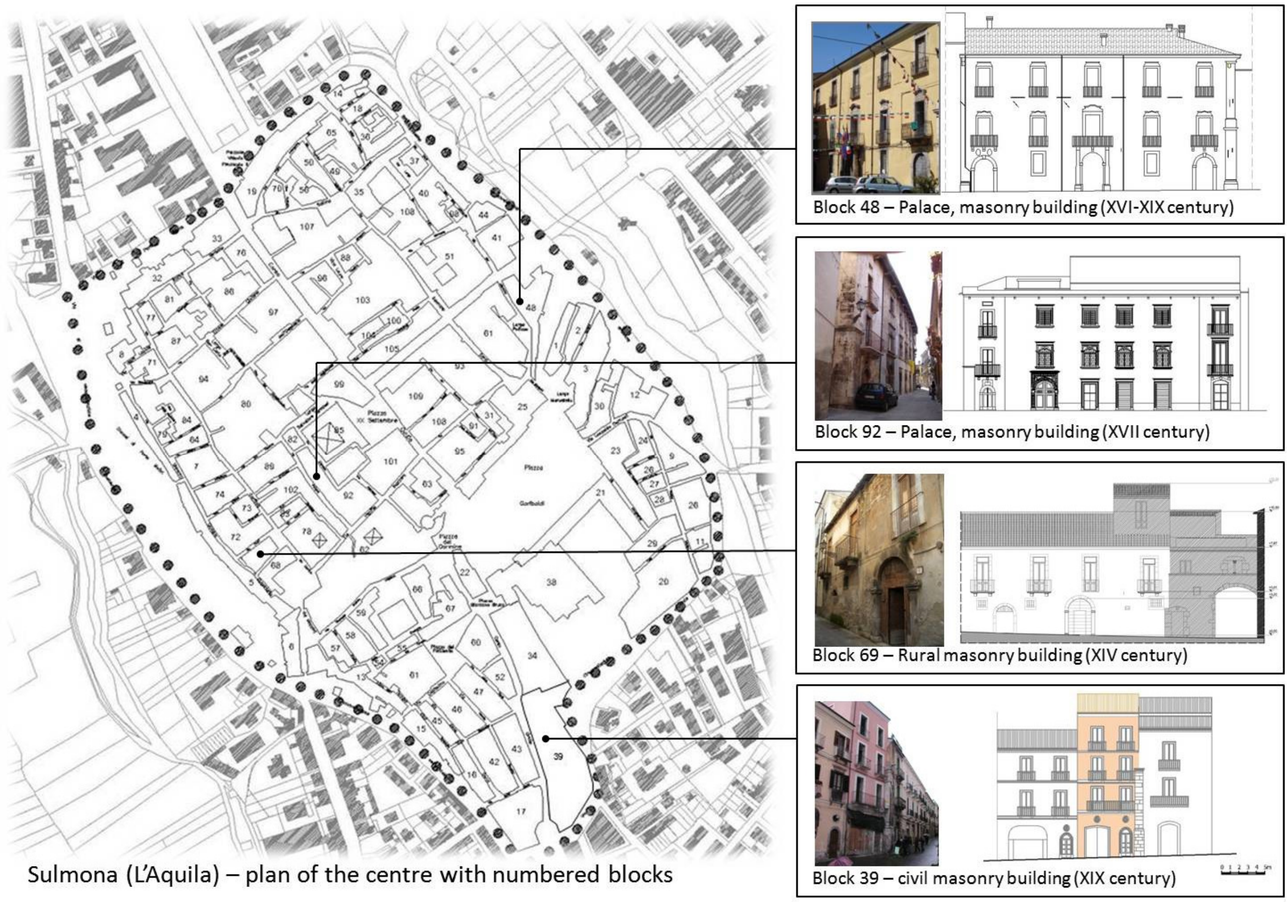


Figure 5.32: Plan of the centre of Sulmona with the indication of the blocks taken into account for the research study (layouts are a courtesy of Professor A. Anzani and Arch. G. Cardani, rearranged by the author).

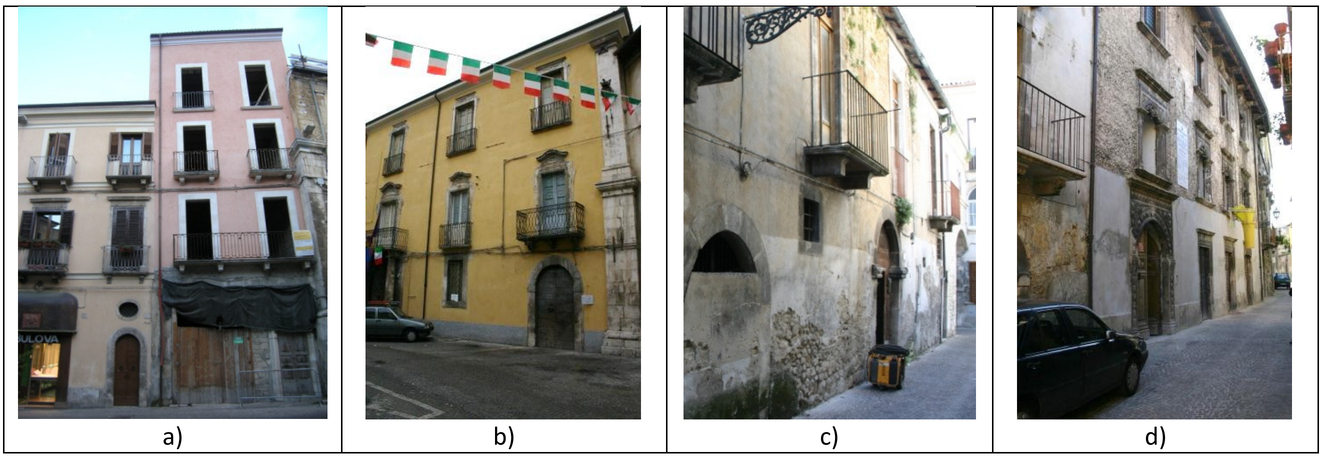


Figure 5.33: View of the main facades of the investigated building: a) civil building in block 39; b) Sardi Palace in block 48, c) civil building in block 69; d) Meliorati Palace in block 92 (pictures by the author).

Figure 5.34: Comparison between the 4 investigated building typologies (layouts, rearranged by the author, are a courtesy of Professor A. Anzani and Arch. G. Cardani).

5.2.2.2 Results of the tests campaign on the historical centre of Sulmona

As mentioned before, the study of the masonry quality was developed through several procedures. After the availability of historical information and of existing surveys, the main structures of each building were studied in depth through the analysis of the masonry textures: the presence of horizontal courses was observed and even the presence of the vertical alignment of the joints was taken into account (Figure 5.35). Furthermore, direct sonic tests were carried out to characterize the masonry section. The quality of the masonry wall requires this kind of test to verify the supposed performance of the structure indicated by the simple observation of the masonry texture. Ancient walls, with relevant thickness, could hide layers with different characteristics, hardly detectable by the surveys of the external layers.

Civil building in block 39

The civil house placed in the block 39 was investigated in two positions (see the plan in): masonry 1 (a shear wall) and masonry 2 (the wall of the main facade). The masonry texture appears irregular, made by stones with different shapes and dimensions. The results of the sonic tests show a non-homogeneous distribution of the velocities and the value are comprised between 385 and 1289 m/s for masonry 1 and 557 and 1750 m/s for masonry 2.

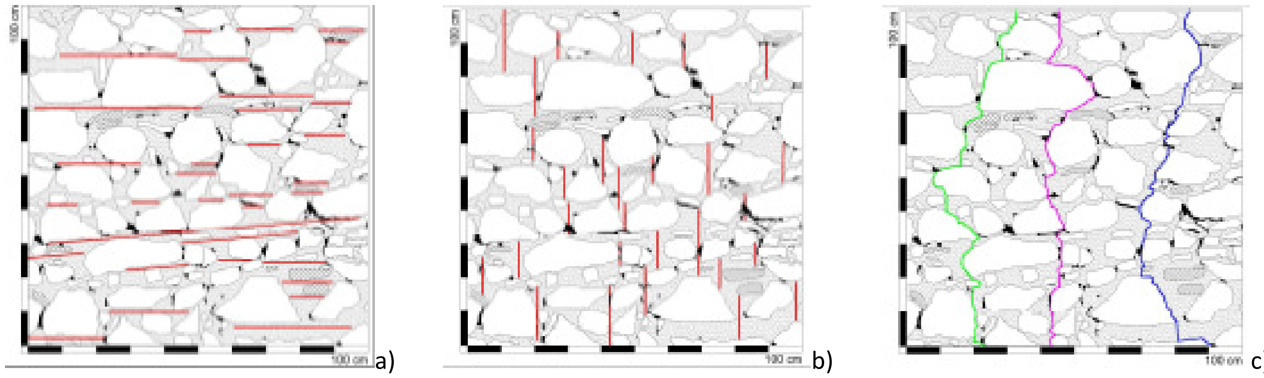


Figure 5.35: Example of the vulnerability study of a masonry texture: a) evaluation of the presence of horizontal or sub-horizontal courses; b) observation of the alignment of the vertical joints; c) detection on the seizing on the external layer (courtesy of professor A. Anzani and Arch. G. Cardani).

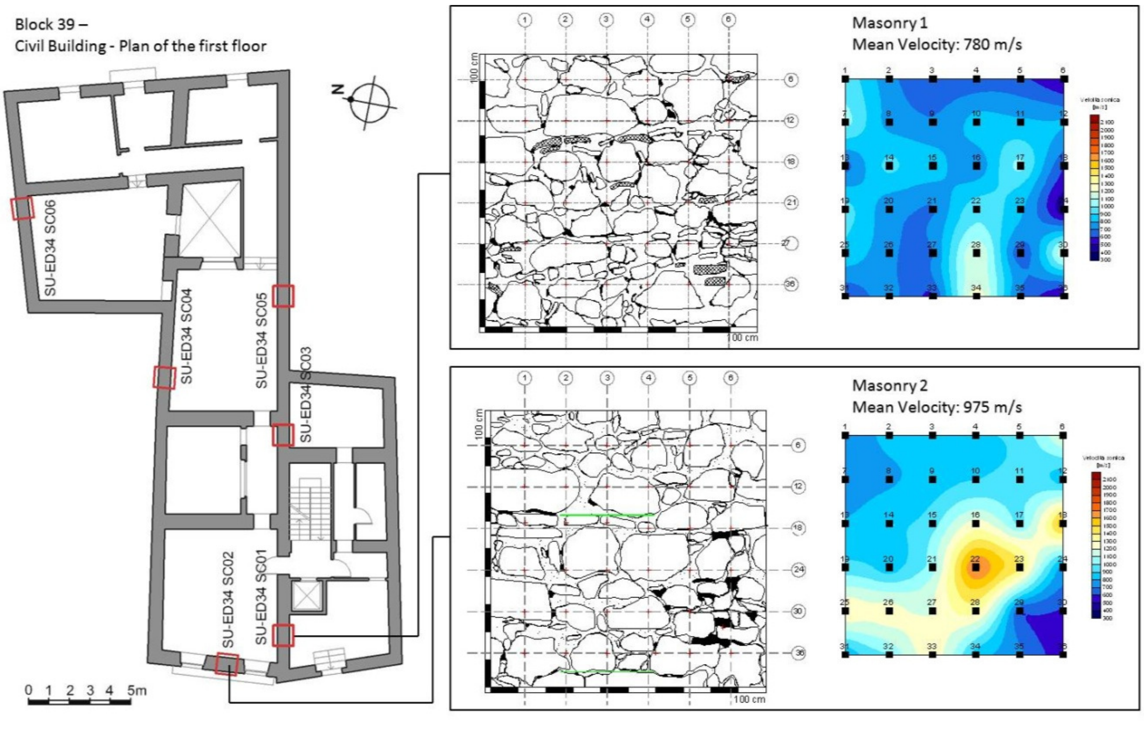


Figure 5.36: Didect sonic tests carried out in the civil house belonging to the block 39: tests positions; layout of the tests on the masonry texture and maps of the velocity (layout by the author).

Sardi Palace in block 48

Sardi Palace (block 48) was investigated applying sonic tests in 4 positions (masonry 1, 2, 3 and 4). According to the historical development of the building, each position was representative for a constructive phase of the building. The observation of the masonry textures indicate that all the investigated walls were realized with irregular stone blocks, but providing horizontal courses and avoiding vertical alignment of the mortar joints (Figure 5.37).

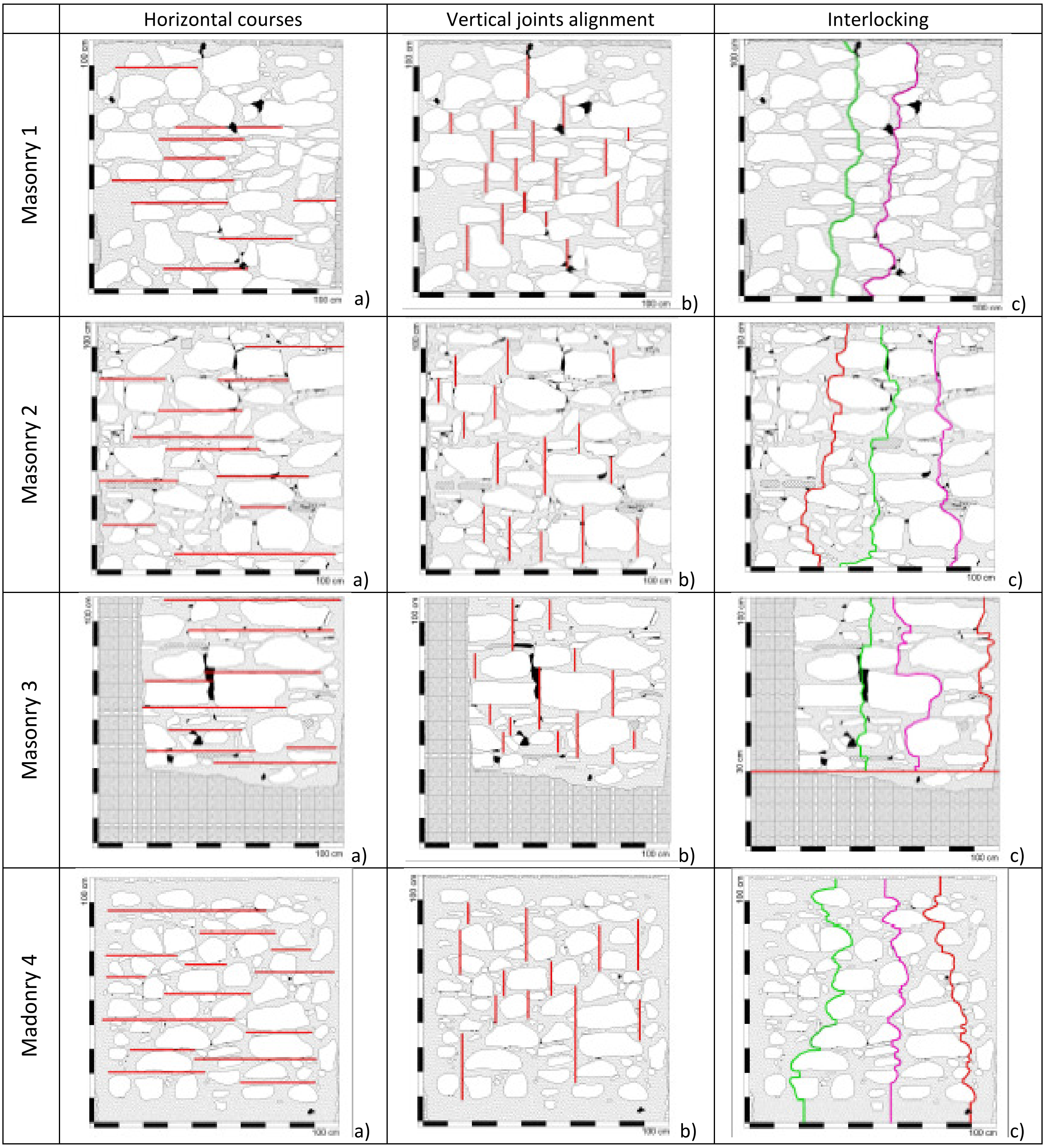


Figure 5.37: analysis of 4 masonry textures belonging to Sardi Palace (block 48) (courtesy of professor A. Anzani and Arch. G. Cardani).

The fair quality of the four masonry sections was confirmed by the direct sonic tests. The results indicate that masonry 3 has rather lower velocities respect to the other results. Masonry 1, 2 and 4 are more homogeneous and the presence of periodical connecting elements characterise both masonry 2 and 4.

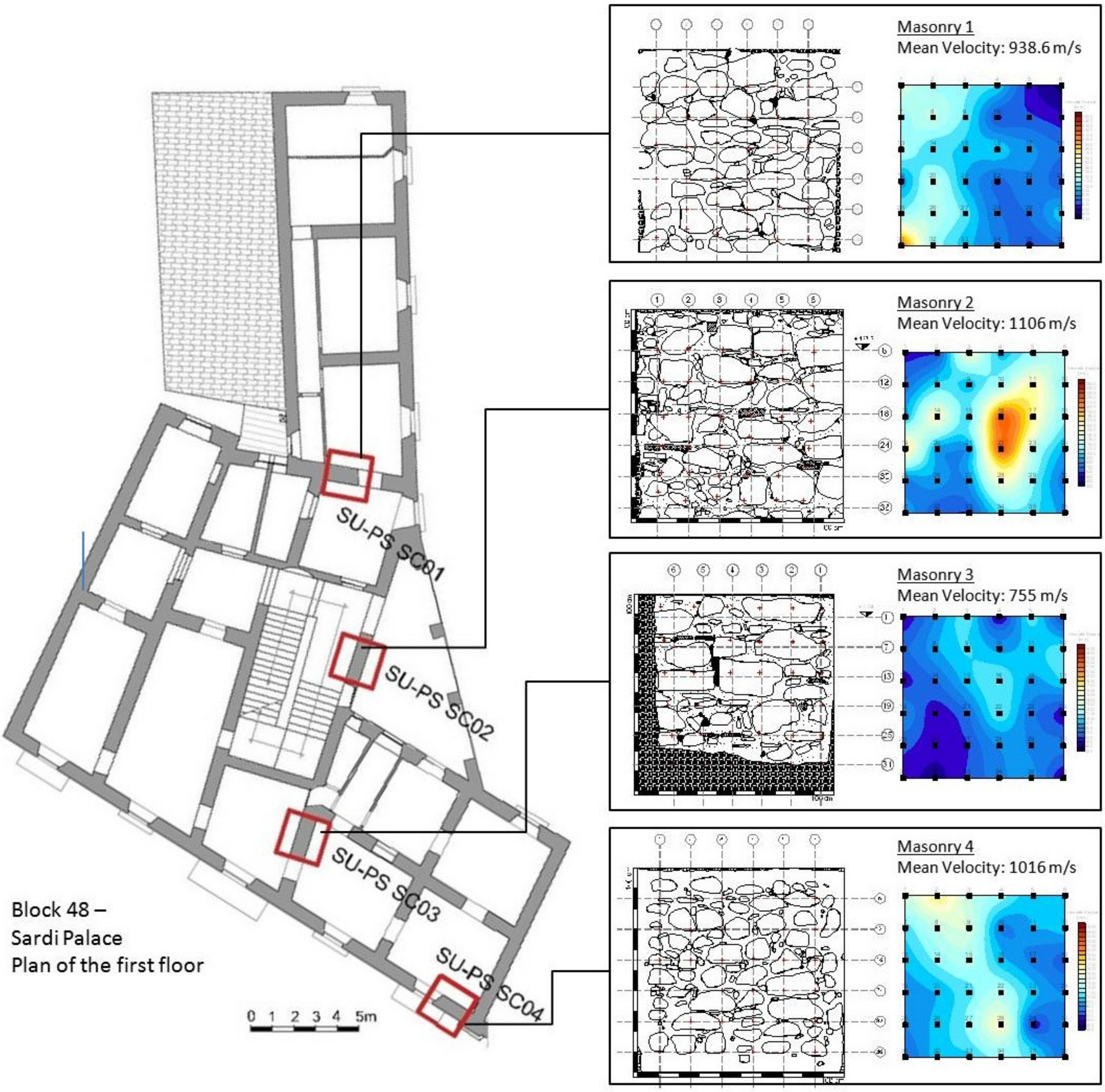


Figure 5.38: Direct sonic tests carried out in Sardi Palace (block 48): tests positions; layout of the tests on the masonry texture and maps of the velocity (layout by the author).

Rural building in block 69

The rural building in the block 69 was studied taking into account two masonry walls with irregular texture and a pillar externally composed by regular stone blocks.

The textures of masonry 1 and masonry 2 show the presence of sub horizontal joints for the first one and horizontal courses for the second one. The vertical joint alignment is correct in both cases, whilst the mechanical seizing appear poor (Figure 5.39).

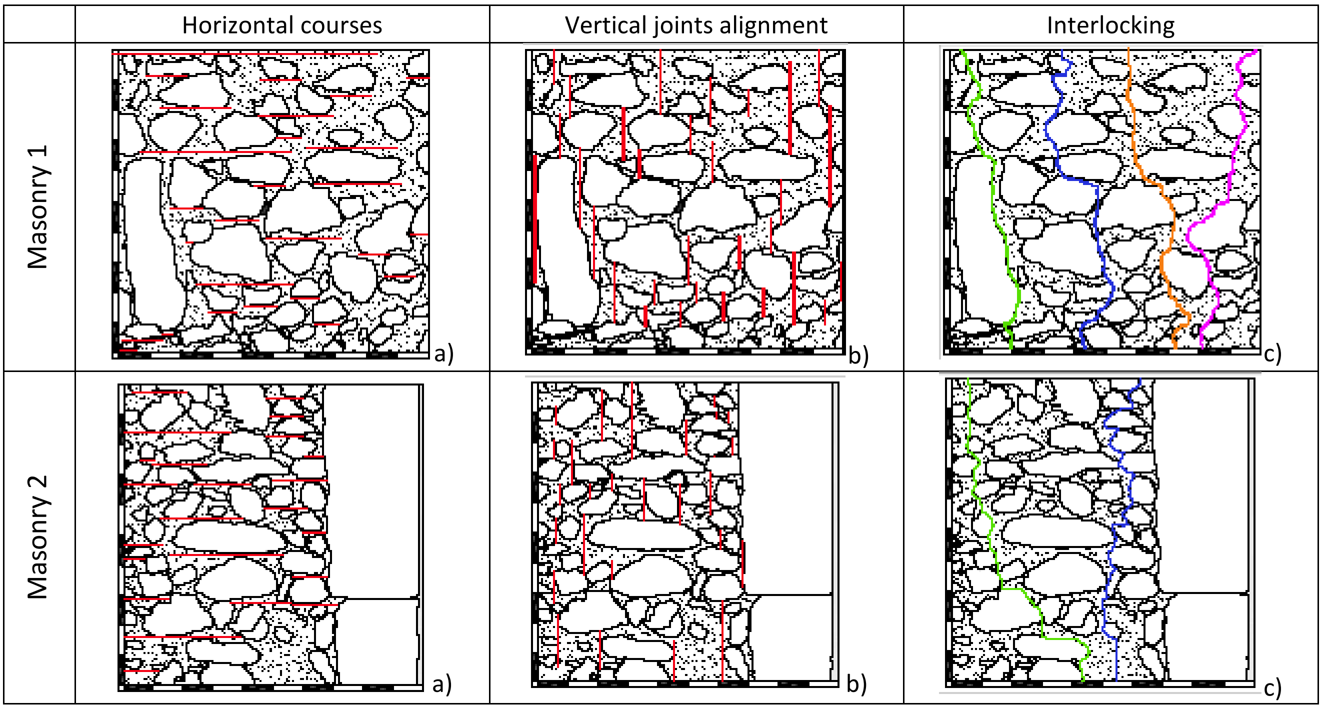


Figure 5.39: Analysis of the masonry texture for two walls belonging to the rural house in block 69. (courtesy of professor A. Anzani and Arch. G. Cardani).

The direct sonic tests carried out on masonry 1 and 2 present a distribution of the velocities that is very closed with the previous examples. According to historical information about this building, the investigated walls were built in XIV century. The textures present some differences respect to the other observed cases and through the survey their characteristics seem to have lower quality than the other artefacts. The results of the sonic tests demonstrate that the section of the walls present the same fair connections between its elements (Figure 5.40). Moreover, the direct sonic tests carried out on the pillar with regular stones (masonry 3) shows that this structure contains multiple layers: the velocities decrease from the points along the external profile to the central column points. Also in this case the value of the velocities referred to the central area of the grid is closed to the one observed for the other masonry wall. The pillar is an inhomogeneous structure with an internal leaf composed by elements not particularly well connected and the external leaf composed by well-shaped regular stones.

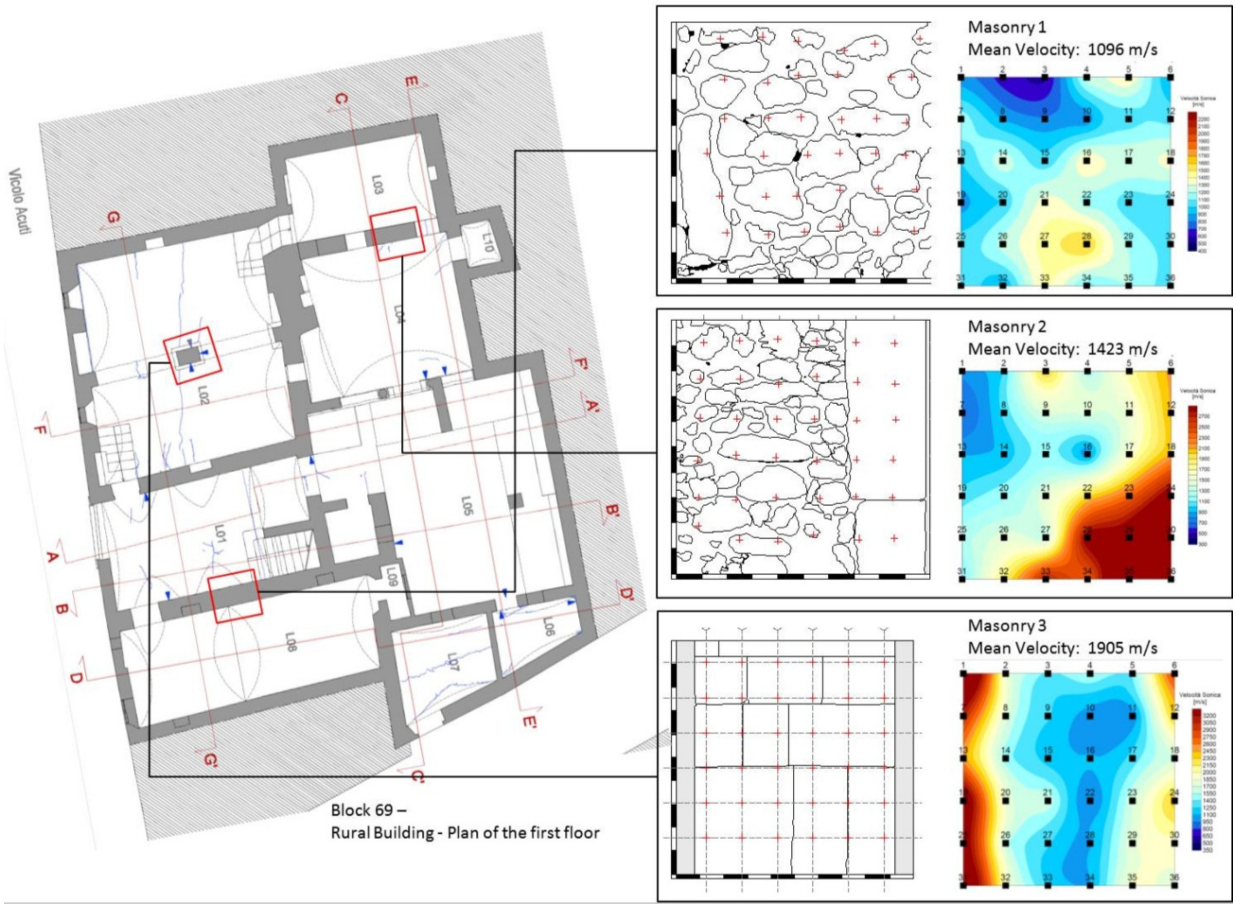


Figure 5.40: Direct sonic tests carried out in the rural house (block 69): tests positions; layout of the tests on the masonry texture and maps of the velocity (layout by the author).

Meliorati Palace in block 92

The last tests were carried out in two positions of the Meliorati Palace (block 92). The masonry texture appear here modified by additions and changings in the building technic: masonry 1 present irregular stones with a small dimension, and a part rebuilt using bricks; masonry 2 seems to be built with more attention (Figure 5.41). Considering the results of the sonic tests, the velocities measured in both positions are very low (Figure 5.42), indicating a general absence of connections between the components of the wall section. The mean values of the velocity, 698 m/s for the first masonry and 617 m/s for the second, are closed to the propagation of the elastic waves in the air. These results indicate a dangerous condition of the load bearing walls and a high vulnerability for the whole building in case of seismic event.

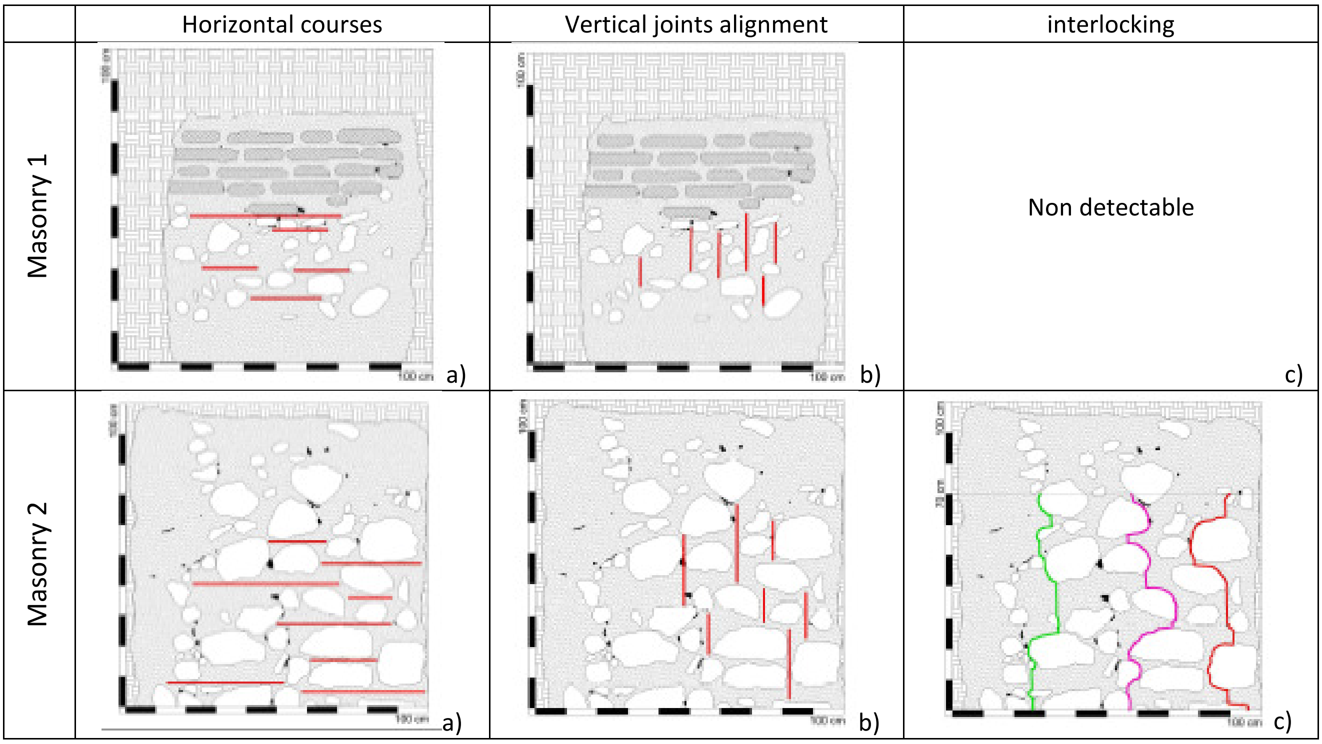


Figure 5.41: Analysis of the masonry texture for two walls belonging to Meliorati Palace in block 92 (courtesy of professor A. Anzani and Arch. G. Cardani).

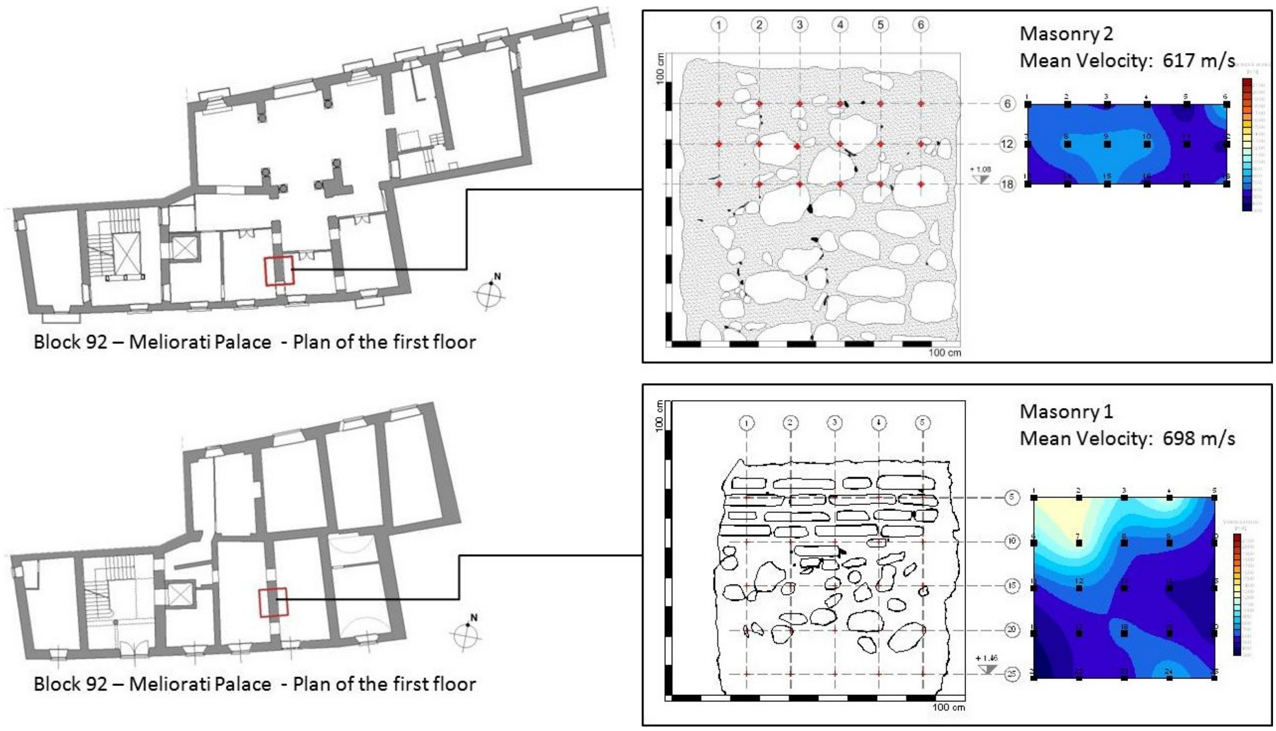


Figure 5.42: Direct sonic tests carried out in Meliorati Palace (block 92): tests positions; layout of the tests on the masonry texture and maps of the velocity (layout by the author).

Even though the sonic tests provided fairly clear results for the interpretation of the main characteristics of the masonry morphology of each investigated masonry wall (Figure 5.43), a classification of the quality of the structures based on the unique application of sonic direct test is not admissible. These results provide an important support for the global characterization of the structures, but they remain qualitative information. In this case, the further execution of double flat jack tests (Figure 5.44) in the same positions investigated by direct sonic tests contributed to validate the sonic method.

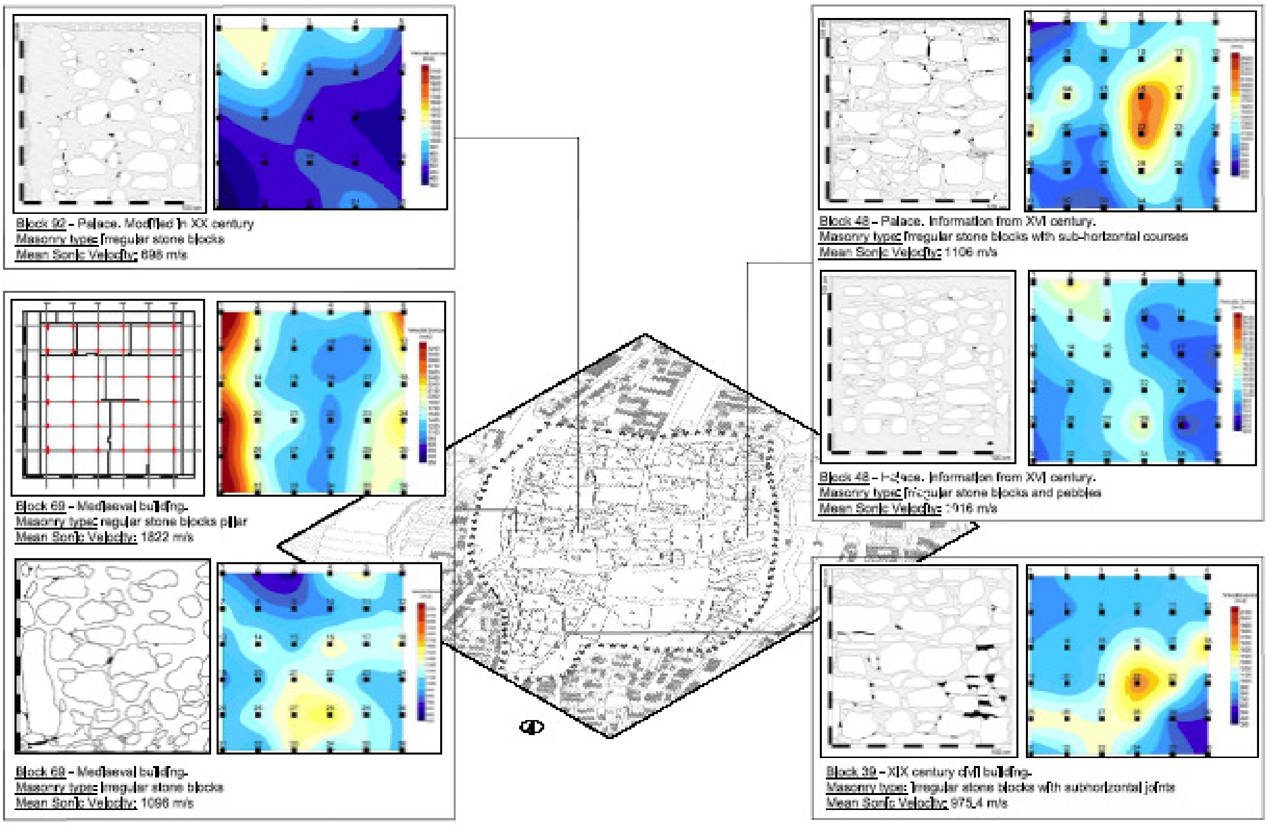


Figure 5.43:Sonic tests campaign in Sulmona: Investigation of the properties of the different masonry typologies by direct sonic tests (layout by the author).

Double flat jack tests (block 39, 69 and 48)

Block 39 was investigated through two double flat jack tests carried out into the area previously characterised by sonic tests. The interpretation of the data allowed to calculate the Modulus of Elasticity of these walls: 368 MPa for masonry 1 and 289 MPa for masonry 2 (Figure 5.45). In Block 69, the double flat jack test was carried out only for masonry 1: the Modulus of Elasticity is here 1168 MPa (Figure 5.46), indicating better mechanical properties, if compared to the results obtained for block 39. Block 48, Sardi Palace, is composed by several additions and for this reason double flat jack tests were carried out on masonry 1 (dated about XV century) and on masonry 4 (dated about XVIII century). The results were: 574 MPa for masonry 1 (Figure 5.47) and 956 for masonry 4 (Figure 5.48). Finally, the double flat jack test carried out in block 92 (Meliorati Palace) was not admissible: here, the renewed masonry texture had very low quality and the necessary conditions for performing the double flat jack test (above all, bounded elements) were not present.

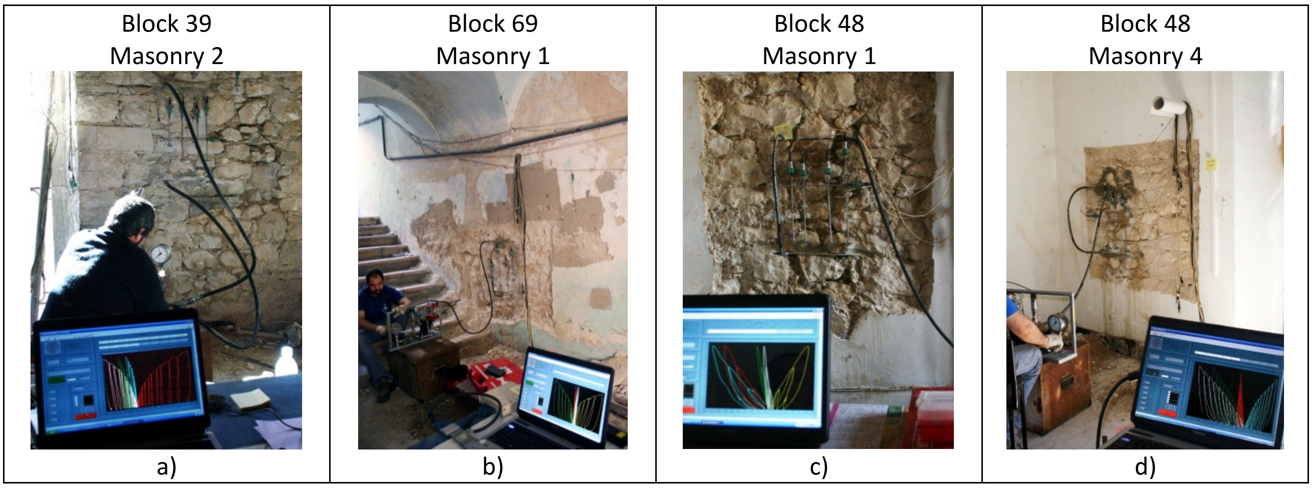


Figure 5.44: Double flat jack tests executed in: a) block 39 (civil building deted XIX century); b) block 69 (medieaval building); c) and d) block 48 (Sardi Palace) (pictures by the author).

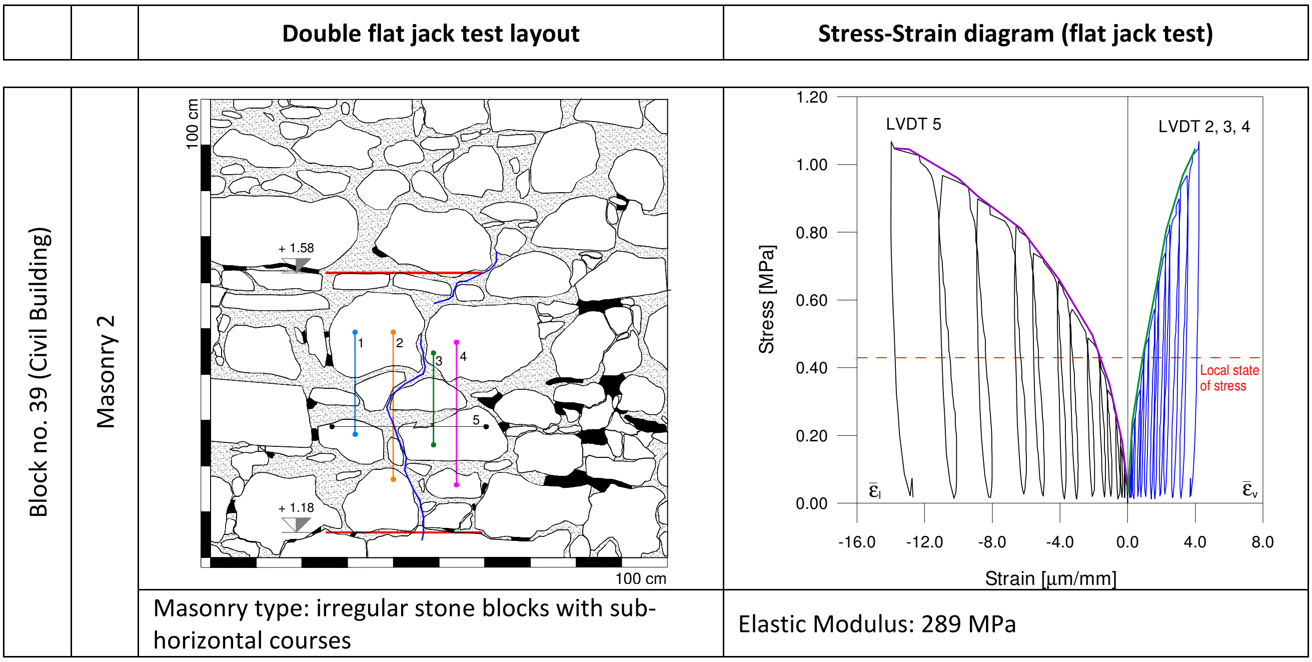


Figure 5.45: Double flat jack test carried out on masonry 2 in block 39: layout of the test and stress-strain graph (layout and elaboration by the author)

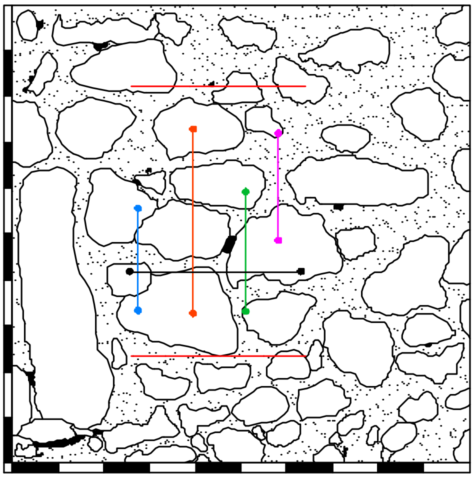
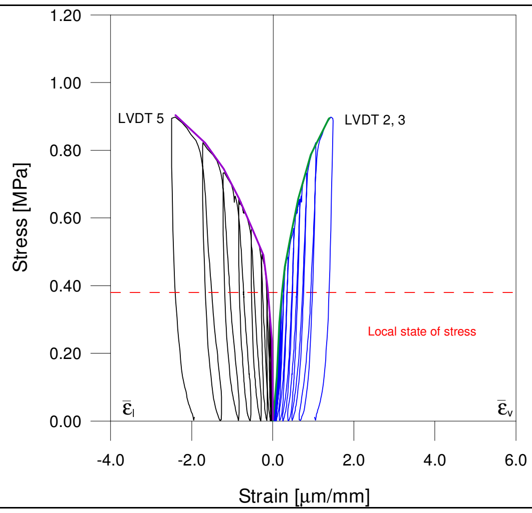
		Double flat jack test layout	Stress-Strain diagram (flat jack test)
Block no. 69 (Rural Building)	Masonry 1		
		Masonry type: irregular stone blocks	Elastic Modulus: 1668 MPa

Figure 5.46: Double flat jack test carried out on masonry 1 in block 69: layout of the test and stress-strain graph (layout and elaboration by the author).

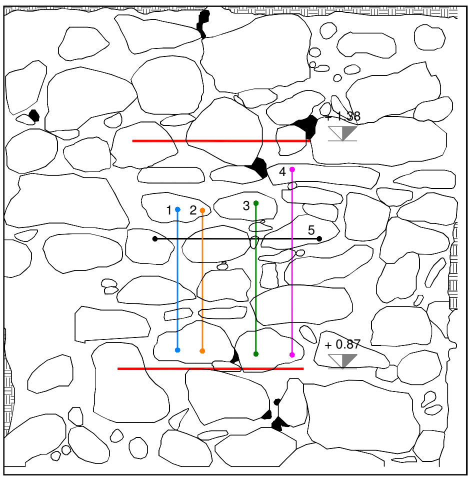
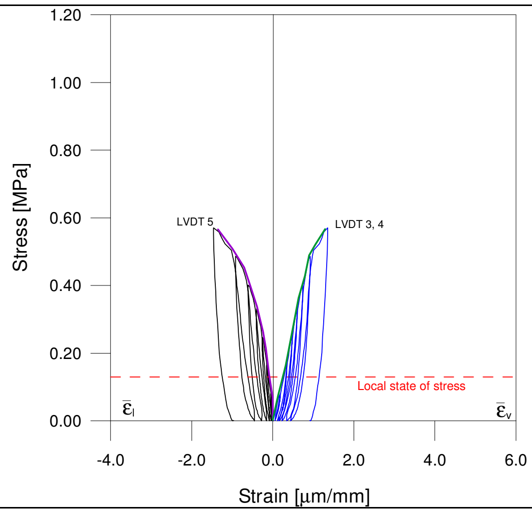
		Double flat jack test layout	Stress-Strain diagram (flat jack test)
Block 48 (Sardi Palace)	Masonry 1		
		Masonry type: irregular stone blocks with sub-horizontal courses	Elastic Modulus: 574 MPa

Figure 5.47: Double flat jack test carried out on masonry 1 in block 48: layout of the test and stress-strain graph (layout and elaboration by the author).

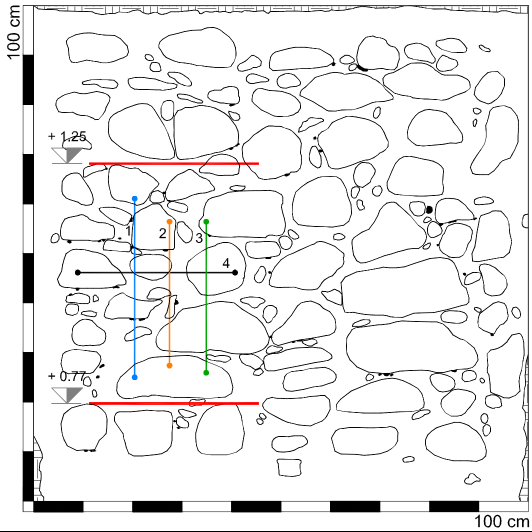
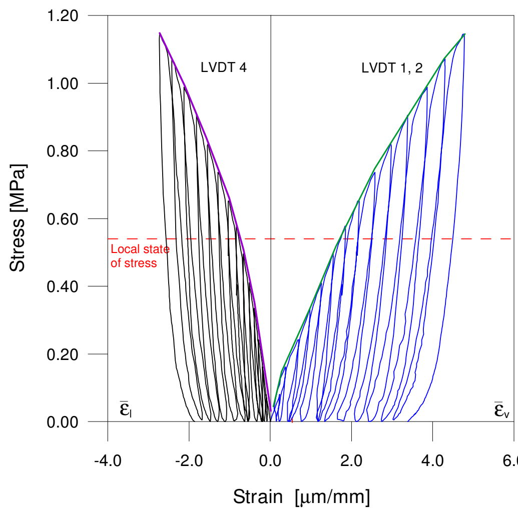
<table>
<tr><th></th><th></th><th>Double flat jack test layout</th><th>Stress-Strain diagram (flat jack test)</th></tr>
<tr><td rowspan="2">Block 48 (Sardi Palace)</td><td rowspan="2">Masonry 2</td><td>
</td><td>
</td></tr>
<tr><td>Masonry type: irregular stone blocks</td><td>Elastic Modulus: 956 MPa</td></tr>
</table>

Figure 5.48: Double flat jack test carried out on masonry 2 in block 48: layout of the test and stress-strain graph (layout and elaboration by the author).

The modulus of elasticity obtained by double flat jacks can be put into relation with the mean values of the sonic velocities: the lower elastic moduli correspond to the lower sonic velocities. This relationship corresponds to a trend, but at the moment is not supported by any other scientific connection. Considering the results collected in Sulmona, the comparison between the sonic velocity and the elastic modulus, respectively obtained by direct sonic tests and double flat jack tests, shows that the investigated masonry typologies present different mechanical properties.

The second investigated wall of the civil building in block no. 39 (dated XIX century and recently renewed) presents discordant results (Figure 5.49). The distribution of the values is not homogeneous, but the mean value of the direct sonic velocity is lower than 1000 m/s. Anyway, the sonic test did not reveal values closed to the sonic waves propagation into air (348 m/s): for this reason the investigated area of the wall cannot be considered as a low quality structure, according to sonic tests. On the contrary, observing the stress-strain graph drawn from the double flat jack, the wall presents very low quality: the Modulus of Elasticity of about 289 MPa cannot be associated to a masonry with high mechanical properties. This discordance between the results of the tests points out the following remarks:

- Masonry typology can be more suitable to be investigated by certain category of tests than others: in this case, the masonry texture of the external layer was not suitable for the execution of the double flat jack test, being too deformable and presenting stone elements badly seized up.
- The complementary use of different testing techniques provide a better interpretation of the results: direct sonic tests, carried out on the whole thickness of the wall, present a global response of the structure, whilst double flat jack tests are applied on a limited portion of the wall (in this case the thickness of the flat jack is 24 cm).
- According to the sonic test, the masonry presents an adequate connections between the elements and this result can drive the interpretation of the double flat jack tests: the high level of deformations observed during the first cycles of the test indicates a negative influence of the masonry texture of the external layer hosting the transducers (LVDTs) used for the test. The local influence of the constructive technique represents here a limit for the execution of the double flat jack test.

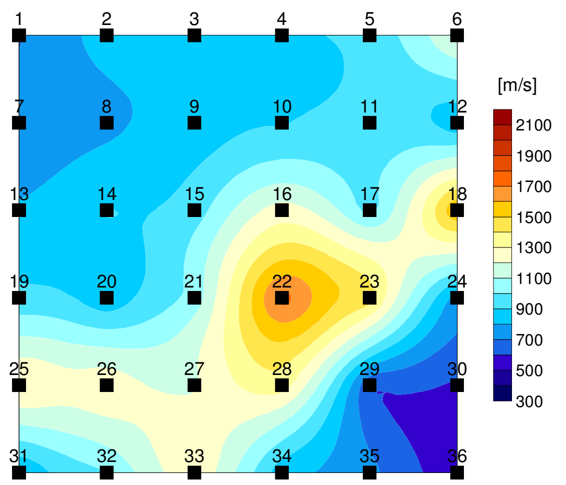
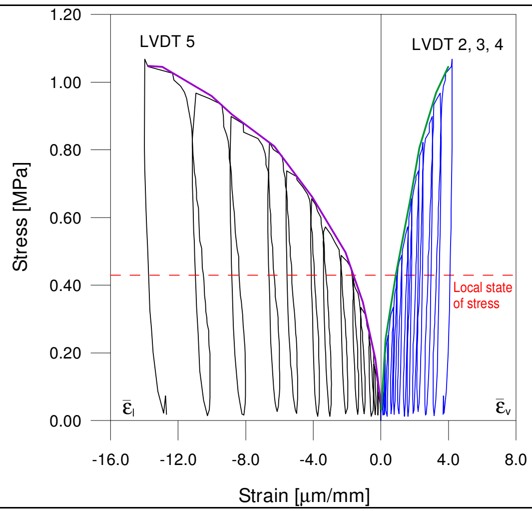
<table>
<tr><th></th><th></th><th>Map of the velocity (sonic tests)</th><th>Stress-Strain diagram (flat jack test)</th></tr>
<tr><td rowspan="2">Block no. 39 (Civil Building)</td><td rowspan="2">Masonry 2</td><td>
</td><td>
</td></tr>
<tr><td>Mean sonic velocity: 975m/s</td><td>Elastic Modulus: 289 MPa</td></tr>
</table>

Figure 5.49: Comparison between the results obtained by direct sonic test and double flat jack test carried out on the masonry 2 in block 39 (elaborations by the author).

In block no. 69, the sonic and flat jack tests indicate in both cases that the structure is composed by appropriately connected stone elements (the mean sonic velocity is 1096 m/s) and the Elastic modulus calculated through the double flat jack (1168 MPa) represents good mechanical properties for the type of masonry tested (Figure 5.50). Observing the stress-strain graph, in this case the mechanical behaviour of the investigated masonry is characterized by contained permanent deformations only for the last cycles of the test, indicating that the constructive technology applied for this structure provide an elastic response to a relevant increment of the compressive strength. The accordance between the tests demonstrates that the masonry texture did not produce here unexpected negative effects to the devices used to achieve the data of the tests.

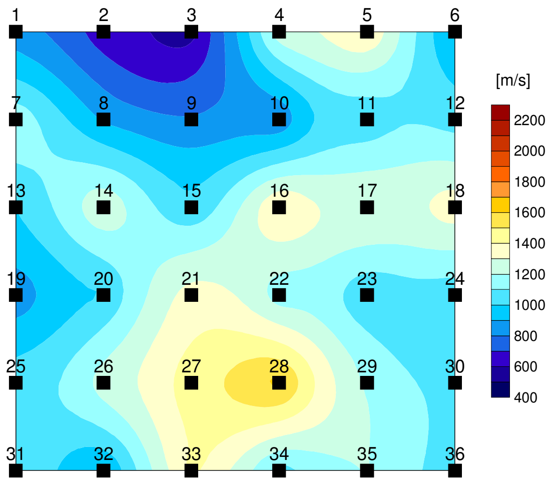
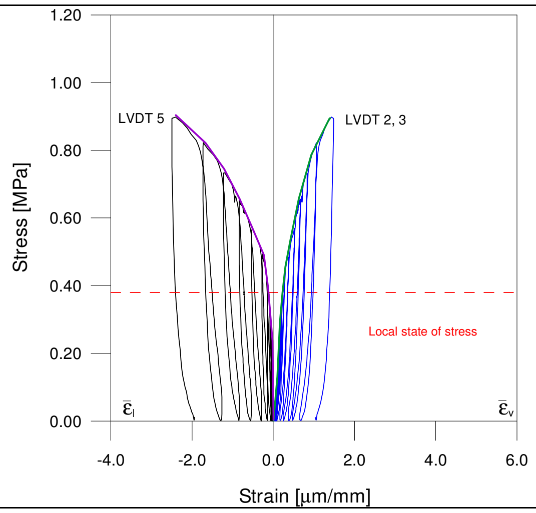
<table>
<tr><th></th><th></th><th>Map of the velocity (sonic tests)</th><th>Stress-Strain diagram (flat jack test)</th></tr>
<tr><td rowspan="2">Block no. 69 (Rural Building)</td><td rowspan="2">Masonry 1</td><td>
</td><td>
</td></tr>
<tr><td>Mean sonic velocity: 1096m/s</td><td>Elastic Modulus: 1168 MPa</td></tr>
</table>

Figure 5.50: Comparison between the results obtained by direct sonic test and double flat jack test carried out on the masonry 1 in block 69 (elaborations by the author).

Other remarks can be made taking into account the two masonries, built in different period, part of the same structural unit in block no. 48 (Sardi Palace): masonry 1 and masonry 4 (Figure 5.51). Masonry 1 (dated XV century) presents a deep inhomogeneity, according to sonic tests: the mean sonic velocity is 938 m/s, but the sonic grid seems to be divided in two separate areas: one characterized by values around 1200 m/s and the other presenting lower velocities (around 700 m/s). The poor quality of masonry 1 is confirmed by the double flat jack test: it provided a Modulus of Elasticity of about 574 MPa. Masonry 4 (dated XVIII century) showed a very close sonic velocity (1016 m/s), whilst the Modulus of Elasticity resulted higher: 956 MPa. These differences show that the similar sonic velocities cannot be associated to the same mechanical behaviour:

both walls don't present high mechanical performance, but the results obtained by double flat jack tests denote a deep difference in their mechanical behaviour.

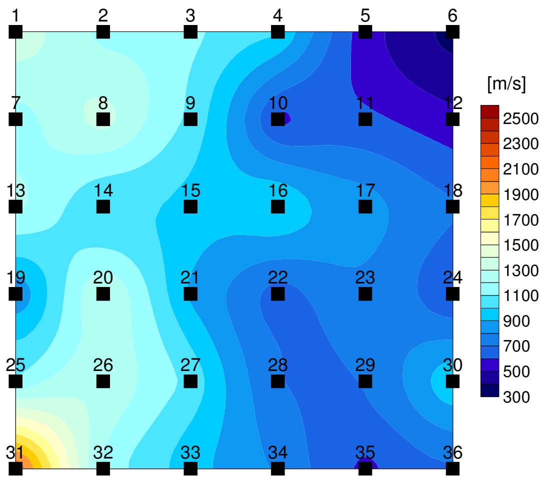
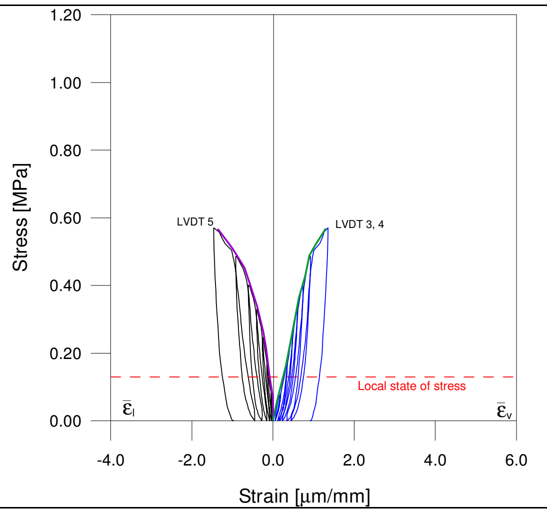
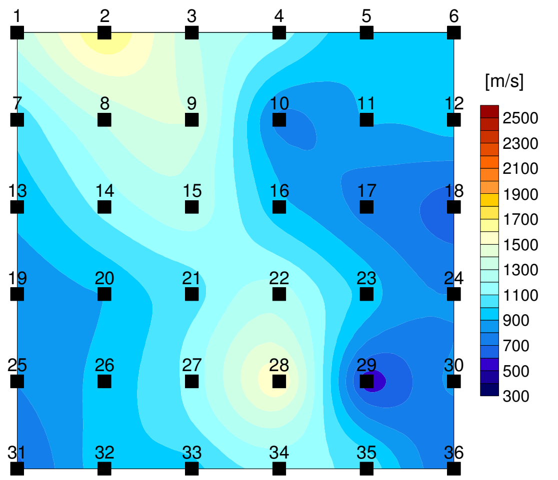
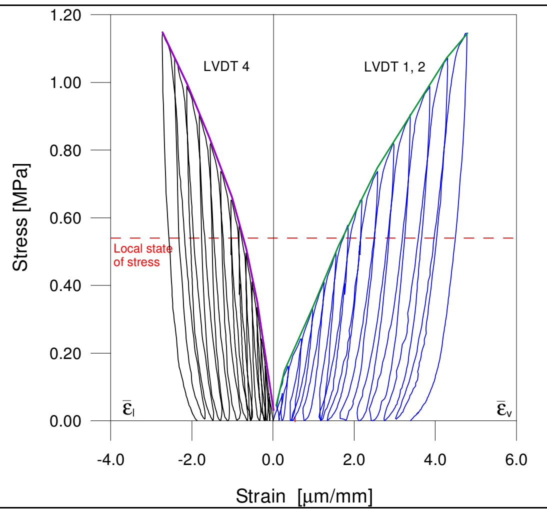
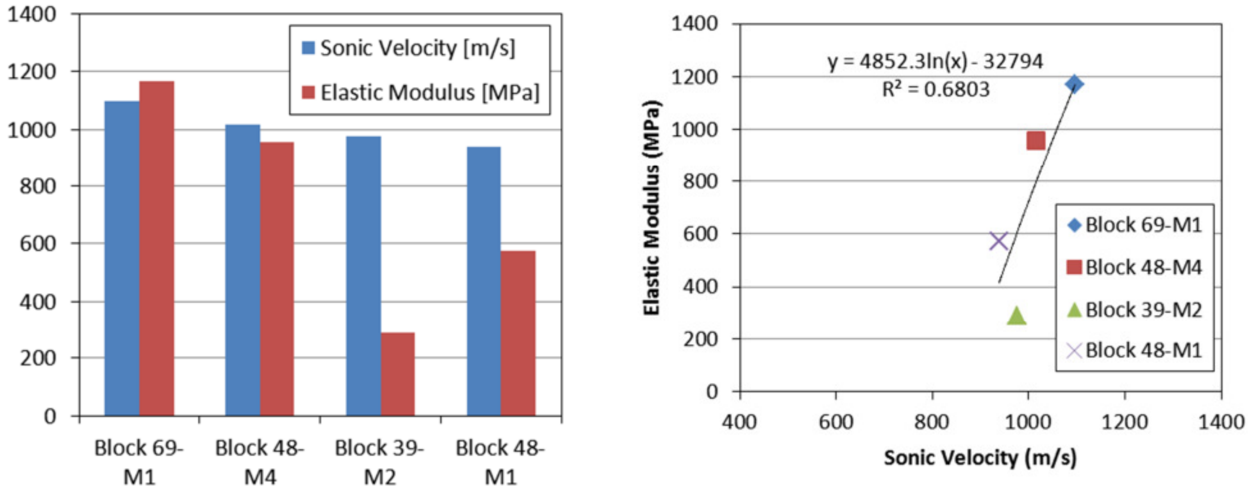
		Map of the velocity (sonic tests)	Stress-Strain diagram (flat jack test)
Block 48 (Sardi Palace)	Masonry 1		
		Mean sonic velocity: 938 m/s	Elastic Modulus: 574 MPa
Block 48 (Sardi Palace)	Masonry 2		
		Mean sonic velocity: 1016 m/s	Elastic Modulus: 956 MPa

Figure 5.51: Comparison between the results obtained by direct sonic test and double flat jack test carried out on the masonry 1 and masonry 4 in block 48 (elaborations by the author).

As anticipated before, taking into account the main results of the Sulmona testing campaign (Figure 5.52a), a trend can be identified correlating sonic velocities and elastic moduli (Figure 5.52b). As shown in the graphs presented in Figure 5.52a, the sonic velocities measured in the investigated buildings respect a trend according to the masonry quality of the walls types built in different periods: the different building techniques can justify the variations in the observed results. Nevertheless, the irregular characteristics of the textures represent a limit for the identification of a trend considering the results computed by double flat jack tests. As a result, the correlation presented in Figure 5.52 is negatively affected by data that are not always representative of the real mechanical response of the whole masonry section: irregular masonry sections, composed by more layers, do not allow to extend the result obtained by double flat jacks on the external layer to the internal ones.



a) b)

Figure 5.52: a) comparison between sonic velocities and elastic moduli and b) E vs. V correlation based on the data achieved during Sulmona campaign (elaborations by the author).

Anyway, the range of the elastic modula computed in Sulmona testing campaign respects the value of the same parameter measured in previous tests carried out on similar masonry typologies. In 2006, the data collected by Binda, after the simultaneous application of sonic and flat jack tests on the same structure, were used to compare the mechanical property of different building typologies[204]. These results were obtained during the study of the masonry quality and the building vulnerability of some historical centre in Liguria and Umbria Region. The Modulus of Elasticity was used to classify rural, civil and monumental buildings (Figure 5.53). It was observed that rural buildings had the lowest mechanical characteristics (E= 303-648 MPa). Civil buildings

[204] 10. Binda L., Cantini L., Cardani G., Saisi A., Tiraboschi C., Use of Flat-Jack and Sonic Tests for the Qualification of Hisotir Masonry, 10th Tenth North American Masonry Conference (10NAMC), St. Louis, Missouri, 3-6/06/07 (Binda L. C., 2007)

presents similar properties (E= 711-938 MPa). Buildings built for particular purposes (castles, churches or palaces) showed values, but also high variability (E= 1349-5043 MPa).

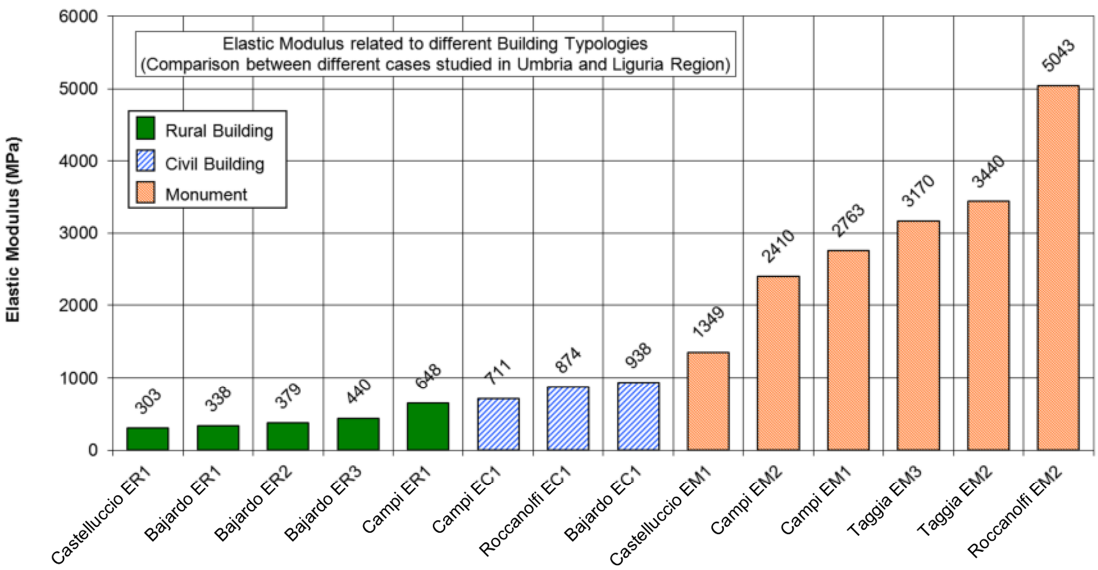


Figure 5.53: E vs. building typology, based on the data collected in Umbria and Liguria Region (graph by the author).

Since the 90s of the last century, thanks to the studies promoted by the GNDT (National group for the defence against earthquakes), a connection between masonry texture typology and mechanical performance was investigated. This idea was founded on previous researches presenting the methodology for classifying the quality of the masonry through the characteristics of the texture. A. Borri gave an important effort to that study and his typological classification of the masonry texture was adopted as one of the main parameter for the estimation of the seismic vulnerability in the recommendation of Umbria Region[205]. In 2005, the Ordinance 3274-2005 introduced the table 11.D.1 (annex D), presenting a short description for 6 masonry texture typologies and providing the corresponding average values for compressive, shear strength and elastic moduli. Recently, a proposal for an updating of the definitions contained in the Ordinance was presented by some RELUIS in order to improve the classification of the masonry types. A comparison between the two descriptions of the masonry typologies is presented in Table 5.1.

[205] Supplemento ordinario n. 1 al “Bollettino Ufficiale della regione dell’Umbria”, n. 31 del 30 luglio 2003 – *“Regolamento Regionale 15 luglio 2003, n. 9 – Norme di attuazione della legge regionale 23 ottobre 2002, n. 18 – Norme in materia di prevenzione sismica del patrimonio edilizio*. (Bollettino Regione Umbria n.31, 2003)

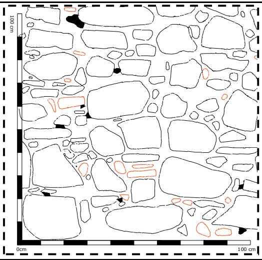
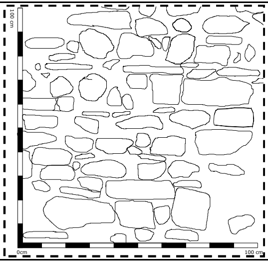
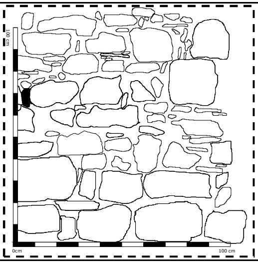
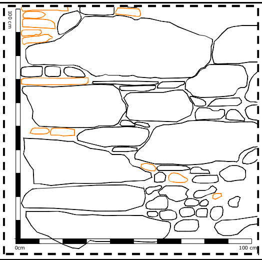
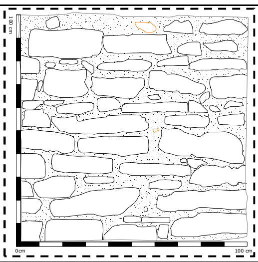
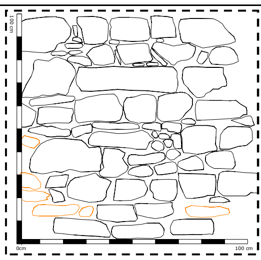
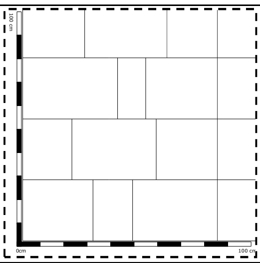
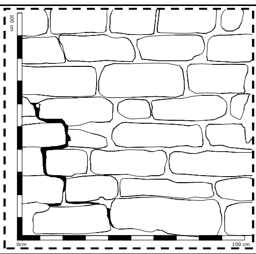
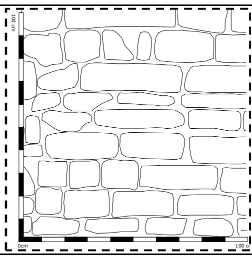
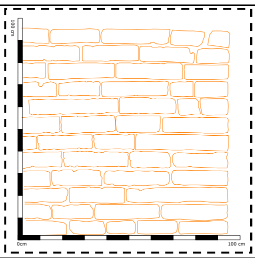
Code	Examples of masonry textures		Definition according to OPC 3274-2005, table 11.D.1, annex D	Definition according to the modifications proposed by RELUIS
A			Irregular stones masonry (pebbles, erratic and irregular stones).	Irregular stones masonry (pebbles, erratic and irregular stones), disordered in the shape, the dimension and the type of materials.
B			Hewn stones with limited depth and presence of internal core.	Hewn stones with variable dimensions and for the most part with horizontal courses.
C			Split shaped stones masonry with good texture.	Split shaped stones (also with irregular shape) with good texture (well-connected textures).
D			Soft stones masonry (tophus or travertine, calcarenite, etc.).	Square soft stone blocks masonry (tophus, calcarenite, etc.).
E			Square stone blocks masonry.	Square blocks masonry with non-soft stones.
F			Masonry in brick and lime mortar.	*No proposal for modifications*

Table 5.1: Definition of 6 different masonry textures according to the Ordinance 3274-2005 and to the modifications proposed by RELUIS

A further effort to the classification of the masonry structures by double flat jack tests was achieved by comparing the common masonry buildings techniques. Masonry composed by regular stone blocks presents the highest elastic moduli, whilst irregular stonework is characterized by a mean value of modulus of elasticity that is lower than the one obtained for brickworks[206]. The data used for that research are collected in Table 5.2 and Table 5.3.

	Place name	Test code	Velocity (m/s)	E (MPa)	Dilation Coefficient	Onset crack. (MPa)	Masonry type	Buildin g type
Umbria Region	Campi di N.	CM200-JD1	1398	648	0.04	0.33	Hewn stones (type B)	civil building
	Campi di N.	CM199-JD3	737	711	0.14	0.4	irregular stones (type A)	civil building
	Campi di N.	CMSA-JD4	1289	2763	0.01	0.49	irregular stones (type A)	church
	Campi di N.	CMC-JD5	914	708	0.12	0.33	irregular stones (type A)	bell-tower
	Castelluccio	CL-SM-J1D	1050.74	1349	0.16	0.66	irregular stones (type A)	bell-tower
	Castelluccio	CL-ST-J1D	611.16	303	0.52	0.33	irregular stones (type A)	civil building
	Castelluccio	CLCA-JD6	1157.35	2358	0.29	0.65	irregular stones (type A)	civil building
	Montesanto	MSTC-JD4	1768	3585	0.14	0.58	irregular stones (type A)	bell-tower
	Montesanto	MSCA-JD6	1052	2126	0.51	0.88	irregular stones (type A)	civil building
	Montesanto	MSCH-J2D	856	1241	0.05	0.35	regular stones (type E)	church
	Roccanolfi	RCC-JD2	1653	5595	0.03	0.86	irregular stones (type A)	palace
	Roccanolfi	RCHDM4	999	874	0.43	0.5	irregular stones (type A)	civil building
	Ponte di Cerreto	PNCA-J3D	979.61	602	0.58	0.5	irregular stones (type A)	civil building

Table 5.2: Masonry parameters collected through direct sonic tests and double flat jack tests applied on different building and masonry typologies in Umbria Region (data collected by the author).

More data were later collected in other testing campaign in Abruzzi and Lombardy in order to develop the correlation between pulse sonic velocity and elastic modulus (Table 5.4 and Table 5.5). Grouping the results in classes, the elaboration and the comparison between values of several elastic moduli with corresponding sonic velocities allow some comments. Due to the dispersion of the values found on different buildings typologies (having their constructive

[206] See reference (Binda L. C., 2007)

peculiarity), a clear correlation with sonic velocity and Modulus of Elasticity was not defined. Dividing the available data in two categories referred to stonework and brick work typology, it was noticed that the stonework gives much higher scattering in the results.

	Place name	Test code	Velocity (m/s)	E (MPa)	Dilation Coefficient	Onset crack. (MPa)	Masonry type	Building type
Liguria Region	Taggia	MT-J1D	1196.4	1050	0.02	0.87	irregular stones (type A)	convent
	Taggia	MT-J2D	1138	2850	0.06	1.82	irregular stones (type A)	convent
	Taggia	MT-J3D	1136.6	3170	0.36	2	irregular stones (type A)	convent
	Bajardo	B2-J1D	1015	338	0.11	0.66	irregular stones (type A)	civil building
	Bajardo	B2-J2D	1306	529	0.07	0.61	irregular stones (type A)	civil building
	Bajardo	B9-J1D	1208	922	0.31	0.79	irregular stones (type A)	civil building
	Bajardo	B9-J2D	1307	1438	0.03	0.7	irregular stones (type A)	civil building
	Bajardo	BC-J1D	767	440	0.13	0.73	irregular stones (type A)	civil building
	Bajardo	BSN-J1D	1464	4831	0.05	1.34	irregular stones (type A)	church
	Savona	HSP-J1D	1982.6	2310	0.25	0.6	Hewn stones (type B)	hospital
	Savona	HSP-J2D	2224	1277	0.02	1.45	Hewn stones (type B)	hospital
	Savona	HSP-J3D	2185	3223	no	1.08	Hewn stones (type B)	hospital
	Savona	HSP-J4D	1793.2	2124	no	0.58	Hewn stones (type B)	hospital

Table 5.3: Masonry parameters collected through direct sonic tests and double flat jack tests applied on different building and masonry typologies in Liguria Region (data collected by the author).

	Place name	Test code	Velocity (m/s)	E (MPa)	Dilation Coefficien t	Onset crack. (MPa)	Masonry type	Building type
Abruzzi Region	Sulmona	SU-ED34-J1D	780	368	0.22	0.41	irregular stones (type A)	civil building
	Sulmona	SU-ED34-J2D	975.4	289	2.44	0.64	irregular stones (type A)	civil building
	Sulmona	SU-PM-J1D	617.4	no	no	no	irregular stones (type A)	palace
	Sulmona	SU-ED69-J1D	1096.4	1168	0.72	0.43	irregular stones (type A)	civil building
	Sulmona	SU-PS-J1D	938.6	574	0.72	0.26	irregular stones (type A)	palace
	Sulmona	SU-PS-J2D	1016	956	0.44	0.56	irregular stones (type A)	palace

Table 5.4: Masonry parameters collected through direct sonic tests and double flat jack tests applied on different building and masonry typologies in Abruzzi Region (data collected by the author).

	Place name	Test code	Velocity (m/s)	E (MPa)	Dilation Coefficient	Onset crack. (MPa)	Masonry type	Building type
Lombardy Region	Boiaco	SPA-J1D	1130	1391	0.08	0.43	irregular stones (type A)	church
	Boiaco	SC-J1D	917	320	0.51	0.38	irregular stones (type A)	church
	Boiaco	SC-J2D	1169	189	0.01	0.4	irregular stones (type A)	church
	Morgnaga	SA-J1S	1223	1732	0.39	0.67	irregular stones (type A)	church
	Morgnaga	CA-J1D	928	518	0.48	0.25	irregular stones (type A)	civil building
	Sabbio Sopra	SM-J1D	1013.6	2923	0.07	6	irregular stones (type A)	church
	Pavone	SGP-J1D	975.8	1402	0.01	0.59	irregular stones (type A)	church
	Bione	PSM-J2D	1326	1250	0.2	0.3	irregular stones (type A)	church
	Bione	PSM-J4D	1444.3	2394	0.1	0.49	irregular stones (type A)	church
	Toscolano	SAM-J1D	1046	4835	0.03	0.75	regular stones (type E)	church
	Toscolano	SAM-J2D	823	4117	0.01	0.75	regular stones (type E)	church
	Toscolano	SAI-J1D	932.8	5260	0.02	0.76	irregular stones (type A)	church
	Pompegnino	SBN-J1D	904.79	803	0.03	0.33	irregular stones (type A)	church
	Pompegnino	SBN-J2D	688.69	1063	0.18	0.34	irregular stones (type A)	church
	Bergamo	MSP-J1D	806.4	710	0.26	0.43	Hewn stones (type B)	monastery
	Bergamo	MSPJ-16D	1076.4	3307	0.2	0.67	Hewn stones (type B)	monastery
	Bergamo	MSPJ-15D	1752	4000	0.01	0.9	Hewn stones (type B)	monastery
	Bergamo	MSP-J4D	1161	2499	0.14	0.87	Hewn stones (type B)	monastery
	Bergamo	MSP-J6D	1039.4	3150	0.33	0.85	Hewn stones (type B)	monastery
	Bergamo	MSP-J7D	871.3	1231	0.26	1	Hewn stones (type B)	monastery
	Bergamo	MSP-J14D	535.2	1800	no	0.82	Hewn stones (type B)	monastery
	Bergamo	MSP-J10D	1121.5	814	0.07	0.75	Hewn stones (type B)	monastery
	Bergamo	MSP-J11D	1145.9	1850	0.17	0.55	Hewn stones (type B)	monastery

Table 5.5: Masonry parameters collected through direct sonic tests and double flat jack tests applied on different building and masonry typologies in Lombardy Region (data collected by the author).

Figure 5.54 presents the correlation *E* vs V (elastic modulus versus sonic velocity), based on 55 experimental results obtained by carrying out sonic and double flat jack tests in the same area of several masonry structures, classified for different Italian regions. The dispersion of the results is high and a clear relationship between the two parameters (E and V) is not detectable. Dividing the data for stone masonry and brick masonry, a better correlation between elastic modulus and sonic velocity can be identified, especially for regular brickwork structures (Figure 5.55).

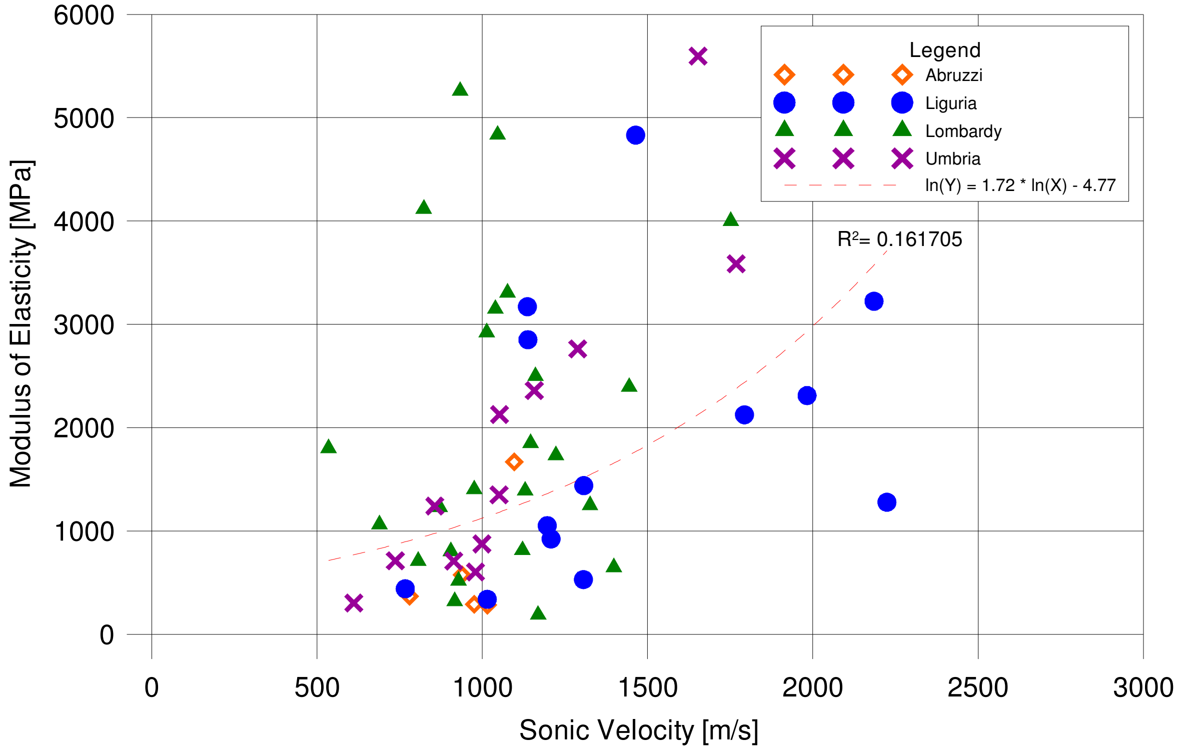


Figure 5.54: E vs. V correlation, based on 55 direct sonic tests and double flat jack tests (elaboration by the author).

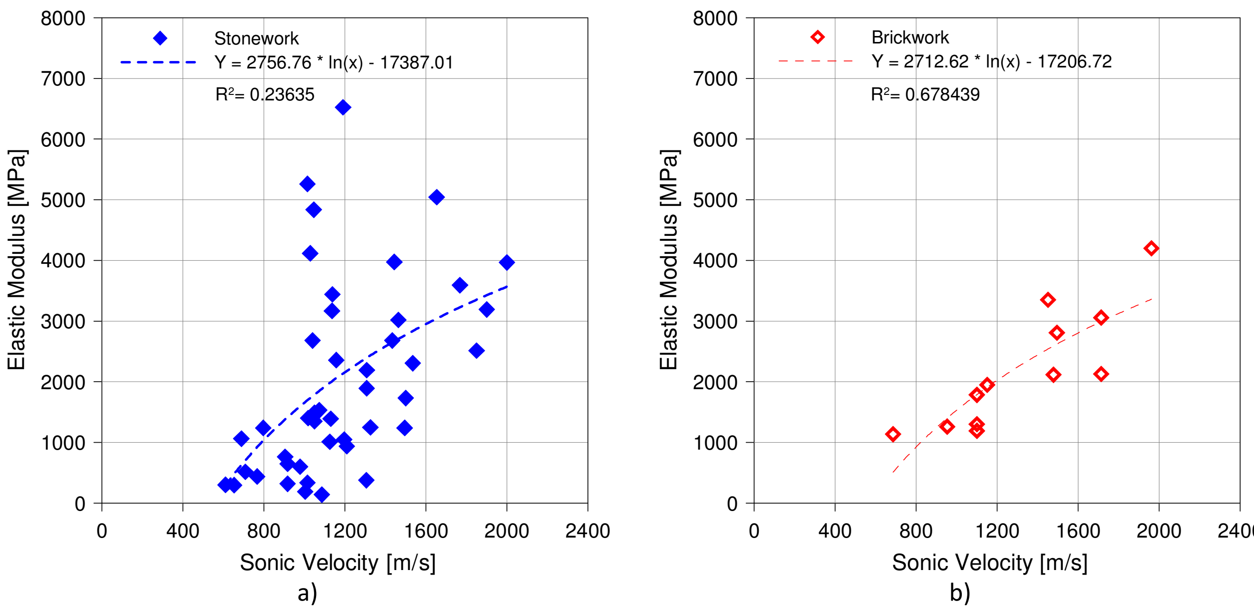


Figure 5.55:E vs. V correlation: a) correlation referred to stone masonry types; b) correlation referred to brick masonry types (graphs by the author).

Even if these data are not still statistically meaningful given the great difference of masonry morphology and materials, however they indicate the tendencies that can be assumed in order to define the quality of the masonry. As shown in the previous chapter, this kind of correlation can be done using the velocity computed by R-waves. Through the development of the methods to acquire the data, the computation of the R-waves could be more assessable and this parameter could provide better correlation with the Modulus of elasticity.

5.3 Advantages of the experimental experience: sustainability of the project

The case studies, described in the previous paragraph, were used to show the development of the knowledge through the diagnostic approach. The assessment of the building and the stratifications of its parts through appropriate structural models require a large amount of tests. In the first case (the convent) the building was studied following the strategy proposed in the Italian Guidelines of the Ministry for Cultural activities: the evaluation of the mechanical behaviour was obtained dividing the buildings into macro-elements: bearing walls, arched structures (the cloisters), vaults, floors, roofing system, etc. Each one of these macro-elements was then categorised according to its structural function and the information obtained by the historical research. The typology and the number of the tests was further defined, taking into account the characteristics of the macro-elements, their state of conservation and all the ambiguous aspects which could not be assessed by visual inspections. Considering this premise, tests were limited to the main representative structures of the building: the bearing walls representing the main phases of the development of the convent (XV, XVI century) and presenting different textures. In this case, due the availability of visible masonry textures, thermographic tests were not performed, but the results obtained by sonic tests were relevant. Direct sonic tests showed structures characterised by well-connected elements for the most part of the walls and for few cases were useful to identify compromised parts. For those cases, a further deeper investigation was obtained through double flat jack tests. The parameters obtained by these tests (respectively pulse velocity and Elastic Modulus) indicate the performance (low or high) of the structures, providing the information to answer the question: conservative or renewal approach?

The diagnostic approach is a way to guide the design activity and to support the quality of the work. According to the new guidelines and codes, uncertainty is no more tolerated in designing since the errors in projects set without an adequate knowledge of the building produced catastrophic results, in terms of human life and waste of resources.

Among several documented interventions on existing buildings, organized in accordance with the present standardized constructive methodology, new attention for a more compatible design was developed in some cases. Since the appearing of the D.M.LL.PP. 16/1/1996, the idea of improving the existing structures (i. e. vertical masonry walls and traditional floors) was not adequately supported: the knowledge of the structural model of the existing building was not seen as the key point of the design process. A total renovation of these elements with the introduction of more familiar contemporary building systems was considered safer (Figure 5.56).

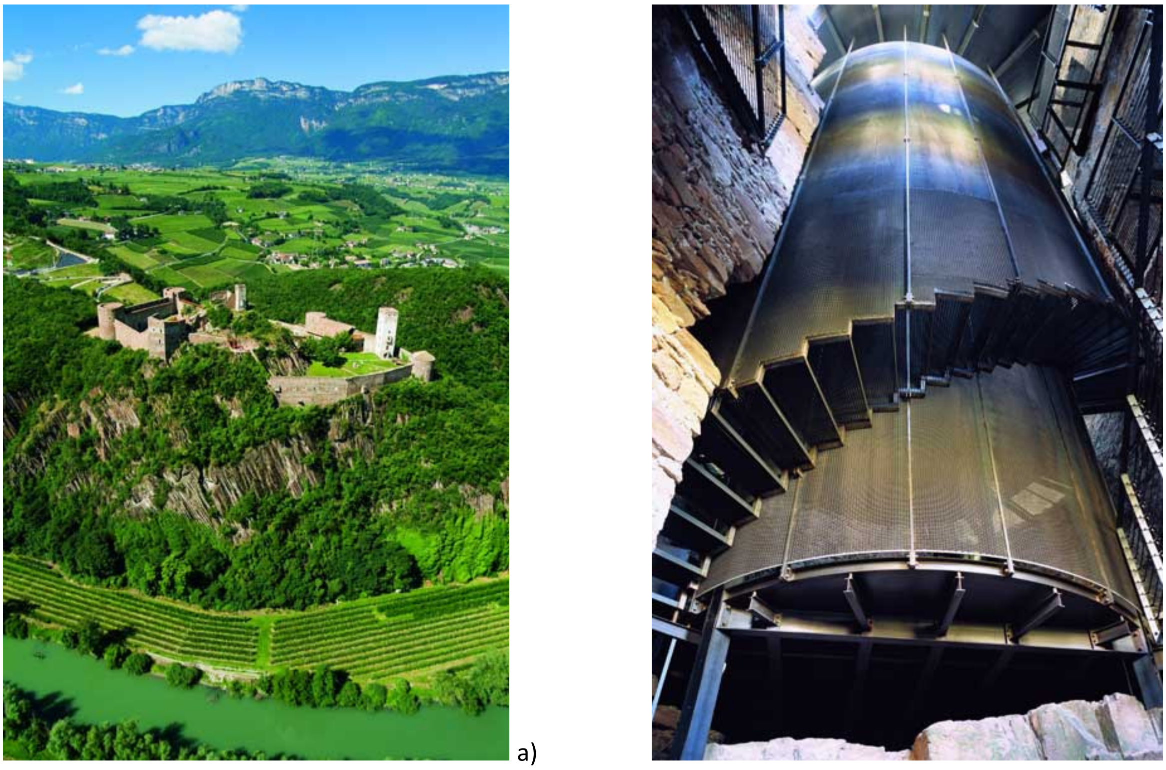

a)


b)


c)

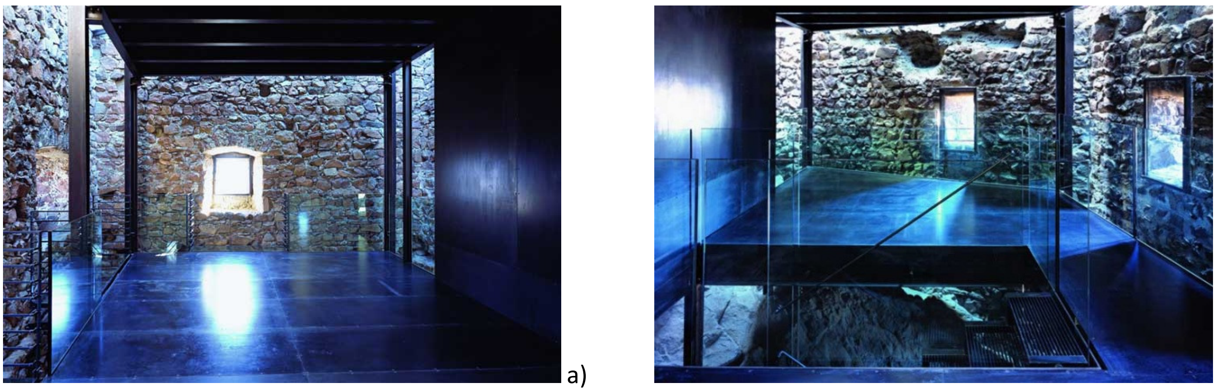
Figure 5.56: Sequence of the reconstruction of a palace stroke by the 1997 Umbria and Marche earthquake: a) 1998 picture showing the conditions of the palace after the earthquake; b) 2002 picture showing the building technology used for the reconstruction (courtesy of arch. A. Saisi); c) 2003 picture showing the modern hollow brick infill between the r.c. structure (picture by the author).

Nevertheless, the progressive use of diagnostic methods for the characterization of existing buildings and the control of the interventions indicated the existence of an alternative approach to the architectural heritage. Strategic solutions were studied by architects and engineers taking into account the relevant wrong consequences of the *adaptation* to safety coefficient of new building applied to historical buildings. The design made by W. Tsholl in Firmiano Castle in Bolzano (in 2002), for example, denotes the respect for the existing ruins and a particular attention for the perception of two levels: the historical structures of the castle, conserved in their material integrity, and the new contemporary addition, based on a present architectural language and founded at the same time on the complementarity between old and new elements (Figure 5.57). The design for the realization of the museum of the mountain is here resolved using the massive structures of the castle to host a new path for the visitors realized by footways, stairs and platforms in rough steel (not painted). These new structures are independent from the existing walls, in order to provide the necessary compatibility and reversibility (Figure 5.58).



a) b)

Figure 5.57: a) view of Firmiano Castle in Trentino; b) new stairs inserted in the south-east tower of the complex (pictures from W. Tscholl' s official web-site: www.werner-tscholl.com).



a) b)

Figure 5.58: Firmiano Castle: views of the new steel floors of the museum (pictures from W. Tscholl's official web-site: www.werner-tscholl.com/).

W. Tscholl faced the project of another existing building in Austria: his proposal for the restoration of the Furstemburg Castle recalls the philosophy used in Bolzano for the Firmiano Castle. In this second case, the main tower of the castle is characterized by the partial collapse of one edge (Figure 5.59). The addition of new floors inside the tower becomes here also a strengthening design for the masonry walls of the partially collapsed tower.


a)


b)

Figure 5.59: Furstemburg Castle: a) view of the partially collapsed tower and b) view of a closed cloister (pictures from W. Tscholl's official web site: www.werner-tscholl.com).

The logic of the intervention, based on the addition of new functional elements (footways and stairs for the visitors), is again developed around the idea of a coexistence of the old and the new parts, without a structural interaction between them (Figure 5.60). This can be a choice of the designer but it is not a necessity: after the correct investigation of the existing structure, the information for evaluating the effects of an interaction between new and old structures can be assessed. As outlined in the second chapter, the interaction between existing structures and new additions was pursued in two complicated cases: the reconstruction of the Noto Cathedral and of the Fraenkirche in Dresden. In those cases, the intensive application of diagnostic techniques allowed a general comprehension of the mechanical behaviour of the survived structures, in order to connect old and new parts in a unique structural system. Nevertheless, as a consequence, the deep linkage between existing and added structures can compromise the reversibility of the intervention, indicated in the Venice Charter. For this reason, when making those choices as a way of no return the decision should be taken after deep investigation and many discussions when apparently there is no way to add but only reconstruction.


a)

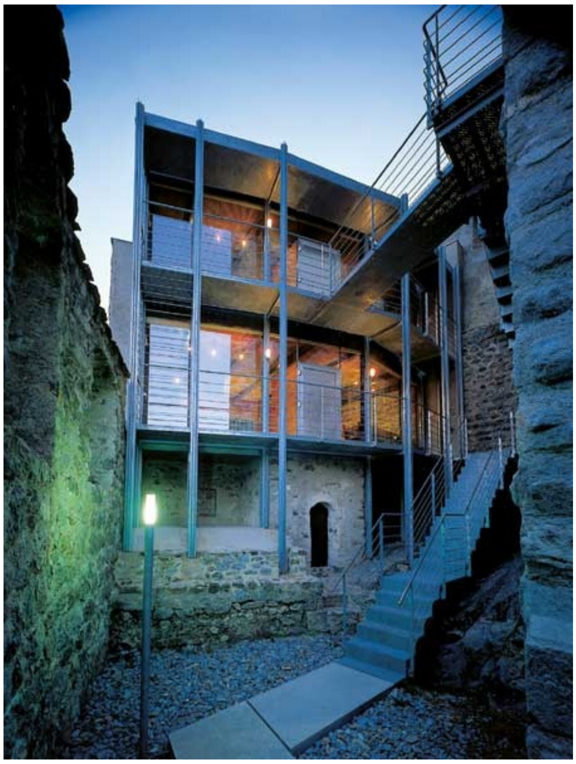

b)

Figure 5.60: Furstemburg Castle: a) view of the partially collapsed tower with the new additions and b) view of athe new horizontal and vertical connections (pictures from W. Tscholl's official web site: www.werner-tscholl.com).

The attention for compatibility experimented in conservation projects and the results showed in recent experiences contributed to reconsider the approach towards existing buildings. A short comparison between the main prescriptions contained in the D.M. LL. PP. 16/1/1996[207] and Circolare 8/11/2002 Min. BB.CC.[208] can summarize the main problems connected to "the arguments around safety and the arguments around conservation", as pointed out by P. Rocchi[209]. He noticed that the D.M. LL. PP. 16/1/1996 produced an involution of the restoration field and before the adoption of the Ordinance 2003, the Ministry for Cultural Heritage proposed a set of rules to correct the negative consequences of the anti-seismic adaptation, to safety coefficients for new building.

[207] Decreto Ministeriale 16/1/1996 – *Norme tecniche per le costruzioni in zone sismiche*. (D. M. LL. PP., 1996)

[208] Circolare 8/11/2002 Ministero dei Beni Culturali, *Istruzioni generali per la redazione dei progetti di restauro per i beni architettonici di valore artistico in zona sismica*. (Circolare 8/11/2002)

[209] P. Rocchi, *Restauro e consolidamento dei beni architettonici e ambientali: problematiche attuali*, in A. Aveta, S. Casiello, F. La Regina, R. Picone, *Restauro e Consolidamento*, Mancosu Editore, Roma, 2005 pp. 81-84, (Rocchi, 2005)

Decreto Ministeriale 16/1/1996 – *Norme tecniche per le costruzioni in zone sismiche* *(Ministry Decree 16/1/1996 – Technical rules for buildings in seismic areas)*	**Circolare 8/11/2002 Ministero dei Beni Culturali, *Istruzioni generali per la redazione dei progetti di restauro per i beni architettonici di valore artistico in zona sismica*** *(Circular 8/11/2002, Ministry of Cultural Heritage – General instruction for the drafting of conservation designs for architectural heritage in seismic area)*
Masonry walls Those masonry walls which are not affected by evident instability as tilting or extended cracks can be repaired; in the other case, they must be demolished (C.9.8.1)	Masonry walls Demolitions of consistent parts showing the evolution of the building should be always avoided, even though they present serious evidence of instability, such as tilting or extended cracks (C.4.2).
R. C. grouting The use of this technique is recommended if consistent connections between load bearing parts should be realized (Annex N. 3§3. To the Instruction for the application of the D: M.)	R. C. grouting This technique must not be applied as a systematic solution for strengthening the masonry structures, due to its negative effects (C.4.2).
Injection of bonding mixtures Injections can be realized by cement mixtures, simple or with additives, or with organic resins (Annex N. 3§3. To the Instruction for the application of the D: M.)	Injection of bonding mixtures … this technique can be applied after demonstrating its compatibility … (C.4.2).
Floors If the substitution of the original floors is required, the new floors must be realized in r.c. type (ordinary or pre-stressed) … In the case that the perimetric walls do not present r. c. curbs at the floor level, curbs must be realized with a height equal or higher than the on of the floor … Wooden floors are admitted only for peculiar architectonic requirements (C.9.8.2)	Floors Wooden floors should be always preserved … the introduction of curbs in gaps opened in the masonry, providing discontinuities in the structure, must be avoided … in the case that the wooden or metallic floor cannot be preserved, due to its state of damage and decay, it should be substituted by an analogous element (C.4.5)
Arches and Vaults A valid reinforcing system consists in the realization of a supporting shell, usually at the extrados, composed by a metallic net spiked to the original structure and by a layer of high resistance antishrink mortar or resin mixtures (Annex N. 3§3. To the Instruction for the application of the D. M.)	Arches and Vaults The use of techniques based on fixing strengthening layers at the extrados must be avoided, as the realization of concrete counter-vaults, reinforced or not. Reduction of the loads and/or the eccentricity are recommended (C.4.4.).
Stairs Masonry stairs must be substituted by r.c. or steel stairs.	Stairs Masonry stairs must be preserved, using, if necessary, reinforcing elements which must not transform their architectural characteristics and in any case their typological and formal value (C.4.6).

Table 5.6: comparison between two different approaches for the interventions on existing buildings in seismic areas, showing the changings in the interpretation of the problem since 1996 to 2002.

As mention in the previous paragraph, the Ordinance 3274-2005 introduced 6 classes of masonry typologies with their corresponding mechanical parameters (Table 5.7). The parameters were the average values of:

- compressive strength of the masonry (f_m);
- shear strength of the masonry (τ_0);
- elastic modulus (*E*);
- tangential elastic modulus (G);
- density of the masonry (*W*).

	Values contained in the Ordinance 3274 - 2005, Table 11.D.1, Annex D					
Code	**Masonry Typology**	**f_m (*N*/cm^2)** min-max	**τ_0 (*N*/cm^2)** min-max	**E (*N*/mm^2)** min-max	**G (*N*/mm^2)** min-max	***w* (k*N*/m^3)**
A	Irregular stones masonry (pebbles, erratic and irregular stones).	60 90	2,0 3,2	690 1050	115 175	19
B	Hewn stones with limited depth and presence of internal core.	110 155	3,5 5,1	1020 1440	170 240	20
C	Split shaped stones masonry with good texture.	150 200	5,6 7,4	1500 1980	250 330	21
D	Soft stones masonry (tuff or travertine, calcarenite, etc.).	80 120	2,8 4,2	900 1260	150 210	16
E	Square stone blocks masonry.	300 400	7,8 9,8	2340 2820	390 470	22
F	Masonry in brick and lime mortar.	180 280	6,0 9,2	1800 2400	300 400	18

Table 5.7: Mechanical parameters of 6 different masonry typologies, according to Ordinance 3274-2005.

The data introduced in table 11.D.1 of the Ordinance are an important benchmark for the development of the design of existing masonry buildings. The table provides quantitative information for the interpretation of the mechanical properties of masonry structures, which behaviour represents always the main enigma for the designer. It should be remarked that these values come from experimental on-site tests on some types of masonry and can be improved.

Among the various parameters (only mechanical), the table does not take into account other qualifying values, e. g. the sonic velocity. This is a point that could improve the indications for interpreting the behaviour of the masonry. Above all, direct sonic tests can better qualify the masonry sections. Since the table of the ordinance suggests a classification of typologies based only on the masonry texture of its external layers, a range of velocities associated to the minimum and maximum values of the mechanical parameters could support the identification of the characteristics of the masonry section together with direct sampling: the principle of the table is that the detectable masonry texture is representative of the section of the wall, but this can be a limiting view of the problem.

As shown in Figure 5.55, the variability of the results obtained through on-site tests for determining sonic velocity and elastic modulus depends on the different density of the masonry sections: the survey of the external textures of the wall cannot qualify also the internal layers of the structure. The necessity of a deep investigation of the properties of the masonry section is remarked in the NTC-2008 (Technical recommendations for buildings) and in the circular for their application (Circolare 2 febbraio 2009, 617[210]).

Figure 5.61: Map of Italy with the administrative regions (picture from the website www.big-italy.uk); b) map of the seismic risk of Italy (map from the website http://zonesismiche.mi.ingv.it/).

The identification of the mechanical response of load bearing walls plays a strategic role especially in a territory characterised by seismic risk. As already mentioned in the second chapter,

[210] Circolare 2 febbraio 2009, n. 617, *Istruzioni per l'applicazione delle «Nuove norme tecniche per le costruzioni» di cui al decreto ministeriale 14 gennaio 2008*. (G.U. n. 47 del 26-2-2009 - Suppl. Ordinario n.27). (Circolare n.617, 2009)

the new Italian map of the seismic risk indicates that the entire national territory is subjected to seismic events (Figure 5.61), even though with different levels of intensity. This thesis work supports the application of thermovision and sonic tests for investigating respectively the masonry texture (if not visible) and the masonry morphology. As shown in the last paragraph, the velocity of the elastic waves is a parameter that cannot satisfy a complete knowledge of the mechanical properties of the masonry, but a correlation with the deformability properties detected through double flat jack tests is well promising.

Collecting the data obtained by several applications of on-site sonic and double flat jack tests, a considerable amount of results for the masonry categories indicated in the ordinance 3274-2005 and the different seismic areas of the Italian territory is now presented. These results are representative of specific regional contexts (Figure 5.62). A first selection of the data presents a comparison between the results achieved in 5 regions, according to the different masonry textures (Table 5.8).

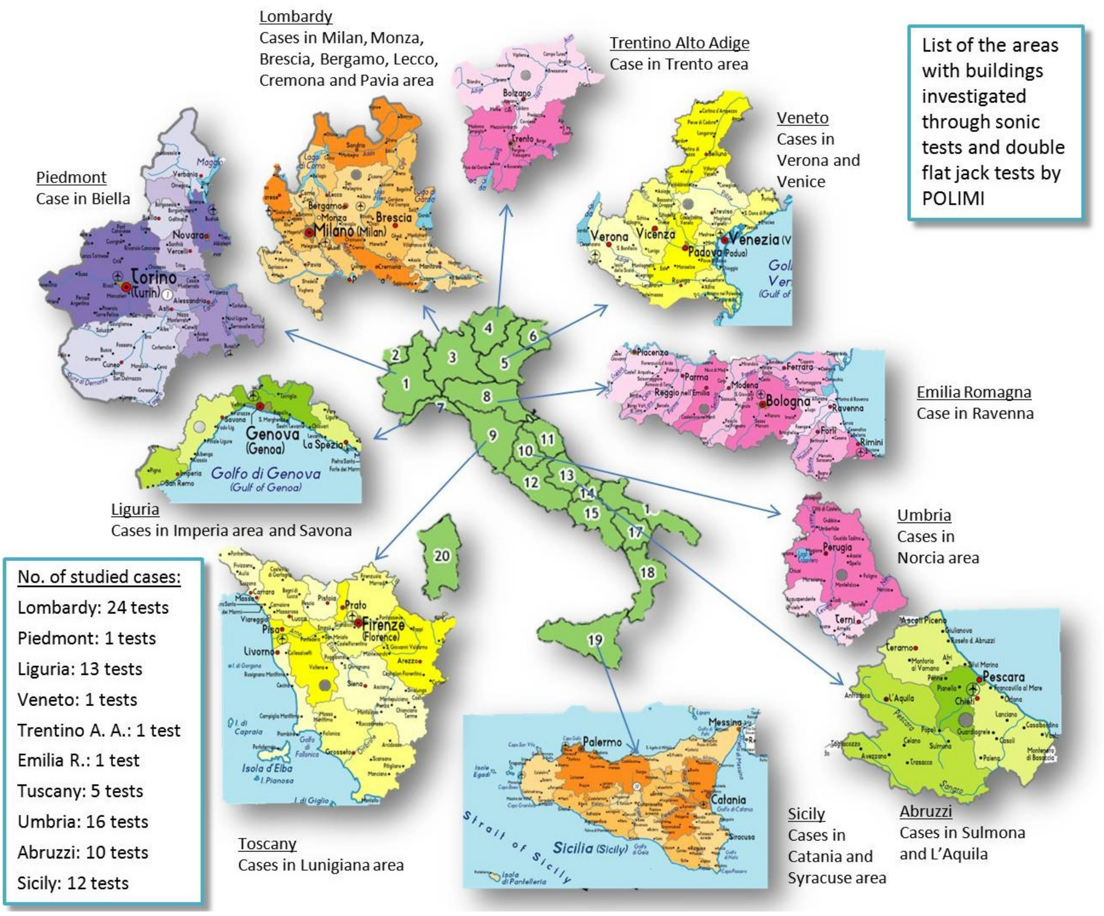


Figure 5.62: Representation of the distribution of sonic and double flat jack tests carried out by POLIMI in different Italian Regions (maps rearranged by the authors from http://www.big-italy-map.co.uk/).

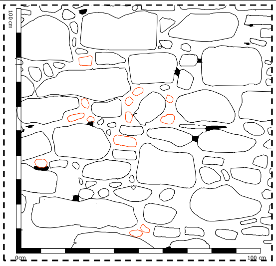
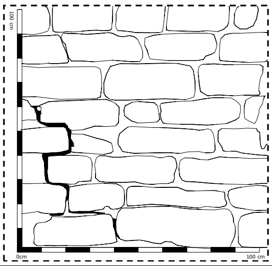
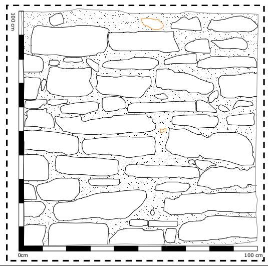
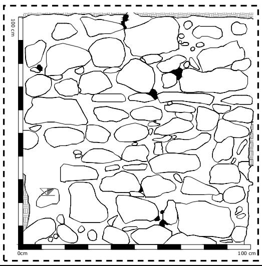
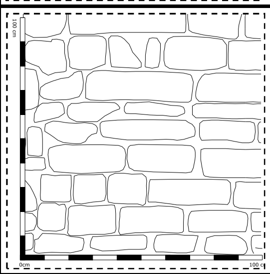
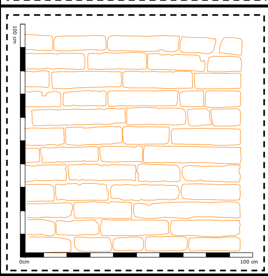
Masonry Texture Typology according to ORDINANCE 3274-2005		Data obtained through on-site sonic and double flat jack tests					
Masonry Texture	**Texture example**	**Geographic Area**		**onset crack (MPa)**	**E (MPa)**	**V (m/s)**	**Test name**
A. Irregular stones masonry (pebbles, erratic and irregular stones).		Abruzzi	min.	0.56	282	1016	SU-PS-J2D
			MAX.	0.43	1668	1096	SU-ED69-J1D
		Liguria	min.	0.73	440	767	BC-J1D
			MAX.	1.82	2850	1138	MT-J2D
		Lombardy	min.	0.4	189	1169	SC-J2D
			MAX.	1.2	9514	1412	SMA-J1D
		Umbria	min.	0.5	602	979	PNCA-J3D
			MAX.	0.49	2763	1289	CMSA-JD4
		Tuscany	min.	0.23	594		SAJ3D
			MAX.	0.84	2990		PFJ3D
B. Hewn stones with limited depth and presence of internal core.		Abruzzi	min.	0.49	3381	1332	SBJ2D
			MAX.	0.8	9099	1482	SBJ1D
		Liguria	min.	0.66	338	1015	B2-J1D
			MAX.	1.34	4831	1464	BSN-J1D
		Lombardy	min.	0.43	710	806	MSP-J1D
			MAX.	0.9	4000	1752	MSPJ-15D
		Umbria	min.	0.33	303	611	CLSTJD4
			MAX.	0.41	5043	1653	RCCJD2
		Tuscany	min.	0.16	992		FVJ2D
			MAX.	0.64	13592		CSJ2D
C. Split shaped stones masonry with good texture.		Abruzzi	min.				
			MAX.				
		Liguria	min.	1.45	1277	2224	HSP-J2D
			MAX.	1.08	3223	2185	HSP-J3D
		Lombardy	min.	0.41	649	917	PCJ2D
			MAX.	0.43	1391	1130	SPAJ1D
		Umbria	min.	0.33	648	648	CM200-JD1
			MAX.	0.5	874	874	RCHDMJD4
		Tuscany	min.				
			MAX.				
D. Soft stones masonry (tuff or travertine, calcarenite, etc.).		Abruzzi	min.	0.41	368	780	SU-ED34-J1D
			MAX.	0.26	1737	938	SU-PS-J1D
		Liguria	min.				
			MAX.				
		Lombardy	min.				
			MAX.				
		Umbria	min.				
			MAX.				
		Tuscany	min.				
			MAX.				
E. Square stone blocks masonry.		Abruzzi	min.				
			MAX.				
		Liguria	min.				
			MAX.				
		Lombardy	min.	0.75	4117	823	SAM-J2D
			MAX.	0.75	4835	1046	SAM-J1D
		Umbria	min.	0.35	1241	856	MSCH-J2D
			MAX.	0.45	19495	1939	PNCOMJ1D
		Tuscany	min.				
			MAX.				
F. Masonry in brick and lime mortar.		Abruzzi	min.				
			MAX.				
		Liguria	min.				
			MAX.				
		Lombardy	min.	1.51	1193	1100	TMJ7D
			MAX.	1.32	4200	1962	G8J1D
		Umbria	min.				
			MAX.				
		Tuscany	min.				
			MAX.				

Table 5.8: Comparison between data obtained through sonic and double flat jack tests

Table 5.8 contains the minimum and the maximum values of the elastic modulus and sonic velocity for each masonry typology. Grouping these results for macro-areas, the tests collected during POLIMI diagnostic campaigns can be used to represent the masonry mechanical properties for North-East, North-West, Centre and South Italy (Table 5.9). Velocity is added to the other parameters as a qualitative indicator of the masonry characteristics. This organization of the table could be improved for future integrations of the ordinance, in order to bypass the present limits connected to the ambiguity of the relationship masonry texture/Elastic Modulus that should be supported by a deeper knowledge of the masonry section.

	Italian Regions	masonry typology	No. of cases	V (m/s)	onset crack (MPa)	E (MPa)	G (1/3 E) (MPa)
MACROAREA 1: North-West	**Liguria**	A	6	1120	3.35	1490.5	496.8
	Liguria	B	6	2046	2.35	2065.6	688.5
	Liguria	C	1	1164	0.70	1440.0	480.0
	Piedmont	F	1	1262	0.10	921.0	307.0
MACROAREA 2: North-East	**Lombardy**	A	7	1114	1.24	1173.4	391.1
	Lombardy	B	12	1121	1.06	2906.0	968.7
	Lombardy	E	2	1046	0.43	4476.0	1492.0
	Lombardy	F	13	1340	1.19	1793.3	597.8
	Trentino Alto A.	A	1	1535	Not Reached	6500.0	2166.7
	Veneto	B	1	1097	Not Reached	1500.0	500.0
MACROAREA 3: Centre	**Abruzzi**	B	5	830	0.79	636.2	212.1
	Emilia Romagna	F	1	1478	1.0	2116.0	705.3
	Tuscany	A	3	-	0.76	2396.6	798.9
	Tuscany	B	1	-	N. R.	2030.0	676.7
	Tuscany	C	1	-	N. R.	600.0	200.0
	Umbria	A	1	979	0.60	600.0	200.0
	Umbria	B	4	1540	0.37	1332.5	444.2
	Umbria	C	6	2230	0.70	7488.3	2496.1
	Umbria	D	1	611	0.30	300.0	100.0
MACROAREA 4: South	**Sicily**	A	7	-	0.48	1014.8	338.3
	Sicily	D	3	1125	0.9	4508.0	1502.7
	Sicily	E	2	2000	1.4	7050.0	2350.0

Table 5.9: Mechanical parameters obtained through on-site sonic and double flat jack tests, grouped for 4 Italian macro-areas.

Conclusions

According to Homer, the craftsman had, in the past, the ability of combining technics and community. This assumption was taken again by R. Sennett[211] to consider that in a capitalistic society the collaboration is not assumed as the right way to support the quality of the work. The idea of the capitalistic model is that the competition can stimulate the increasing of quality in human activities. This idea is disproved by Sennett, who used the example of the assisted design to demonstrate that the passage from the craftsman laboratory to the mechanized production brought to a low quality of the work. Taking into account the project based on CAD programs, he showed that the abuse of computerized processes had the effect of a reduction of the intellectual comprehension of the operators which use these systems as interface with the real world.

J. Ruskin represented the opposition to the mechanization of work activities. Through his material experience, Ruskin discovered the beauty of the stones used in the venetian mediaeval architecture[212]. He used drawing to access to a tactile experience. In opposition to a society which in that period was characterized by an excess of objects (the London exhibition with its industrial goods took place in 1851), Ruskin was the promoter of the rediscovery of sensorial reactions with objects. One issue of this thesis is the safeguard of the material consistency of the architectural heritage. Considering the long path from the first definition of restoration to the concept of conservation presented in chapter 1, it can be shown that the work of the restorer can compromise the protection of the existing buildings.

The supremacy of the theoretical knowledge respect to the one obtained by empirical approaches goes back to the immanence of Plato's ideas, respect to the limited durability of the objects produced by the humans. This assumption was followed by many designers which faced the problem of conservation of existing buildings. In many cases, as shown in chapter 2, the lack of knowledge on the real characteristics of the building (above all its mechanical properties)

[211] Cit. (Sennett, 2009)
[212] Cit. (Ruckin, 2000)

determined disastrous consequences, in terms of human life and waste of resources. The legislator tried to correct this trend proposing guidelines and codes to support the "path to knowledge" referred to the architectural heritage. Also Vitruvius distinguished between theory and practise. In his opinion arts are composed by *opus* (technique) and *ratiocinatio* (theory). These two components of the knowledge process determined the success of the craftsman's activity: going back to Ruskin, in "The Stones of Venice" he introduced the idea of a flamboyant (flaming) worker, who is able to reach the result facing the risk of the empirical experience. According to Ruskin, discoveries are luck accidents. In this way, he introduced the "seven lamps" to light up the activity of the craftsman: the second lamp, the lamp of Truth, is an invitation to accept the ambiguity. This is the main characteristic of the existing building: its preservation cannot be designed following common rules and pre-determined layouts. This was the logic used to reform the Guidelines for evaluation and mitigation of seismic risk to cultural heritage in 2007. As R. Cecchi says in the introduction of the Guidelines:

Safeguarding our cultural heritage in Italy from seismic risk is fundamentally an act of preservation, which until now has rarely been accomplished […]. However, the conservation of our cultural heritage also depends greatly on the nature of the projects which are realised. A strengthening intervention of poor quality is worse than not intervening at all[213].

The problem of the quality is remarked also in the thesis. It is clear that the effects of projects set by a superficial knowledge of the real conditions of the architectural fabric addressed the legislator to the direction of a methodology for the study of the problems connected to the ambiguity of the existing buildings.

As a consequence, the diagnostic approach for the definition of the final design was introduced and supported through national codes and international organizations. Chapter 3 of the thesis presents the main testing methodologies developed in the field of the University research. It's a state of the art of the main diffused tests used in conservation field for the characterization of the mechanical behaviour of existing buildings. Between these experimental tests, two techniques are considered to be suitable for the highest number of cases: thermovision and sonic tests. The

[213] Cit. (Moro, 2007)

definition of a diagnostic approach based on these two specific tests is a limited part of the design process, but it represents a strategic path to knowledge: widely accessible for the precision of their results and easily applicable on different buildings typologies.

According to R. Sennett's opinion, the laboratory and the on-site research was carried out following the attitude of the craftsman: the ability was based on the intuitive improvement, accepting the cognitive dissonances of the work activity. Chapter 4 introduces the experimental results obtained by innovative applications of thermographic and sonic tests. These techniques can provide qualitative results, but through the experimentations of new applications, the effectiveness of their results and the importance of their impact on the design process were remarked.

Thermovision was used to study the hidden masonry textures of different buildings. The on-site application of this non-destructive techniques supported the first step of knowledge of the building characteristics, integrating the information collected by the survey (geometrical, material and decay) with other detailed indications: the shapes of the material forming the external layer of the structures; the presence of discontinuities or detachments of the plasters or other protecting layers.

The opportunity of studying the application of indirect sonic tests in the laboratory of Earthquake and Structural Engineering of the University of Porto allowed to evaluate the potentiality of this testing methodology. The velocities calculated through the identification of compressive waves (P-waves) and Rayleigh waves (R-waves) are two useful parameters: P-waves velocity is suitable for direct sonic tests and able to qualify the masonry section of masonry walls; R-waves velocity is indicated to detect the transversal component of the wave propagation. Both P-waves and R-waves velocities were compared to Elastic Moduli obtained experimentally by applying direct compressive stress or double flat jack tests. The literature presents some example of correlation between sonic velocity and Elastic Modulus, but a linear relationship between these parameters is not verified. The inhomogeneity of the historical masonry sections does not allow to obtain qualitative results by sonic tests. Nevertheless, the use of R-waves velocity to estimate the mechanical properties of the external layers of the wall represents a field of study that could have further development for estimating the mechanical properties of masonry structures. In chapter four some correlations between Elastic Moduli obtained by double flat jack tests and Dynamic Elastic Moduli obtained R-wave velocity are presented: the results are scattered, but the future development of more refined acquisition systems could allow a more precise estimation of the velocities of the R-waves and the correlation could present a more constant trend.

The diagnostic approach is finally described through some examples in chapter 5. Case studies are a useful evidence of the reliability of the method. As a component of a complex process, diagnostic techniques can support the design activity in its different steps (preliminary studies, control of the correctness of the designed solutions, monitoring of the structure evolution in time, etc.) and their use can drive to the interpretation of the complexity characterising the ancient buildings. The relevant role of the testing techniques is outlined through the description of two cases: one concerning the scale of the single building and one referred to the scale of the town. The two examples are characterised by the same unknown aspects and the interpretation of their characteristics was pursued by the support of non-destructive and minor destructive tests. These case studies showed that the diagnostic approach can provide a detailed knowledge of the investigated buildings only applying strategically a complementary set of tests. In this way, the information requested to match the levels of knowledge proposed by recent regulations can be collected. Following the indications contained in the Ordinance 2374/2003 [214] and its integrations, the qualification of the masonry properties was evaluated. According to the parameters indicated in the ordinance, the mechanical behaviour of historical masonry structures can be estimated by studying their masonry textures and their deformable characteristics. Using a considerable amount of data collected by the experimental activities of the Laboratory for Testing Materials of the Department of Structural Engineering of Politecnico di Milano, a comparison with the values reported in the Ordinance 2374/2003 was proposed. As a result, a high dispersion of the values of the Elastic Moduli of 6 masonry typologies was observed. The introduction of sonic velocities as a parameter for the qualification of the masonry section of the historical buildings can improve the interpretation of each specific case, in order to bypass the generic classification of masonry walls proposed by the Ordinance.

The empirical interpretation of the problem provides new criteria for redesigning the theoretical approach. According to this assumption, the experimental development of non-

[214] Cit. (OPDCM n. 2374, 2003)

destructive and minor destructive tests for the assessment of historical buildings could have positive consequences for the implementation of the conservation methodologies. In this sense, the presentation of some case-studies in chapter 4 and 5 of the thesis showed also the utility of the application of complementary tests: thermovision, sonic, radar, single and double flat jack tests are an example of a methodology of study that was proposed after the calibration of each single technique and the continuous implementation of their execution on real cases. Thanks to the experimentation of those testing techniques on different masonry typologies, their applicability and effectiveness was verified. Non-invasive diagnostic tests are useful for preserving the material integrity of the building heritage, but these techniques provide limited information, unable to cover the whole aspects of the problems of the design process. The execution of a combination of different tests was then adopted as a strategy for supporting the results of each technique. Through the mutual comparison of the information provided by applying the described set of tests, during the activities promoted by the ONSITEFORMASONRY project, the complementary use of NDTs and MDTs was proposed and verified. As a consequence, the described studies on diagnostic techniques were assumed to update the standards concerning the interpretation of the historical buildings. The introduction of the levels of knowledge evaluation was directly connected to the improvement of the diagnostic tests. The diagnostic approach as preliminary phase of the project was then recommended in national and international standards.

Chapter 5 of the thesis pointed out the role of the diagnostic techniques in different fields:

- The relationship between new and historical buildings. The interaction between historical buildings and new constructions is not only a problem of architectural composition, but a question of interpretation of the past evidence. The diagnostic approach can be used as a specific design strategy for supporting the development of the project.
- The introduction of new modern functions in historical buildings designed for other original purposes. The first way of protection for architectural heritage is the maintenance of the building: if the architectural fabric maintains a use (housing, working, entertainment, etc.), it can be conserved as an "alive building" (using Boito's metaphor). The diagnostic approach can provide a guide for the evaluation of the attitude of the existing structures to face the introduction of new functions on the original building, considering factors like the increasing of the loads, the safety of the people, comfort conditions, etc.

- The preservation of historical layered complex buildings. The presence of historical centres and isolated villages composed by aggregates is perhaps a peculiarity of the Italian territory. The Italian landscape maintains a deep connection between architectural aggregates and the surrounding territory and the safeguard of this patrimony requests a serious investigation of the structural peculiarities of these buildings: their vulnerability is, above all, the most important issue that is still presenting several uncertainties.

The thesis focuses especially on thermovision and sonic tests: two techniques particularly suitable for extensive and complementary use on masonry buildings. The possibility to apply both tests on-site and in laboratory allowed to increase the experimentation of these techniques, taking into account their applicability on different masonry typologies. Since the large number of masonry typologies represents the main limit for the standardization of the presented techniques, the results collected in the thesis have the aim to validate the testing methods and to support future studies on this field.

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