

# Understanding of historical masonry for conservation approaches: the contribution of Prof. Luigia Binda to research advancement

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**Abstract** Prof. Luigia Binda was a Full Professor in Restoration at the School of Architecture of Politecnico di Milano. She began her career teaching building and construction techniques, then strengthening and reinforcement of masonry buildings and preservation of cultural heritage. L. Binda, in her long scientific activity, addressed her interest to historic masonry structures, with a strategic broad knowledge of the process and merging knowledge from different research fields. Thanks to her multidisciplinary attitude, a deep passion toward puzzling problems and a gentle approach, she was able to combine conservation and safety issues with a robust experimental knowledge of masonry behavior, giving an extraordinary impulse to the research into the

experimental understanding, modelling, strengthening and preserving the cultural heritage. The paper shortly illustrates the main aspects of selected topics among the most outstanding contributions given by Prof. L. Binda in research, and describes the advancements made possible in many related fields, both academic and of professional practice. The title of each chapter starts with a typical sentence L. Binda used to remind people, which summarizes at a glance the importance of that specific aspect in the topic. In the authors view, it also implicitly indicates the innovative character of her insights and her extraordinary dedication to research.

**Keywords** Masonry · Vulnerability · Creep · NDT · Grout injection · Durability

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## 1 Introduction

The conservation and valorization of cultural heritage involves many aspects and requires a multidisciplinary approach, which could account for tangible and intangible aspects, the object of conservation having widened its limits from a single monument, to the historic centers, until the widespread heritage (consisting of villages and networks of distributed assets, i.e., the so-called “minor” or even vernacular architecture) and the landscape [1]. Present challenges posed to cultural heritage are given by increasing threatening conditions due to climate change, war bombing, mass tourism, speculation and abandonment. On the other hand, new opportunities could be found in a greater awareness of the heritage importance at a local and a global scale [2], (<https://europa.eu/cultural-heritage/>), in more and more sophisticated technologies for diagnosis and intervention in multidisciplinary research institutions.

Conservation of historic buildings requires a deep knowledge of structures and materials, of their properties, context features and use conditions, of the possible state of damage and its causes. Prevention and rehabilitation measures can be successfully accomplished only if a proper diagnosis has been formulated, so that historic buildings can be preserved as much as possible as historic documents of our past, keeping an use as compatible as possible with the structure [3].

The approach involves not only an accurate investigation of the building, but even the development of a research concerning “compatible” intervention techniques aimed at improving the structural behaviour or to limit risks. These items open several research paths, starting from the characterising of the several building techniques and materials of the architectural heritage to the development of investigation techniques and procedures, to the study of repair techniques, their compatibility with the existent materials and structures and their durability.

L. Binda during over 40 years of research and studies gave an outstanding contribution to the field, from both a methodological and a practical viewpoint, providing many pioneering approaches, which added outstanding value to advancement of both academic research and professionals training. Her

dedication established her as a leading figure internationally referred to as the “first lady of masonry”.

Being impossible to include all the studies L. Binda promoted and developed during her career, this paper illustrates some selected topics among the most innovative insights, which gave important directions to new perspectives of the research, regulations and practice, still in progress today.

However, besides the exceptional scientific rigor and the relevance of L. Binda studies, the text also implicitly acknowledges her untiring and passionate character, the thousands of encounters to share and develop ideas worldwide, the education of generations of students and professional development of researcher, technicians and professionals to a more aware and cautious approach to the preservation of historical heritage and human cultural values.

## 2 “Masonry is a complex material”: the evaluation of load-bearing masonry quality in built heritage

A large part of L. Binda’s research was dedicated at studying historic load-bearing masonry and to analyze its behavior under different states of stress. The definition of the parameters influencing its mechanical behavior guided her research to a methodology for evaluating the masonry quality based on both an accurate visual inspection and a proper diagnostic investigation.

### 2.1 The connection between constructive technology and building typology

Masonry is a non-homogenous material made of mortar and stones or bricks. As it is a composite material, its structural behavior depends both on the characteristics of the single components and on their interaction. The word “masonry” describes an extremely diversified system not only in terms of materials used but also of the constructive technique according to different historical and territorial realities [4]: the local masonry materials, the ease of retrieval and the ability of local workers, the geographical area location, the economic conditions and the building use. Studying the structural behavior of stone masonry is different and more complex than that of brick masonry, due to the great variety of masonry construction types in Italy and Europe.



Historic buildings with a masonry structure could be classified according to very different types, taking into account their original function and constructive features. Although the masonry materials could be the same, specific construction techniques were generally adopted according to the specific use and the building's typology, so that different masonry types can be recognizable in case of temples, churches, convents, houses, castles, arenas, bridges and so on. Structures can be simple or very complex with peculiar problems strictly connected to their function [5, 6]. The necessity to fulfil a specific use influenced the various constructive solutions as well as the structural analysis (support conditions and constitutive laws) and the intervention technique (different investigation levels and modelling). Different masonry types relate also to different damage mechanisms [7, 8].

## 2.2 The difficult choice of a proper intervention technique

L. Binda focused her interest in studying not only monuments but also widespread architecture. Investigation for knowledge can interest not only a single construction but a group of them or a historical city center as a whole. They are characterized by a complex texture of buildings usually "non-monumental", but not less important, which constitute a fundamental historical artistic and cultural proof.

The extreme varieties of constructive solutions adopted in historic masonry buildings did not help in the choice of the techniques for their repair and strengthening in the XX century. In Italy, first the 1997 earthquake (which struck the Umbria and Marche regions), then the one of 2009 (Abruzzo region) and the last in 2016–2017 (wide part of central Italy), gave the occasion to learn about the effectiveness of the repair and retrofitting techniques applied to existing buildings in the 1970s and 1980s. Those interventions were mainly based on the use of the common modern materials (e.g., concrete and steel). Most retrofitting interventions caused unforeseen effects due to the "hybrid" behavior activated between the new and the old structures (Fig. 1).

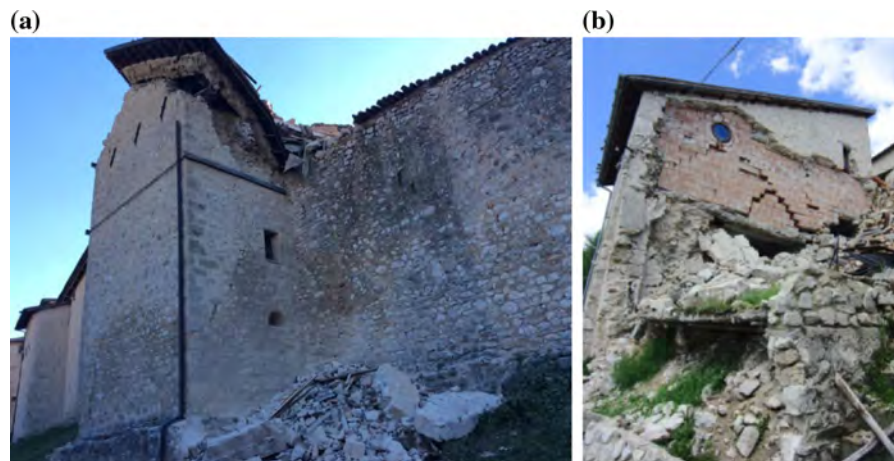
It appeared immediately clear that the main causes of inappropriate choice for the intervention techniques were due to: (a) the lack of knowledge on the material and structural behavior of the peculiar type

of construction techniques used in the past and their quality; (b) the use of structural models far removed from their real behavior, (c) the lack of control on the applicability of the retrofitting techniques. A respectful approach to an existing building in the conservation and strengthening project is not a theoretical principle but also a necessity to avoid physical and structural incompatibility.

## 2.3 The complex study of stone masonry

There is a real difficulty in applying some intervention techniques to certain types of stone masonry, made of not manufactured stones [9]. The presence of defects or the low quality of the constructive techniques can alter the load-bearing capacity of a wall and can be the cause of a local mechanism. The observation of the facing masonry texture only is not enough to reveal how the masonry is made in each parts. When it is not possible to observe the masonry sections directly and in the absence of large visible cracks or collapsed parts, a wall can be slightly dismantled (with hammer and chisel), in a portion not larger than  $40 \times 40/50$  cm (depending on the average stones dimension) and of the cross-section thickness. This should be realized in the same wall portion after carrying out diagnostic investigations with Nondestructive (ND) tests, so that the cross-check can be made between direct survey and experimental results. As an example, a high value of sonic pulse velocity can be related with the possible presence of the transverse connecting elements (i.e., stones especially oriented to connect horizontally the masonry layers) (Fig. 2).

After selecting the masonry area to be analyzed (it may be necessary to remove a portion of  $1 \times 1$  m of plaster), the survey of the masonry texture must consider the following aspects: (a) type of masonry units, e.g., brickwork, stonework, mixed stone and brick elements; (b) regular or irregular shape of stone elements; average stones dimension; type of manufacturing, e.g., cut sides and sharp edges, split stones, non-manufactured sides, round pebbles; (d) thickness of the horizontal mortar joints, made of various types of binder and aggregates, and different aggregates dimensions; general description of the mortar consistency; (e) course horizontality (masonry can show horizontal, sub-horizontal or irregular courses), offset of the vertical joints (respected, partially respected or



**Fig. 1** Damage due to irregular interventions on masonry walls: **a** damage of stone masonry bearing modern r.c. roof; **b** collapse of stone masonry bearing new floor made with modern technique and detachment of external leaf in composite walls



**Fig. 2** Analysis of wall cross-section: **a** masonry texture and starting of first stone extraction; **b** hole after masonry disassembling; **c** drawing of left vertical face of cross-section (without reaching other side) [12]

non-respected), presence of wedges and levelling of different materials; (f) cross-section type of the masonry wall (Fig. 3), e.g., single or multiple leaf, well interlocked or not, the presence of transverse connecting elements [10, 11].

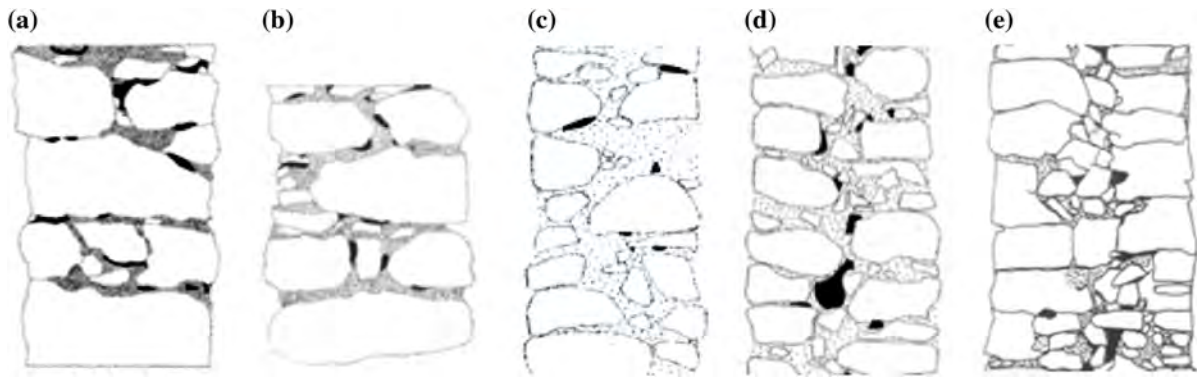
Data can be collected in a suitable survey form [12] following a procedure developed for the definition of the quality of masonry, which must start from the choice of the most representative areas of the masonry walls. In addition, historic masonry buildings may have been subjected, throughout the centuries, to several renovations and expansions made with various types of masonry. Then, the stratigraphic method allows subdividing the building into homogeneous portions characterized by relative chronological relationships. Each portion corresponds to a unique building phase, recognized by the

observation of constructive details. This identification will help in choosing the most representative masonry walls [8].

In some cases, the analysis of the present crack pattern can help in defining the masonry quality. The number and the shape of cracks can give indications on the stiffness and the compactness of a masonry wall: a single large crack that splits a masonry wall into two rigid elements is typical of a better masonry quality than a series of small diffused cracks in non-homogenous masonry wall, considering the same loads action [7, 8].

Every time a prevention or repair intervention has to be carried out on a historic building there is the need of defining its masonry quality. To this aim, it is necessary to know: (a) the masonry texture; (b) the morphology of the masonry section; (c) the stress–





**Fig. 3** Examples of masonry cross sections: **a** one single leaf; **b** two leaves well interlocked (with transverse connecting stone); **c** two leaves partially interlocked; **d** two leaves not interlocked; **e** three leaves or multiple leaf [12]

strain behavior of the masonry together with its mechanical parameters, as elasticity modulus and strength values.

The evaluation of the masonry quality may assume quantitative values if the survey is followed by some appropriate *in situ* diagnostic tests, thanks also to the recent developments of advanced investigation procedures [12–15]. A correct characterization of the masonry can be achieved by evaluating: (a) the wall compactness by sonic pulse velocity; (b) the stress–strain behavior, Young’s modulus and Poisson ratio, shear modulus by flatjack tests; (c) the section morphology (one leaf, multiple leaf) through a small disassembling; (d) chemical, physical and mechanical parameters of the components, by means of laboratory tests on sampled materials.

Building codes [16] are generally able to provide semi-empirical formulae for estimating the strength but only in the case of modern brick masonry based on the mechanical properties of its components. On the contrary, there is a lack of procedure to analyze existing historic masonry buildings. The Italian technical code for constructions [17, 18] recognized this necessity, supplying guidelines for masonry investigation with different levels of knowledge (KL1, KL2 and KL3) and reporting a table including some general mechanical parameters, referred to a list of masonry type classes, to be used for the seismic evaluation, in case no direct parameters are available.

L. Binda always remarked that a visual inspection of the external texture only has some limits in the masonry quality evaluation. Investigation through borescope supplies only a very local stratigraphy, without giving information about the constructive

aspects. The masonry properties can be detected only experimentally, *in situ* and in the laboratory, as well as the mortar properties can be deduced only from samples taken out from the core of a masonry wall and not from the surface wall, where past re-pointing or decayed mortar can be found. When dealing with historic masonry, the physical and mechanical characteristics of the masonry elements do not supply, directly or indirectly, the mechanical characteristics of a masonry as a whole. As a final remark, when dealing with the historic masonry quality, before choosing an intervention technique, which should be able to improve the efficiency of weak masonry walls, the recognition of the properties that helped them to last for centuries and survive to modern times is necessary.

#### 2.4 Further research developments

Thanks to the recognised importance given to the definition of the masonry quality in the structural evaluation process of existing buildings and given the variety and complexity of historical stone masonry, research should be able to classify existing masonry according to their construction technique, subdividing them by geographical areas or regions, thus constituting databases. This should improve the knowledge of the different construction techniques belonging to a place, sharing the results of the experimental investigations carried out and providing comparable mechanical parameters. Refining both the diagnostic investigation techniques and the survey procedures of the masonry texture (as in the above mentioned survey form) can help in finding new

correlations between constructive aspects and mechanical properties.

This approach also contributes to the improvement of analyzing and modelling the global and local response of historic buildings, as well as to reliable seismic assessments and further validation of the resistance criteria proposed in the regulations and the technical literature.

These are some of the objectives of an extensive ongoing research project supported by the Italian Service of Civil Protection [19], which also focuses on the seismic vulnerability assessment of historic buildings. In that context, a multi-disciplinary procedure addressed to an articulated knowledge of morphological and constructive aspects of the masonry elements is recommended; it is based on indirect and direct sources of information, leading to the identification of the most typical failure mechanisms activated by the earthquake and thus allowing for appropriate analytical models [20].

### **3 “Diagnosis investigation increases awareness”: onsite diagnosis and complementarity of procedures**

The interest of L. Binda concerning the historic structures developed almost naturally from her being an Architect involved in structural research, and working in the School of Architecture of the Politecnico di Milano. Her early research, in fact, was carried out within several Master Theses of the School of Architecture, still very relevant for the applied methodology; her interest subsequently matured thanks to several collaborations, firstly with P.P. Rossi of ISMES and later with C. Modena of the University of Padua.

P.P. Rossi was a pioneer in calibrating the well known technique of single and double flatjack [21], but L. Binda had the merit to catch the potential interest of the technique and to push its diffusion throughout international contacts (in particular J. Noland and Atkinson, Boulder, US) within the RILEM Committees; this activity led to the only standardized documents concerning flatjack within ASTM and RILEM [22–25].

#### **3.1 The diagnosis project**

Being active in the field of the diagnosis of historic structures, L. Binda felt the need of systematic practice in structural problems (Figs. 4, 5, 6, 7), crossing and merging information from several fields, including historical studies and giving a vivid impulse to the international debate through her participation to the ICOMOS-ISCARSAH and RILEM committees. Furthermore, recalling the personal involvement of the architect/engineer responsible for the building, she stimulated the development of guidelines concerning the diagnosis and several investigation techniques, which should be integrated to national codes.

The research of L. Binda and her collaborators focuses the key role of the survey design planned by those responsible for the building. Crucial points in the analysis of the ancient structures are: the weak knowledge of the building technology, the alteration in time, and the contribution of progressive damage/decay and its diffusion [3]. Workmanship highly affects the masonry quality with local meaningful changes of the mechanical behaviour (Fig. 4); the distribution of the masonry properties is difficult to explore by testing because of the restrictions of the number and diffusion of sampling. Furthermore, the scientific debate concerning the relationship between the results of local and global tests (Fig. 5) and their merging aimed to calibrate analytical models of the structure is still ongoing. Other open questions concern the effects of changes in the course of time, and the damage and the following interventions, all issues strongly undermining the present state of preservation of the ancient structures.

Progressive investigations carried out to recognize building morphologies and technologies, or possible pathologies, permit to organize information from several subjects and orient the subsequent studies, interventions or periodic controls.

The approach consists in subsequent steps, starting from the survey of the geometrical layout, the materials, the decay and the damage, with keen investigation of the building techniques and of its historical evolution; the research should be carried out with a strict and detailed comparison between the direct survey and the results of bibliographic and documentary research. The appropriate interpretation of the outcomes might lead to the identification and

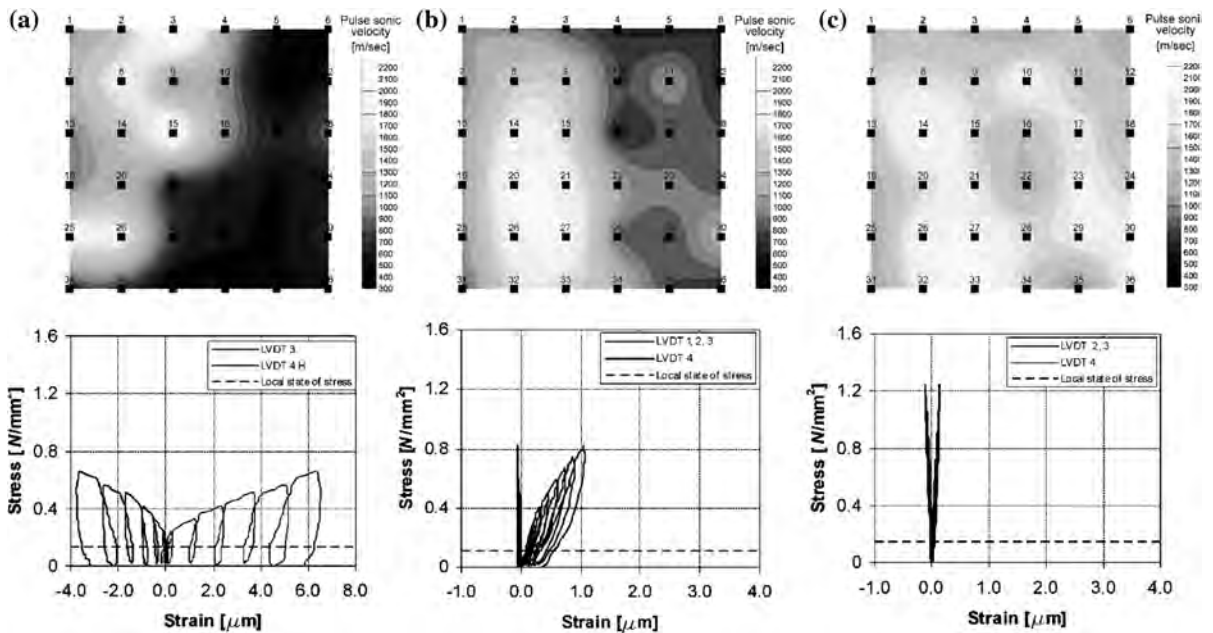
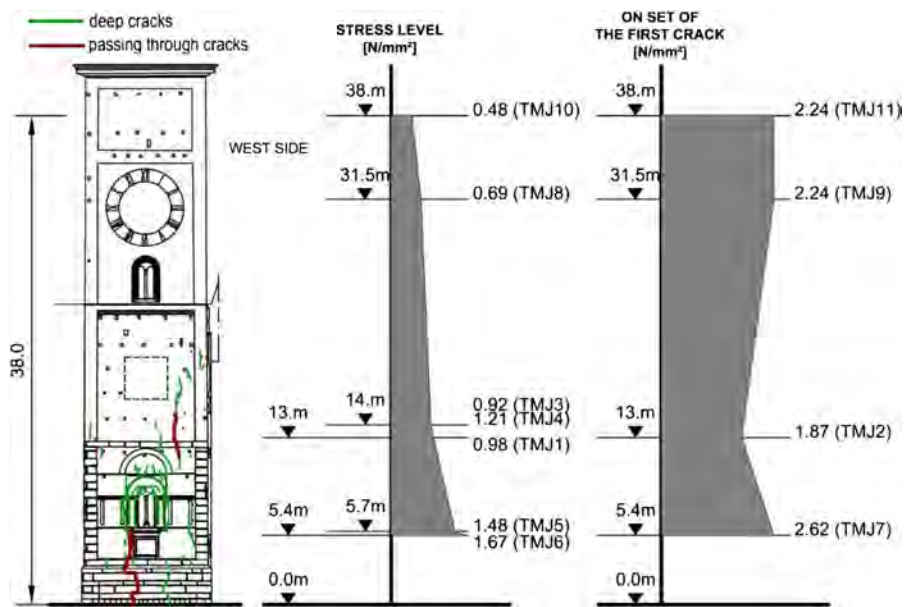


Fig. 4 Results of pulse sonic tests and single/double flatjack tests carried out to evaluate masonry quality

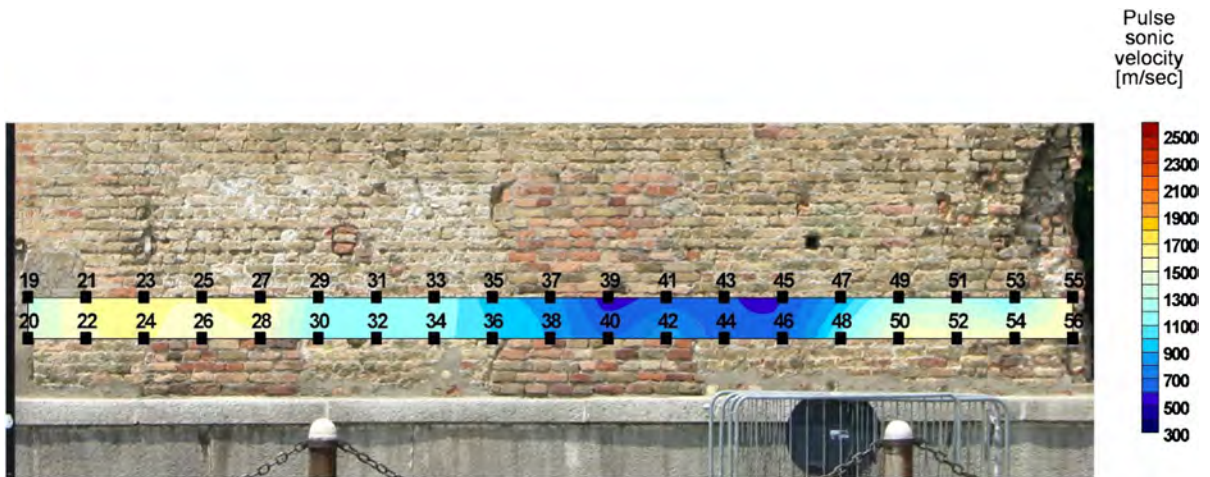
Fig. 5 Stress distribution by single flatjack and values of cracking onset by double flatjack



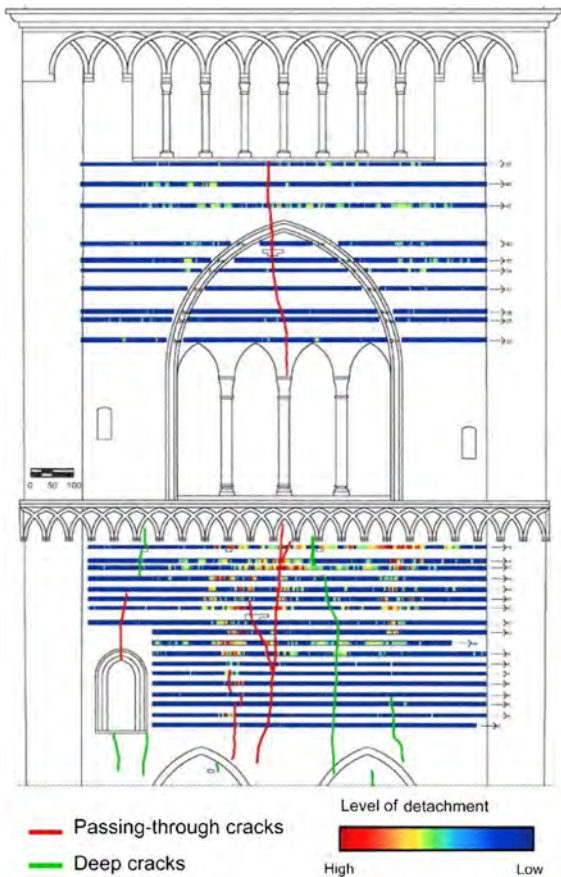
the localization of characteristic or anomalies requiring additional research or periodic controls. Furthermore, structural interventions might require specific diagnostic steps both before and during the works, as well as during periodic maintenance programs.

The assessment of the condition or of the structural behavior of an ancient masonry building could spring from several issues, such as the: (a) control of the integrity of the structure after extreme events (earthquakes, storms, etc.); (b) transformations of the building or changes of use; (c) evaluation of the quality of the intervention carried out locally on the





**Fig. 6** Distribution of pulse sonic velocity measured by transmission at base of Isso Tower at Castellone showing presence of infilled opening



**Fig. 7** GPR used in Cremona Torrazzo to map detachment of large part of cladding

materials or on the structure; (d) continuous monitoring of the structural behavior, of the material decay or of eventual further relevant parameters for the building in question.

Within the assessment of historic structures and the possible following interventions, in her works L. Binda stressed the importance of preliminary investigation oriented to ascertain the efficiency of the solutions together with their compliance with recognized conservation principles.

In Italy, structural interventions carried out in the last 50 years on ancient buildings after long neglecting and poor maintenance, frequently showed their ineffectiveness after the earthquakes. The applied techniques failed because of their low compatibility with some building technology (e.g., stone masonry structures) and poor applicability. The damage surveyed after earthquakes was frequently correlated to the low knowledge of the actual buildings characteristics and state of preservation at the moment of the intervention. This enhanced the need of robust cultural and technical frameworks aimed at managing the intervention on historic structures; the approach should merge and harmonize multidisciplinary information for the structural assessment prior to the intervention, and acting at several levels, including the whole ancient town centre, as well [26, 27]. Without the knowledge of structure integrity and the reliability of the intervention, the behaviour of the buildings is indeed often unexpected; at first, the diagnostic investigation should explain the



correlation between surveyed damage and the possible cause.

For the monumental heritage, the need of a preliminary analysis is a wide shared concept for the full realization of the conservation process. The principle is less diffused for vernacular or historical architecture, when not specifically protected by laws or codes. This is the case of the widespread architectural heritage of ancient town centres; the quality of the intervention is often not fully respectful of the preservation principles and of the most updated practice for the seismic protection.

In her scientific and dissemination activities after the Umbria Earthquake of 1997–1998, L. Binda was one of the scholars involved in the highlighting the above mentioned important issues and the need of specific investigation for the architectural non-monumental heritage, as well. These activities highly affected the following revision of the Italian seismic code.

### 3.2 Nondestructive and minor destructive techniques

L. Binda was very active within RILEM and led the activity of several technical committees concerning the calibration and application of traditional and innovative tests to the diagnosis of historic masonry structures, like the TCs 127MS, 177MDT, 216SAM, which produced a number of important documents.

Within the diagnosis project, L. Binda remarked that the application of Nondestructive techniques (NDTs) and/or Minor Destructive Techniques (MDTs) to the detection of hidden features or structural damages—or other problems—can be successful only if, from one hand, the problem to be solved is clearly defined and, from the other hand, the limits and advantages of the NDT are known. Her research was addressed to the interpretation of the NDT results and their correlation with masonry characteristics; L. Binda was interested in the possibility of using NDTs in the detection of the effectiveness of some repair techniques (e.g., grout injections, repointing, etc.) [28, 29].

The choice and the application of minor or nondestructive investigation for the study of ancient structures is a challenging task, which requires specific expertise and active collaboration. Clear and detailed procedures help to carried out effective

investigation, i.e., when the correlation between the specific problem to explore and the investigation technique is proven. Nevertheless, the variety of masonry types and technology, the material inhomogeneity, the data interpretation and their merging, affect the reliability of most of NDTs. As known, frequently NDTs were developed and calibrated for other investigation purposes or other materials (e.g., concrete). The direct application to masonry is often ineffective, requiring preliminary calibration of the equipment, control of the procedures and of the data interpretation (Figs. 5, 6).

This means that advantages and limits of each technique have to be clear to the designer of the possible restoration intervention. In fact, very seldom, a single technique can solve the problem; complementarity of NDTs and MDTs in the diagnostic investigation must rather be recommended. To this purpose, L. Binda considered mandatory the production of guidelines for the correct application of investigation techniques to diagnosis problems of different classes of masonries [30].

From the knowledge accumulated in the application of various investigation techniques to the study of masonry structures, as well as in the problems emerged from the past application, L. Binda investigated the complementary use of different techniques to solve the problem of detecting hidden masonry features [31–33]. In fact, no single tests can give all the required information, whereas a complementarity of different tests (thermovision, georadar, flatjack, etc.) has to be considered to achieve the necessary physical and mechanical masonry parameters (Fig. 4).

L. Binda frequently collaborated with other Scholars in the calibration of innovative investigation technique, within EC projects and RILEM TCs. Together with G. Lenzi (ISMES, Italy) and L. Zanzi, she carried out the first systematic research in the application of radar tests to masonry problems [32–35] (Fig. 7).

### 3.3 Case studies

L. Binda was responsible of many projects concerning the diagnosis of historic structures, starting from her research after the collapse of the Pavia Bell-tower. They could be considered, still now, meaningful examples of a sound methodology based on

systematic and integrated use of direct survey, historic documentation collection, NDT and local inspections. Among the several investigated buildings it is possible to mention the bell Tower in Monza [28], the Noto Cathedral [29], the Church of San Nicolò l’Arena in Catania [31], the Torrazzo in Cremona [35], the Syracuse Cathedral.

### 3.4 Further research developments

L. Binda’s work set an example for a generation of scholars interested in the development of new investigation techniques or in the improving the existent ones.

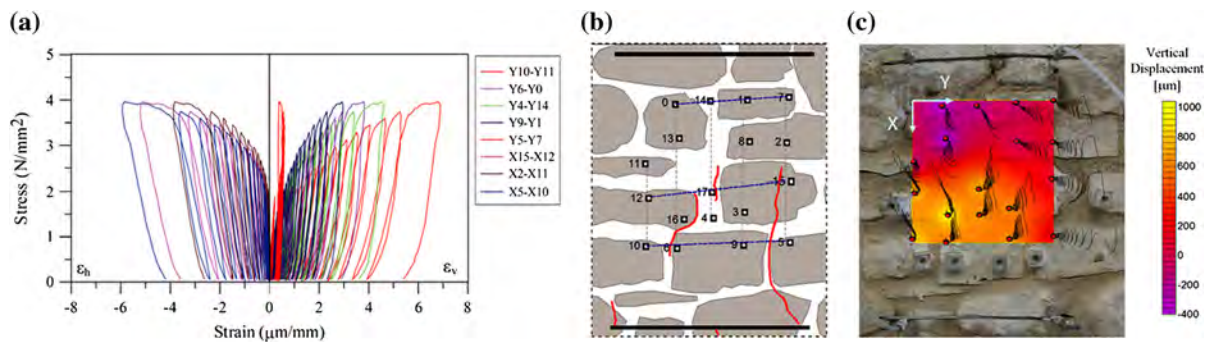
In the case of flatjack tests applied to irregular stone walls, the traditional measurement methodology used to record the displacements in chosen points of the masonry under stress variation proved not exhaustive for the movement description. In particular, the relative displacements between the gage points are measured without taking into account the displacements referred to an initial configuration. Recently, an optical system has been proposed, based on the use of a video camera as a video optical extensometer (Fig. 8) [15].

Furthermore, following the first tests carried out on the Bell-Tower of the Cathedral of Monza [36] Ambient Vibration Testing (AVT) and dynamic monitoring were improved and progressively diffused [37, 38]. At present, AVT and dynamic monitoring coupled to historic research, visual inspection and geometrical survey could be considered the most reliable procedure in the investigation of Towers. Moreover, up to now, most of the investigation

techniques applied to historical masonry constructions are not standardized within national or international codes. Despite her interest in the continue development of innovative techniques, L. Binda was definitely convinced of the necessity of rules and standards for the test repeatability and quality control that only official codes and guidelines can guarantee. Further activities, then, should be addressed toward the development of standards linked to the several national codes.

### 4 “Also masonry suffers creep”: the long-term behavior of massive structures

At the end of the 1980s, time-dependent behaviour was well-known in rock mechanics and had been studied to describe the response of stiff clays, soft rocks and concrete to permanent loading conditions [39]. It had also been observed in the case of new brickwork constructions [40], whereas the behaviour of historic masonry had never been referred to as time-dependent. The unexpected failure of the Civic Tower of Pavia can be regarded not only as a terrible loss, because of four victims and the collapse of a remarkable monument, but also as the starting point of a breakthrough research destined to throw new light into the understanding of the complex factors affecting the safety of massive ancient buildings [41]. L. Binda found herself involved within one of two committees, which were formed for investigating the causes of the collapse. Thanks to her multidisciplinary attitude, a deep passion toward puzzling problems and a gentle approach she was able to



**Fig. 8** **a** Typical stress–strain diagram obtained from different couples of markers on masonry; **b** markers fixed on wall and evidence of vertical crack; **c** amplified trajectories of markers

and map of final displacements acquired by optical system during double flat jack tests

combine conservation and safety issues with a robust experimental knowledge of masonry behavior. Being an architect with a sound background in structural mechanics, she was aware that masonry, despite being the most ancient architectural technique, was also the least understood and its knowledge could not rely on reassuring hypothesis like homogeneity, continuity, isotropy, and linear elastic response. Her willfulness led her to access the rock mechanics interpretation of long-term behavior and to apply creep tests to study ancient masonry; subsequently, she set up more suitable testing procedures based on pseudo-creep testing and explored different modelling methods based on both rheological and probabilistic interpretation. At present, the assessment of ancient massive constructions, including towers and cathedral pillars, cannot ignore the results she achieved in terms of laboratory experimentation, as well as theoretical knowledge and on-site applications.

#### 4.1 Risk factors threatening ancient structures

Considering the external factors characterizing the damage of ancient masonry, a lack of maintenance, a load increase due to building changes, land subsidence, mechanical stress due to earthquakes, fires and more should be included [42]. Among its intrinsic characteristics, the lack of homogeneity of the load-bearing section, the presence of several leaves badly joined, creep and the creep-fatigue interaction proved to play a major role. In particular, high persistent loads have shown to be the cause of a continuous damage.

The problem of achieving a reliable lifetime estimate of ancient massive masonry structures involves many uncertainties and can take advantage from the experimentally observed relationship between the secondary creep strain rate and the residual life of the material, as shown in the following.

#### 4.2 Experimental understanding of masonry creep

The influence of time on the mechanical behavior of soft porous materials can be described as an increase of deformation characterized by three phases: a visco-elastic branch at decreasing strain rate and

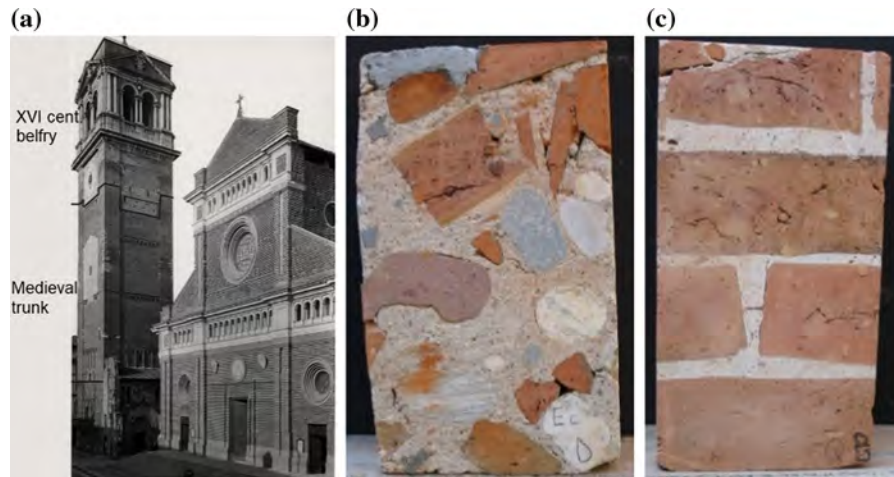
reversible strain, called primary creep; a visco-plastic branch at a constant strain rate, called secondary creep; a final highly unstable branch, characterized by strain developing at increasing rate and ending with the specimen failure, called tertiary creep [39]. The appearance of one or more of these phases and the strain rate value of the secondary creep phase depend on the stress level.

After the collapse of the Tower of Pavia, which was built in different phases between XI to XVI century, many prisms of different dimensions were obtained from the large blocks forming 7000 m<sup>3</sup> of ruins (Fig. 9). The prisms, subjected to mechanical tests, were initially obtained from the rubble masonry coming from the medieval trunk of the structure, characterized by three-leaf walls 2800 mm thick. Subsequently, prisms coming from the plain brick masonry constituting the XVI century belfry of Pavia were also tested. It was certainly not involved in the initiation of the collapse, but could offer an interesting comparison with similar historical masonry, e.g., that of the bell-tower of Monza, of the same age, which was suffering major cracking [43].

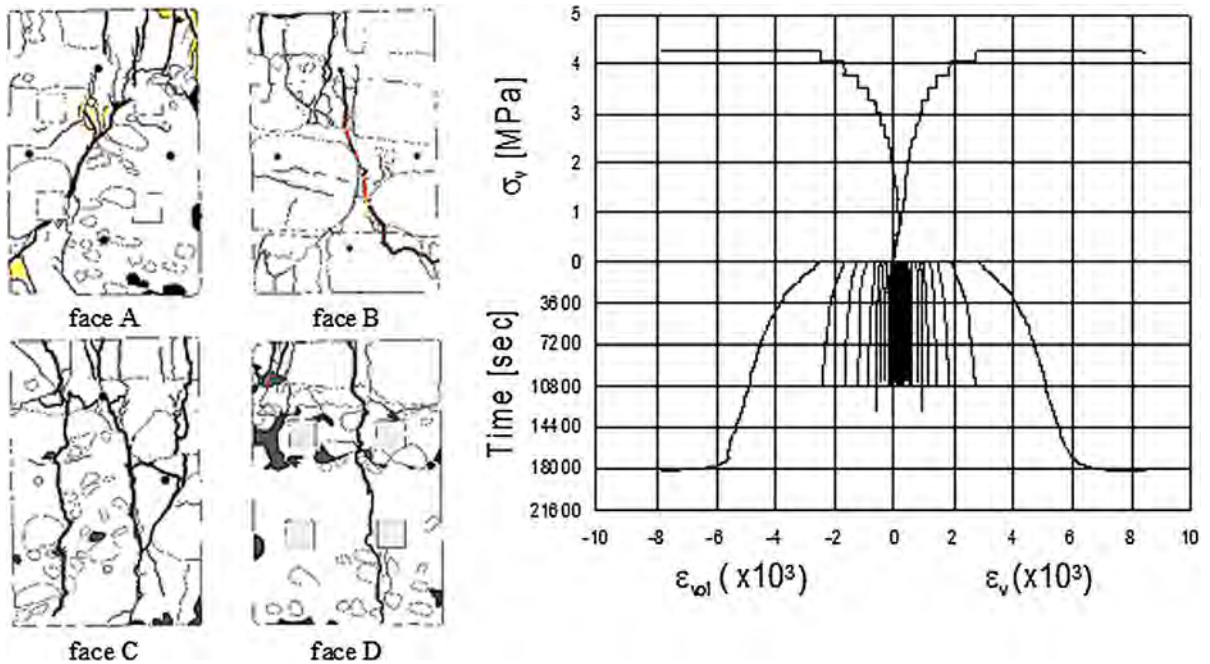
Eventually, also prisms coming from the crypt of Monza were tested, which was involved in partial demolition due to a project aimed at opening a door, given the impossibility of destructive sampling on the contemporary tower.

The testing activity was initially aimed at identifying creep behavior as a possible cause of the collapse of buildings, associated to the effects of wind (simulated through unloading reloading cycles tests). Subsequently, possible factors affecting creep (e.g., rate of loading, stress level) were investigated and the most suitable testing procedures to understand the phenomenon tried to be set up. Finally, significant parameters (e.g., strain rate of secondary creep phase) that may be referred to as risk indicators in real structures wanted to be identified [44].

Pseudo-creep tests turned out to be a suitable procedure for analyzing creep behavior, having the advantage of being able to be performed more easily than long-term tests. They were carried out by applying the load through subsequent steps of the same amount (generally 0.25 or 0.3 MPa) kept constant for specific time intervals (between 300 to about 30,000 s). The limit between primary and secondary creep phase could be satisfactorily caught, as well as the influence of the masonry morphology



**Fig. 9** a View of Civic tower of Pavia before collapse; b medieval rubble inner leaf; c XVI cent. plain masonry



**Fig. 10** Pseudo creep test on masonry of Monza crypt: crack pattern (left) and stress–strain–time diagram (right)

on the qualitative and quantitative mechanical behavior.

In Fig. 10 the results of tests carried out on the crypt of Monza masonry are shown. According to the trend of the stress–strain plot, its behavior can be considered linearly elastic below a stress value of 2.5 MPa. Correspondingly, the strain–time plot shows that, within this interval, only primary creep

develops. After that level, the stress–strain diagram indicates non-linear behavior and, correspondingly, the strain–time plots exhibit secondary (or steady-state) and eventually tertiary creep phases. The volumetric strain keeps almost naught values during the first twelve load steps and subsequently gets decreasing negative values until collapse. Decreasing volumetric strain can certainly be considered as an



increase of material damage. Figure 10 also shows the crack pattern across the specimen at the end of the test. It can be seen from the drawings that the prism was characterized by the presence of a large stone, occupying most of its face D and large parts of faces A and C. Basically, the crack pattern developed in sub-vertical direction, with fissures opening mostly along discontinuities which were already present at start of the test, whereas bricks were not cracked.

In Fig. 11, the results of pseudo creep tests carried out on the medieval inner leaf rubble masonry and on the XVI century belfry plain masonry of the Pavia Tower are compared. Initially, primary creep develops, then secondary creep and eventually tertiary creep shows for both materials. As expected, the prisms of the inner leaf (less regular and less homogeneous) reached failure well before the prisms of the plain masonry. Horizontal strain takes higher absolute values than vertical strain, indicating that at failure dilation takes place.

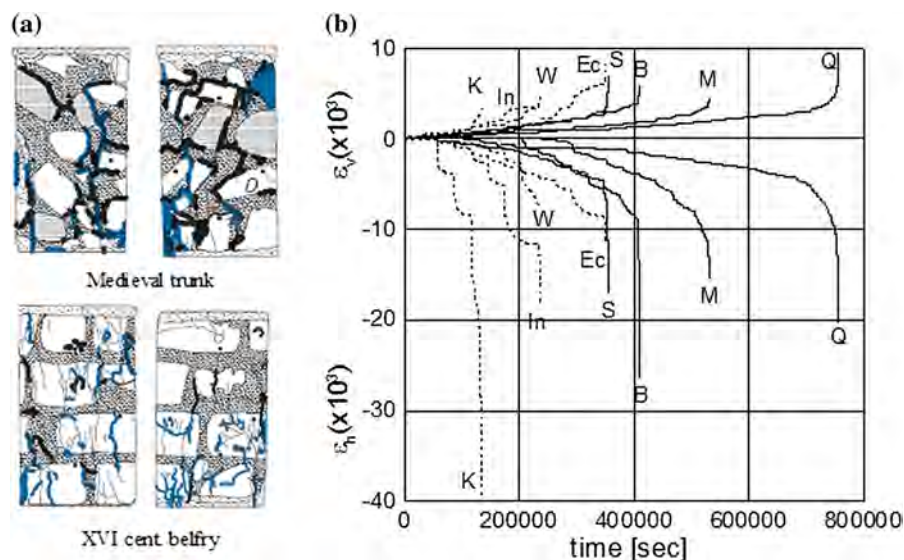
#### 4.3 Further research developments

To prevent total or partial failure of monumental buildings, the precocious recognition of structural critical states needs to be achieved, which can be pursued once relevant risk factors have been detected. In particular, from the experimental analysis, a limit

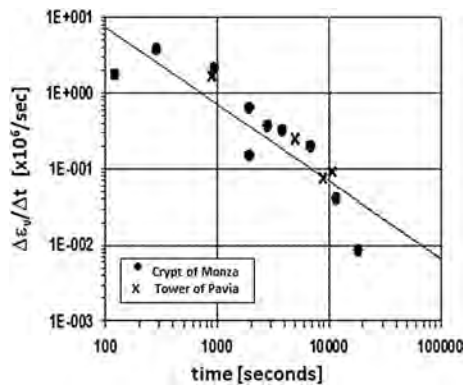
threshold of secondary creep strain rate turned out to be a sensible indicator of damage.

When studying the long term behaviour of ancient structures, a crucial issue is finding a way of predicting the residual life of a building. Based on the experimental results of pseudo-creep tests, a relationship was searched between the secondary creep strain rate and the residual life. The representative parameters were obtained from the last load step of every test and, particularly, the duration of the last load step was assumed as the residual life of the material. This was put in relationship with the secondary creep rate calculated before collapse. Figure 12 shows the comparison between the values obtained on the masonry of Monza crypt and those obtained on the ruins of the tower of Pavia: the strong correlation between creep time to failure and secondary creep rate is evident for both materials.

In view of preserving the historical heritage, the choice of significant geometric parameters to be monitored is an important issue, which should be made according to the masonry morphology and constructive technique. In fact, whereas rather brittle materials like plain masonry tend to crack with sharp visible patterns, plastic materials like multiple leaf masonry are mostly characterized by cracks diffused in the rubble inner leaf and not visible on the facade. Therefore, in the former case, the evolution of crack



**Fig. 11** Results of pseudo creep test on masonry of Pavia tower: **a** crack pattern; **b** strain versus time diagrams: (dashed line) Medieval trunk and (solid line) XVI cent. belfry



**Fig. 12** Secondary creep strain rate before failure versus duration of last load step

opening rate would be a suitable parameter, whereas in the latter an alternative geometric parameter indicating damage should be selected [45]. For instance, the rate of wall thickness increase at the base of the building may be feasible, since it indicates transversal material dilation which is associated with the material progressive damage.

A theoretical approach of the long term damage and an estimate of the lifetime of historic buildings toward the effects of permanent loads was also carried out by L. Binda and her research team, through both rheological models and a probabilistic method [46]. The results obtained from the interpretation of laboratory tests as well as tentatively of the results of a tower monitoring indicate an interesting research direction.

## 5 “Masonry is a smart material”: the role of mortar joints in the mechanical behavior of masonry structures and their durability

L. Binda’s scientific interest was early dedicated to the mechanical compression behaviour of the masonry [47]. Since the end of the 1980s, L. Binda and her colleague G. Baronio followed a systematic methodology to study the damage caused to masonry by salt crystallisation. On the basis of the state diagrams of the most diffused and harmful salts, the sodium sulphate was chosen as the most aggressive in the shortest duration of the test [48].

In the past, masonry has been treated as a composite material made up of rigid elements able to provide a high mechanical response. According to

Hilsdorf [49], calculating the mechanical strength based on the properties of the constitutive materials (mortar and bricks) is not correct, because the two materials interact in a very complex way and have too different characteristics (e.g., irregularities and dimensional variations of the bricks or mortar joints might cause high stress concentrations). On the basis of Hilsdorf’s research, Hendry et al. [50] implemented a mathematical theory and model, which analytically explain the brick/mortar interaction.

### 5.1 The role of mortar joints in the mechanical behavior

At the end of the 1990s L. Binda and G. Baronio’s interest was attracted by the study of Byzantine churches (S. Vitale basilica in Ravenna, Italy, 5th cent. AD) and particularly by the use of thick mortar joints (Fig. 13). The feature of that masonry, similar to that of other Byzantine buildings, is represented by the joints thickness, which is approximately the same height of the bricks (40–50 mm) [51]. The use of thick mortar joints was very frequent during the Byzantine Empire, although it was already adopted in the late Roman Empire. Currently, a thick mortar joint is considered a weaknesses affecting the strength of the masonry. Historians gave several explanations for this use; the most diffused among them referred to economic reasons, as thick mortar joints in a wall required less bricks. Nevertheless, due to the fact that the size of the aggregates was carefully increased according to the thickness of the joint, L. Binda was also convinced that the technique had certainly to be reliable from a mechanical point



**Fig. 13** View of thick mortar joints of St. Vitale basilica in Ravenna (Italy)

of view, since it lasted more than 1000 years. Though its reasons could have been economical, still the use of thick joints also proved to play a conservative role from the structural safety viewpoint.

The joint properties (thickness and material type) have a great influence on the strength and deformation values of masonry, therefore L. Binda and G. Baronio started their research on mortars made with lime and brick dust, and pebbles as binders [52]. The function of the bricks was well known also in the past, even if not described scientifically.

To better understand the role of these thick joints [51] in a brick masonry with large thickness (90 cm in the case of the basilica of S. Vitale), a series of stack bond prisms were built with mortar joints 40 mm thick and then subjected to long-term compression tests. Mortars were made of a binder based on hydrated lime putty and either siliceous or calcareous aggregates, with addition of brick pebbles and brick dust. The ratio binder/aggregate of the mix was 1:3, the same composition to those used in S. Vitale. Putty lime and bricks were made on purpose to develop a slow but effective mutual pozzolanic reaction. The bricks used for the stack-bond prisms had dimensions of  $310 \times 310 \times 40$  mm and were produced with ferrous clay adding quartz sand fired at  $950^\circ\text{C}$  (Fig. 14). The specimens were cured up to the day of testing at different times (28, 60, 90, 365 days) at  $20^\circ\text{C}$  and 65% RH, and pre-loaded (constant load of 0.5 MPa).

After 28 day of curing, specimens showed cracks in the mortar joints at a very low load value and in the



**Fig. 14** View of some specimens in pre-loading phase

bricks at a much higher one, whereas after 365 days the formation of larger fissures was observed both on joints and the bricks [53].

The laboratory reconstruction of the thick mortar joints from the studied composition of the ancient mortar demonstrated the high deformation occurring at early stages and the research contributed to increase the knowledge on the role of these joints in the mechanical behavior of masonry.

A high joint thickness does not seem to influence negatively the strength of the masonry even at an early time of curing, as the theory seems to stress. The joint properties (thickness and material type) have a great influence on the strength and deformation values of masonry. A research carried out by Francis et al. [54] on prisms made of bricks without mortar, gave strength values nearly double with respect to the ones given by normal mortar joints. Another research developed by Morsy [55] with joints made of various materials (from rubber to steel), showed also a mechanism of failure of the rubber joints very similar to the one described by Hilsdorf. This helps understanding the importance of calibrating the aggregate grain size distribution according to the joint thickness; on the contrary, the horizontal and vertical deformations are much higher than the case of thin joints, especially at short time curing [56]. Therefore, the Byzantine masonry proved to be a “smart material” [53], highly suitable to react towards possible stresses occurring during the structure long life span.

## 5.2 The choice of the joint thickness for the reconstruction of collapsed pillars

After the terrible collapse of the pillars of the Noto cathedral (Italy) in 1996 and the consequent decision to demolish the remains of the survived pillars (Fig. 15), an extensive on-site investigation was carried out by L. Binda and G. Baronio aimed at identifying the cause of the collapse to avoid new damages in the future [57]. A parallel work was done in the laboratory and on-site, to identify and characterize the materials used in the construction. On-site investigation was aimed at studying the morphology of wall and pillars and the state of damage of the remaining pillars to evaluate the possibility of consolidation by the grout injection technique. Mortars and stones were characterized in the laboratory to



**Fig. 15** View of entrance of Noto cathedral after removal of ruins

detect their composition and their mechanical and physical behaviour [58].

At first, the architects wanted to reproduce the traditional mortars used in the area in the 19th cent. Nevertheless, on the basis of the experimental results [59] and due to the lack of proper materials on the site and the impossibility of having a constant quality from the different suppliers and a good workmanship, it was decided to use a ready-to-mix mortar (based on hydraulic lime binder). To select the proper stones for the reconstruction, samples were taken from different quarries. Although it was impossible to use the same limestone as the original one, care had to be taken in order to use new materials with similar characteristics to the ones used in the historical construction. Then, the proper thickness of the mortar joints was studied in the laboratory. The joint thicknesses were measured in the cathedral and then statistically elaborated, whereas the aggregate size distribution of the mortar had to be chosen. The results of the compressive tests carried out on specimens made of limestone cubes of 200 mm per side, with different thickness of the mortar joint, highlighted that the best results were obtained with joints 5 mm thick and

aggregate size varying from 0 to 1.7 mm (Fig. 16) [60].

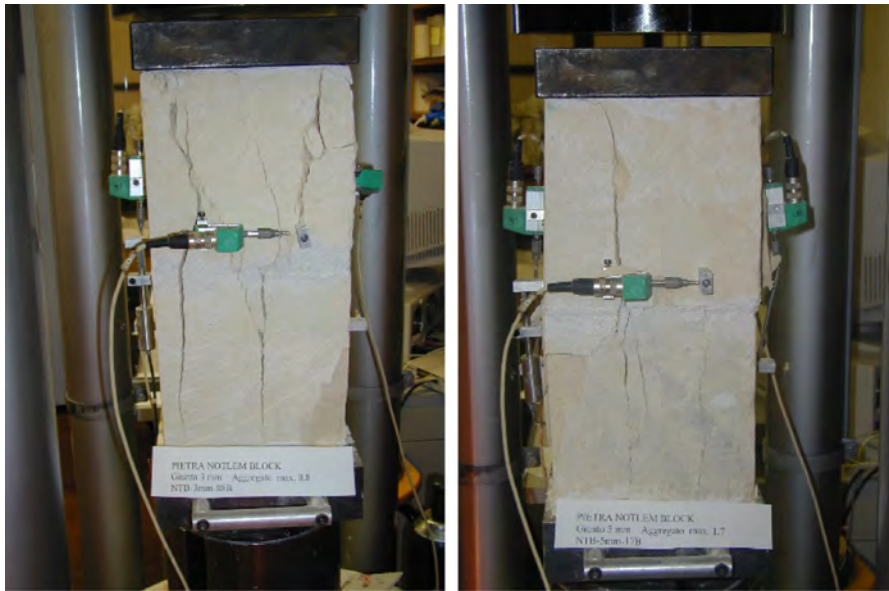
The study provided a guideline for the choice of the most suitable materials to apply for the reconstruction of partially collapsed historic buildings, based on on-site measurements and laboratory experimental investigations. The approach requires: (a) the selection of compatible mortars following the decision that the traditional ones could not be remade; (b) the identification of quarries to select the most appropriate type of stones replicating the original ones; (c) the evaluation of the optimal thickness of the joints and of the grain size distribution of the mortar aggregates.

### 5.3 Durability of building materials

The decay of masonry is also highly influenced by the environment aggressiveness and by the combination of the masonry constituents.

The mutual influence of the masonry components in the surface damage was studied on masonry prisms damaged by salt crystallisation in the laboratory and on full scale models built in a polluted area of Milan (Italy). In order to accelerate the damage, a sodium sulphate solution was inserted into the building foundations so that the ageing came by capillary rise. Crystallisation tests in the laboratory were carried out on masonry prism according to RILEM recommendations [61]. A laser profilometer was used to measure the degradation of the external surface [62]. Then, a suitable data acquisition system transforms these measurements in surface roughness profiles, which describe the decay as a function of time and space. The values of the chosen parameter measured over time can constitute the input data for a deterministic or a probabilistic mathematical model, to study the material behavior and the durability of surface treatments in the presence of different soluble salts and different quantities. This approach was used not only to model the decay mechanisms, but also to reduce the time duration of the accelerated ageing tests and to prevent the occurrence of the decay, particularly when using surface treatments and/or material substitution [63]. Results can help in the choice of appropriate repair and protection techniques for external surface of historic buildings.





**Fig. 16** Couple of limestone specimens after compression tests

#### 5.4 Further research developments

Further research is being carried out on-site and in the laboratory to gain new knowledge, especially on the effect of masonry deformations on the long term behavior of thick mortars joints and on the damage caused by salt crystallization not only to masonry but also to concrete [64] and fiber reinforced clay brick masonry [65].

The joint thickness is one of the parameters highly influencing the masonry mechanical behavior. Very thin joints, made of plastic material similar to glue, can improve the strength of masonry. Nevertheless, if the binders used and the grain size distributions of the aggregates are adequate to the thickness of the joint, also the walls with high joints can have a good behavior.

Recently, some analysis were made on the apparent deformations recorded on the walls of San Vitale in Ravenna, in order to verify the great deformation capability experimentally detected, and to relate it with the possible differential soil settlements that the walls of the ancient basilica experienced in the past, without apparent damage.

#### 6 “Architectural preservation can contribute to archaeology”: the restoration of the peculiar masonry of the Mỹ Sơn temple in Vietnam

In 1997, a new program of research and redevelopment on the archeological area of Mỹ Sơn was undertaken, thanks to an agreement among UNESCO, the Ministry of Culture and Information (Vietnam) and the Lerici Foundation of Politecnico di Milano. The activity aimed at drawing up a management plan that took into account international protection standards, also in view of the nomination of Mỹ Sơn in 1999 into the UNESCO World Heritage.

In 2000, the archaeologists of the Foundation and the Institute for Conservation of Monuments in Hanoi invited the Dept. of Structural Engineering (DIS) of the Politecnico of Milano to visit the Mỹ Sơn (Vietnam) archaeological site. L. Binda was involved in the project thanks to her deep knowledge about historic masonry constructions and all the problems related to the compatibility of the materials for the intervention.

Since then, L. Binda and her co-workers have been actively involved in the research, which started with the characterisation of the original materials and the detection of the original construction techniques [66]. The study also concerned the definition of the

conservation conditions and the characterisation of compatible materials, and ended with the proposal of a conservation project based on proper methodologies and intervention techniques, to be taught to the Vietnamese technicians.

Since 2003, thanks to another agreement between UNESCO, Vietnam Ministry of Culture and Information and the Lerici Foundation, a pilot project started in Mỹ Sơn. The study concerned the excavation and conservation of a group of religious buildings built between the eleventh and thirteenth century, partially in ruin conditions (Fig. 17). These buildings were classified by Parmentier with the letter G [67]. Results achieved up to now contributed to answer to numerous open questions of historical and scientific nature, and to give the site a new value through the correct conservation of some of the buildings. Before this project, there were many doubts concerning the construction techniques and the materials used for the erection of buildings. It was widely believed that these architectures were made of raw bricks, afterwards cooked. Furthermore, it was possible to identify the structural problems emerging from the buildings leaning, their crack pattern and the physical, chemical and biological decay of their materials.

After the end of the project, L. Binda travelled from Milan to Mỹ Sơn twice a year to follow the restoration works. She also contributed to the training of a number of Italian students, who worked in Mỹ Sơn for several months in partial fulfillment of their MS and PhD theses. She also activated an exchange of researchers with the Institute for Conservation of Monuments (Hanoi, Vietnam), which allowed the



**Fig. 17** Group G before intervention



training in Milan of two Vietnamese researchers at the DIS Laboratory for Materials Testing.

### 6.1 The site of Mỹ Sơn

The archaeological area of Mỹ Sơn is one of the most important examples of Hindu monumental complexes of South East Asia. The site was discovered and cleaned from the jungle vegetation only at the end of 1800, after centuries of complete abandonment.

From 1897 to 1945, the researchers of EFEO (École Française d'Extrême-Orient) were the only ones who studied the culture and the architectural heritage of the Cham people who built Mỹ Sơn, thanks to the work of Parmentier and his archaeological excavations, that lasted until the half of the twentieth century. The research continued for a short period from 1982 to 1986 thanks to a Vietnamese-Polish mission, which restored some temples in Mỹ Sơn. This mission worked not only on the Mỹ Sơn site, but also in the most important Cham sites in the Vietnamese territory. At the end of the Vietnam War, most of them were reduced to ruins.

The Hindu temples of the archaeological site of Mỹ Sơn were built from the tenth to the fourteenth century with brick masonry and very thin joints, consisting of natural resin. In several examples of preservation interventions, invasive techniques and inappropriate materials were adopted, such as cement mortar [68], which had caused a quick degradation of the new parts and an increase of the deterioration phenomena. Furthermore, the peculiar construction technique with thin natural resin joints in the masonry does not permit the use of repair techniques familiar to Europeans. The thin joints made by natural resin excluded, indeed, a common technique of intervention using mortar, which would not permit the continuity in the masonry pattern.

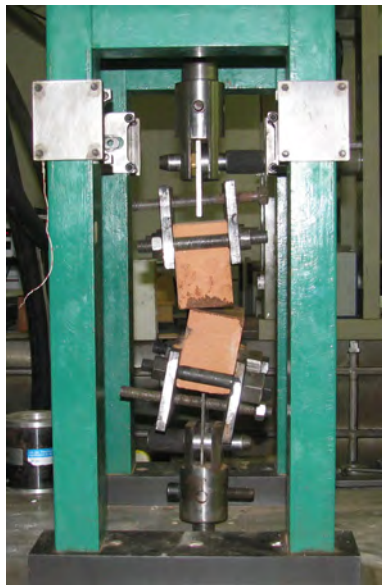
### 6.2 Main results and guidelines for preservation

It is well known that an appropriate design for the preservation of a historic building can only be established when a deep knowledge is collected and a diagnostic investigation is carried out on-site and in the laboratory, following a dedicated methodology [69]. Therefore, beside the on-site analysis, some materials samples were collected to be tested in the laboratory of the Politecnico di Milano.



**Fig. 18** Couple of bricks with original joint

The most important results concerned the material used for the binder. The joint appearing on the external face of the brick masonry was so thin that it was impossible to recognize it as a real joint (Fig. 18). The chemical analyses demonstrated that the joints were not made of lime, but included many organic components, among which *Dammarenediol*. It is a component of the Dammar resin, widespread in the Southeast and East Asia, which can be extracted from some families of conifers, including *Araucariaceae* and *Dipterocarpaceae*. The same material was found in two commercial resins from the area of Mỹ Sơn:



**Fig. 19** Couple of bricks specimen bond with new natural resin after tensile test

one is used to caulk wood boats, while the other is a glue that comes from *Dipterocarpus alatus* trees.

Several mechanical tests were carried out before deciding how to use the resin for the restoration, whether it had to be mixed with brick powder or lime or used alone, cold or hot (Fig. 19). The best results were obtained by using the natural resin after heating and eliminating all the contained impurities as burned bark.

Another peculiarity of Cham masonry is the fact that it is composed of three leaves: the two external layers are made of bricks with the joint of natural resin, while the central one consists of bricks or half bricks and clay, chamotte (i.e., fragments of fired clay) and quartzitic temper as a binder [70].

As for the intervention, it was decided to use the new natural resin for the external layers, while for the central one a new type of mortar was adopted. Since it was impossible to find lime (hydrated or hydraulic) near the area of Mỹ Sơn, after several chemical analyses a natural lime based on shells powder was adopted as a binder. To obtain a hydraulic mortar, lime was mixed with brick powder characterized by variable particle sizes, which was found to be pozzolanic [71].

The intervention on the first building started in 2004. In 2005, after some good results had been obtained, the same procedure was applied to the other buildings (Fig. 20).



**Fig. 20** Part of group G after intervention

During the spring of 2011, guidelines for the archaeological research and repair interventions respectful of conservation were sent to the UNESCO Office in Hanoi. These guidelines were developed thanks to the direct on-site experience of L. Binda. Even if a good part of her experience was developed in Mỹ Sơn, these guidelines can be considered of general interest for the Cham monuments in Vietnam and also for other monuments.

Between 2010 and 2012, thanks to a project supported by the Lombardy region [72], it was possible to visit several Cham sites in Vietnam, including Mỹ Sơn. Further samples of material (bricks and joints) from different buildings were taken and the analyses of the joints were compared with that of Mỹ Sơn. The spectroscopic analyses showed an additional component in the other joints, even if it was not possible to be defined [73].

Today, the restoration work continues in Mỹ Sơn following the principles and methods proposed by L. Binda, and several researchers from Politecnico di Milano still work there.

## **7 “Only knowledge should bring to intervention”: a comprehensive approach to the grout injection technique**

The definition of the guiding criteria for the choice of proper intervention techniques was among the main subjects studied by L. Binda and her research group, with the fruitful cooperation of engineers and technicians. Inter-disciplinary research supported by experimental testing and numerical modeling actively contributed to the international debate around the conservation of existing masonry constructions (RILEM TCs RHM, SGM, DHM, MSC, CSM; NIKER project [74]). The design of a technique as a direct result of the knowledge process, the selection of compatible materials, the experimental validation before application, the on-site control and the check of the intervention effectiveness should be mentioned among the crucial advices that contributed in changing the methodological approach of consolidation and restoration works [75–79]. Those studies provided simple solutions applied to masonry components, based on conservation principles (e.g., minimum intervention, compatibility, removability) and either traditional or innovative materials, as in the case of

the bed joint reinforcement technique, that was proposed in cooperation with C. Modena of the University of Padova, to face the problem of creep in brickwork massive structures [80–84]. As for stone masonry, a tremendous work was accomplished in the field of grout injections, one of the most common but also controversial technique, in terms of parameter design. The technique aims at consolidating cracked components, but can be particularly effective in multi-leaf rubble masonry with incoherent core, that is an extremely vulnerable wall type under seismic loads [7, 85, 86]. The interest around this intervention is still high, as injections can improve the mechanical behavior of low quality masonry by increasing its transverse connection to achieve monolithic cross-sections. Outstanding research contributions were done since the 1990s by the studies of L. Binda and are still topical in the field. They encompass several aspects to foster a more comprehensive approach to the masonry and its complexity, i.e.,: grading of binders according to crack or voids dimensions; compatibility and durability according to the existing masonry constituents; injectability checking; guidelines for application in historic context; use of ND procedures before and after intervention to check feasibility and effectiveness, respectively; mechanical improvement. [87–90].

### **7.1 Requirements for the optimization of grout injections in rubble stone masonry walls**

The studies on the grout injection technique mentioned above provided a solid background for further experiences aimed at contributing to the upgrading of the knowledge in the field and the extension to a greater context of quantitative parameters useful for design and assessment. According to Binda et al. [91], being masonry (especially in historical contexts) highly variable in its types, and in order to reduce the probability of unsuccessful intervention, the applicability of grout injection technique cannot be generalized, but it has to be optimized according not only to the actual presence of voids but also to their mutual interconnection. The probability to involve isolated cavities or holes without knowing the receptive capacity of the wall can be very low, and even the application of ND procedures, as sonic pulse velocity tests, which are fundamental for pre-





checking of and post-evaluation of the intervention, cannot capture the exact position of voids and their dimensions [92].

Following the very few contribution available in literature (all focused on cement grouts) about experimental works including multi-level evaluations (i.e., the contextual characterization of basic materials, injectability tests, mechanical tests on injected cylinders and on full-scale walls before and after injection) [93, 94] a comprehensive research was carried out at the University of Padova [78]. A natural hydraulic lime-based grout was designed and optimized in its constituents (i.e., in terms of  $w/b$  ratio, % and type of additives) to fit the feasibility and injectability requirements of a series of three-leaf rubble stone masonry panels (50 cm thick, 180 cm tall) with an incoherent core (14 cm thick). According to the approach provided by Binda et al. [91], admixtures should be selected taking into account primarily their compatibility (especially of binder, as aggregates can be rarely present, depending on particular morphologic conditions) with the current constituent materials (mortar and stone, and other possible inclusions). Then, their composition has to satisfy some prerequisites (fluidity, stability), which are not depending on the substrate to be injected, but are strongly influencing some design parameters (e.g.,  $w/b$  ratio, presence of additives to regulate rheological properties). This means that without proper fluidity (i.e., ability of the grout to migrate into voids for a proper time) [95] and stability (i.e., the indicator of the homogeneity of the grout) [96], as well as other basic properties (e.g., proper setting time and low shrinkage), the grout is not suitable for injection, regardless any masonry category. Finally, the method permits to calibrate the optimized grout according to the specific masonry type by testing its injectability on Plexiglas cylinders filled with the material to be consolidated (i.e., the rubble core in three-leaf cross-sections) and reproducing the same arrangement of the real wall. The injectability test on cylinders has many advantages, as it simulates both the procedure and the effect of the injection. Some design parameters of the technique can be defined, e.g.: the pressure applicable to the grout, to permit the correct diffusion inside the holes; the distance among holes drilled on the wall to cover properly the portions to be consolidated; the opportunity of internally pre-moistening the wall. In addition, other

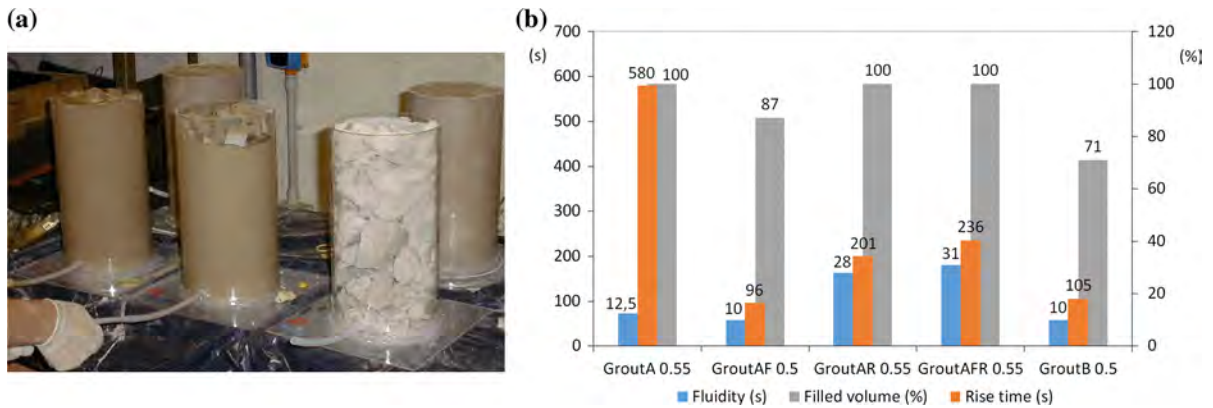
parameters can be re-calibrated after the preliminary selection of grout constituents, e.g., the fluidity, which can suffer from the absorption of the masonry materials, especially in the presence of ancient mortars. At last, after curing, the injected cylinders can be tested in the laboratory under mechanical conditions (compression, splitting) to get mechanical parameters to be included in formulas for the strength prediction of consolidated walls [97].

## 7.2 Experimental validation of injectability

Injectability tests were performed in the laboratory, according to [98] on a series of Plexiglas cylinders ( $300 \times 152$  mm, height  $\times$  diameter) filled with coarse material (limestone and mortar pieces, about 38% and 13% in volume, respectively, the remaining 48% being voids) reproducing the rubble core of ancient multi-leaf masonry walls. The mortar was based on hydraulic-lime binder and lime putty. Compressive strength of mortar (after 28 days of curing) and limestone were 1.58 MPa and 164 MPa, respectively. Hydraulic lime-based grouts were injected from the base of the cylinders with a pressure of about 0.05 MPa. Five admixtures were selected among 25 combinations of various  $w/b$  ratios and type of additives (i.e., fluidizer or water retainer), according to the above mentioned prerequisites [99]. One of the selected admixture was a premixed product (GroutB), whereas the other four admixtures were composed of the same basic binder (GroutA) of GroutB plus a fluidizer ( $F$ ) and/or a water retainer ( $R$ ), both added as 0.25% of the binder weight. Three cylinders for any condition were tested, for a total of 15 specimens. Grouts were mixed with a double-screw drill, by applying 1500 RPM for 3 min. The Plexiglas cylinders permit a direct inspection of the grout rising and the measurement of both height covered and time of filling, so that the design of the most suitable admixture can be eventually optimized. After 28 days of curing, the specimens were tested under compression and indirect tension (splitting) to characterize the mechanical properties of the consolidated core and inspected after failure.

The results confirmed the high injection capability of such coarse cores, as all cylinders were fully permeated by grouts (Fig. 21a). Times to cover the whole height vary according to the fluidity of the grouts (measured as efflux time at the ASTM cone

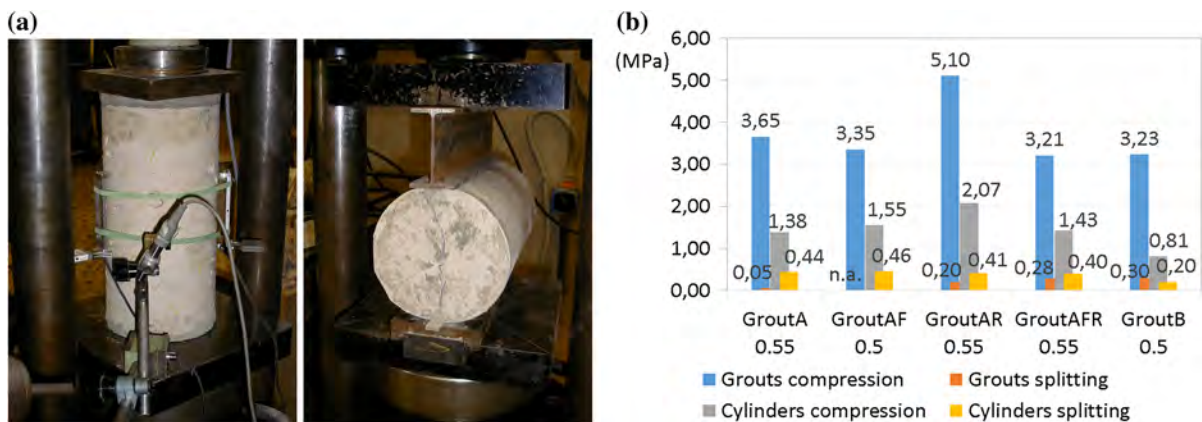




**Fig. 21** Results of rheological properties: phase of injection of cylinders (a); comparison between fluidity of grouts and injectability of cylinders (average of three cylinders for condition) (b)

[95]), especially for the additive-added admixtures. In particular, GroutB and GroutAF (both with  $w/b=0,5$ ) referred to the lowest rise times, whereas the grouts including water retainer, even with higher  $w/b$  ratio, were highly slowed down (more than 100% compared to the previous ones). However, the positive effect of additives is clear, as the simple GroutA, even with high  $w/b$  ratio, had a quite difficult migration to fill the whole cylinders. By comparing the volume of grout introduced through the injection (computed as the weight of the consolidated cylinder divided by the density of the fresh grout) with the volume of voids (quantified as the amount of saturating water before injection) the high effectiveness of the injection was estimated, varying those ratios from 86% to 100% (Fig. 21b).

Experimental results on hardened cylinders (for both compression and splitting tests) (Fig. 22a) showed a very low variability in comparison with the mechanical strength of grouts (particularly the compressive strength) (Fig. 22b). Inspection after test pointed out the good bond between grout and mortar (better than with stone surface); this was due to the higher roughness of the mortar compared to the stone pieces but also to the higher absorption coefficient (12.7%, compared to 0.4%). The research demonstrated the feasibility of the injection intervention technique and the control of its effectiveness by the preventive optimization of the grout composition, also taking into account compatibility requirements.



**Fig. 22** Results of mechanical properties (hardened specimens): compression and splitting tests on cylinders (a); comparison between grouts and cylinders strengths (b)

### 7.3 Further research developments

Experimental research and on-site observations on the effects of current practice of intervention applications on masonry components showed that the application of strengthening/repair techniques cannot be generalized; on the contrary, to foster an actual improvement, they need to be properly designed and validated on the specific conditions (mechanical behavior, damage proneness, quality of materials) of the masonry construction. In this connection, a catalogue able to identify proper solutions according to the variety of historic structures (e.g., houses, churches, towers, free-standing remains), giving also parameters for the characterization of both static and dynamic (seismic) behaviors, has been developed in the framework of the NIKER project [74, 100–102]. This tool constitutes a technical support for both professionals and researchers, to promote knowledge and awareness by sharing experiences.

## 8 Conclusions

L. Binda was active at an international level to debate many topics related to preservation of existing masonry construction in historical centers and archaeological sites. She was able to foster scientific dialogue among architects and engineers, archeologists and material scientists, always promoting multidisciplinary and multi-level approaches among academy, industry, public and religious institutions, technicians and professionals. Her contributions on knowledge of materials, structures, constructive and conservation techniques, durability and compatibility, diagnosis, structural monitoring and modelling, and her exceptional attitude to share and refine her scientific approach provided a continuous inspiration and encouragement to advance research towards a responsible and more respectful use of historic buildings and cultural heritage sites.

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to the development of this research and have shared her passion and enthusiasm over the years, are also fully acknowledged. Figs. 2 and 3 are “reprinted by permission” by IGI Global from the source: “Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures”, Panagiotis G. Asteris and Vagelis Plevris Eds.

### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no competing interests.

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