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Typology based Methodology for In situ Testing of Masonry

Dorit Chesler

Portugal | 2014

ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

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University of Minho

Czech university of Prague

Education and Culture

Erasmus Mundus

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This Masters Course has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Portugal | 2014

DECLARATION

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Year: 2013-14

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

University: University of Minho

Date: 15 July 2014

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ACKNOWLEDGEMENTS

First of all I would like to thank the Consortium for granting me sthe scholarship, which allowed and incuraged me to dedicate this year to my field of pasion.

I would like to thank my two supervisors, Professor Luís F. Ramos and Professor Francisco Fernandes, for their close guidance and their forthcoming approach in helping me fulfill my vision of this thesis. Professor Ramos, whose direction obliged me to pursue this topic to its maximum potential, and Professor Fernandes, which did not spare any effort to contribute his expertise to my work and education.

To my Engineer friends, Mafalda, Leidy, Michele, Giorgos, Josè, Andrès and Alessio, thank you. I could not have done it without you. Your help allowed me to exceed what I believed where my limits, and to excel in a field in which I was almost foreign. To my fellow Architects, Salma, Houcem and Lasha, my partners in crime, our mutual encouragement and partnership is something which will stay very close to my heart.

Finally, I want to thank Shay, my other half, for taking this year off and investing it in me and my education, and for walking hand in hand with me through all the challenges and difficulties that came along. This achievement is yours as much as it is mine.

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ABSTRACT

Masonry and stone masonry in particular, has been the main building material throughout history in vast parts of the world. This extremely rich and variable material has a unique and not completely comprehendible nature, both in spatial-architectural terms and from the engineering point of view. The knowledge of material properties of historic masonry is often lacking, and furthermore, even when material properties are available, the constitutive laws coming from a good knowledge of the material are not enough. Many academic and practical efforts have been made offering different approaches to classify historic masonry, striving to unfold its complexity and to cast logic into its diagnostic approach.

The aim of this thesis is to contribute to the gained knowledge of historic masonry in Portugal and its diagnosis procedures. The main objective is to propose practical methodologies for diagnosis of historic masonry structures, corresponding to their typological characteristics. The study is based on the Portuguese architectural landscape, yet has global classifications, and thus can be useful for any diagnosis procedure of a historic masonry wall.

In order to develop such methodologies, information relating to historic masonry typologies in Portugal is gathered and classified. Consecutively, techniques for assessment of historic masonry are studied, and all information is integrated and utilized to develop typology oriented diagnosis procedures. These procedures are classified into rural, urban and military building types, and offer general guidelines for diagnosis of such structures, as well as in depth suggestions for specific diagnosis procedures. In addition, the recommended methodology is tested and validated in a diagnosis campaign carried out in the Guimarães Castle.

The development process illustrates that many advantages can be drawn to the field of historic heritage diagnosis by utilizing typological information. By considering both physical (geometry, morphology, etc.) and theoretical aspects of the typologies, different approaches to their diagnosis arouse. The validation process highlights the importance and value of precise pre-planning of the diagnosis procedure on one hand, but finds the necessity of flexibility in the on-site campaign on the other.

In order to employ this approach in practical campaigns, further study and classification must be attained. Yet hopefully this work can take us one step closer to decipher the comprehension of historic masonry.

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RESUMO

A alvenaria e a alvenaria de pedra em particular têm sido o principal material de construção ao longo da história em vastas civilizações no mundo. Este material, extremamente rico e variável, tem natureza única e não completamente conhecida, tanto em termos espaciais e arquitetónicos, como do ponto de vista da engenharia. O conhecimento das propriedades da alvenaria histórica é muitas vezes inexistente. Muitas e diferentes abordagens têm surgido para classificar a alvenaria histórica, numa tentativa de compreender e reduzir a sua complexidade, a fim de se alcançar uma lógica nas abordagens de diagnóstico e de análise estrutural.

O objetivo da presente dissertação é contribuir para o conhecimento adquirido sobre a alvenaria histórica em Portugal e para os procedimentos mais corretos de diagnóstico estrutural. O objetivo principal é propor metodologias para a prática do diagnóstico de estruturas históricas. O presente estudo baseia-se no panorama arquitetónico Português, utilizado a sua classificação global para trabalho, podendo ser uma ferramenta útil para qualquer procedimento de diagnóstico de uma parede de alvenaria de uma construção histórica.

Para desenvolver as metodologias propostas, foram recolhidas e classificadas informações relativas às tipologias construtivas das alvenarias em Portugal. Consecutivamente, foram estudadas técnicas de inspeção. Toda a informação foi integrada e utilizada para o desenvolvimento de procedimentos de diagnóstico, orientados para cada tipologia. Os procedimentos foram desenvolvidos para três tipos de construções – rurais, urbanas e militares – e oferecem diretrizes gerais para o diagnóstico, bem como algumas sugestões para aprofundar cada diagnóstico específico. Além disso, a metodologia recomendada foi testada e validada numa campanha de diagnóstico realizada no Castelo de Guimarães.

As metodologias propostas permitiram concluir que, utilizando as informações tipológicas, muitas vantagens podem ser atraídas durante a fase de diagnóstico. Ao considerar tanto os dados físicos (geometria, morfologia, etc.) como os aspetos teóricos das tipologias, diferentes abordagens para o diagnóstico estrutural foram sugeridas para cada tipologia. O processo de validação da metodologia demonstrou, por um lado, a importância do valor do planeamento prévio das campanhas de inspeção, mas considerou, por outro, a necessidade de flexibilidade na utilização dos métodos de ensaio aquando dos trabalhos de campo.

Para que seja possível aplicar na prática estas abordagens, será necessário um estudo mais aprofundado das classificações e da metodologia proposta. No entanto, espera-se que este trabalho tenha contribuído para aumentar o conhecimento sobre a alvenaria histórica.

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תקציר

הבניה באבן, על סוגיה השונים, היוותה את שיטת הבניה העיקרית לאורך ההסטוריה ברחבי העולם. כחומר בניה, האבן מגוונת ורב שימושית, ובעלת מאפיינים ייחודיים וטבע שלעיתים אינו לחלוטין מובן. זאת הן בהקשרים חלליים-אדריכליים והן מנקודת המבט ההנדסית. לרוב, הידע הקיים על תכונותיה ההנדסיות של האבן כחומר בבניה היסטורית הינו חסר, ומעבר לכך, גם כאשר קיים ידע מעין זה, החוקים הקונסטיטואטיביים הנובעים ממנו אינם מספקים. מחקרים אקדמיים, כמו גם ניסיונות מעשיים רבים, מציעים גישות שונות לסווג בנייה היסטורית באבן, בשאיפה לפשט את מורכבותה ולייצר גישות אבחוניות מותאמות לסוגיה השונים.

מטרת עבודה זו, היא לנסות ולתרום לגוף הידע הקים בתחום הבניה ההיסטורית באבן בפורטוגל ותהליכי האבחון שלה. הכוונה העיקרית הינה להציע מתודולוגיות מעשיות לאבחון מבני אבן היסטוריים בהתאם למאפיינים הטיפולוגים שלהם. המחקר מבוסס על הנוף האדריכלי המצוי בפורטוגל, אך היות והוא נבחן במאפיינים גלובליים, יכול לשמש לכל תהליך דיאגנוסטי של בנייה היסטורית באבן באשר הוא.

על מנת לפתח שיטות אלו, נאסף ומויין בעבודה זו מידע העוסק במאפייני הבנייה ההיסטורית באבן ברחבי פורטוגל. במקביל, נלמדו טכניקות אפשריות לאבחון של מבני אבן הסטוריים, והמידע המשותף תוכלל לטובת פיתוח תהליכי אבחון מבוססי טיפולוגיה. תהליכים אלה מסווגים על פי שלוש קטגוריות בנייה שונות: בנייה כפרית, עירונית וצבאית. ביחס לקבוצות אלו מוצעים קווים מנחים לאבחון קירות הנכללים בקטגוריות השונות, וכן הנחיות לתהליכי אבחון נקודתיים. בנוסף, המתודולוגיה המוצעת נבחנה ותוקפה במערך בדיקות דיאגנוסטי שבוצע הלכה למעשה על קירות הטירה בעיר גימראש בפורטוגל.

תהליך פיתוח המתודולוגיות המחיש כי השימוש במידע הטיפולוגי מייצר יתרונות רבים לתהליך האבחוני של המורשת ההיסטורית. מתוך ההתייחסות לאספקטים הפיזיים (גאומטריה, מורפולוגיה וכו׳) והתיאורטיים של הטיפולוגיות, עלו מן המחקר גישות שונות לאבחונן. הבדיקות המעשיות שבוצעו באתר הדגישו את חשיבות תכנונו של התהליך האבחוני על פי מתודולוגיה ברורה, כפי שמוצעת בעבודה זו. מנגד, עלה גם הצורך בגמישות במהלך ביצוע המערך המתוכנן באתר.

על מנת להשתמש בשיטות המוצעות בעבודה זו בתהליכים דיאגנוסטיים מעשיים, נדרשים המשך בחינה ולימוד של התחום, והמשך שכלולן ופריטתן לכדי כלים פרקטים תקפים. עם זאת, כולי תקווה כי עבודה זו תאפשר התקדמות בצעד קטן נוסף אל עבר פענוח החידה ששמה בנייה היסטורית באבן.

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1. INTRODUCTION

1.1 General

Masonry and stone masonry in particular, has been the main building material throughout history in vast parts of the world. This extremely rich and variable material has unique and inimitable qualities which are apparent in its visibility and through the spatial experience it grants its visitors. These qualities, and the methods to conserve and to reproduce them, have been an issue for study in many research campaigns in current times, as they rise over and over again in the field of historic structures.

From the engineering point of view, correspondingly, historic masonry has some inherent unknown variables and is in many cases an enigma waiting to be studied and solved. This "enigma" has been studied and addressed in many conservation practices in the past years, and is still being unfolded and better acquainted by researchers in small, gradual steps. The knowledge of material properties of historic masonry is often lacking, and furthermore, even when material properties are available, in the case of historic buildings the constitutive laws coming from a good knowledge of the material are not enough.

In Italy, a country rich in historic masonry architecture and its study, researchers offered the idea of classes of masonry buildings or masonry typologies which often correspond to different behavior of the structure (Binda, 2014). This thought offers a perspective to the study of masonry, which suggests qualitative classifications can contribute to the knowledge of this material. This perspective provides the basic idea, of which this thesis is nested upon, and which it aims to practice.

1.2 Objectives and Methodology

The aim of this thesis is to contribute to the gained knowledge of historic masonry and its diagnosis procedures. The main objective is to develop practical methodologies for diagnosis of historic masonry structures, corresponding to their typological characteristics. These methodologies will be based on the Portuguese architectural landscape, but as they have global classifications, can be useful for any diagnosis procedure of a historic masonry wall.

In order to develop such methodologies, information relating to historic masonry typologies in Portugal will be gathered and classified. In addition, masonry structural assessment methodologies will be studied. Sequentially, all information will be utilized for the development of typology-based methodologies. Finally, a validation of the methodology will be carried out in a local case study.

1.3 Thesis Outline

This thesis is composed of eight chapters, including the current introduction.

The second chapter will address the study of structural assessment methodologies for masonry structures. Available non destructive and minor destructive techniques will be outlined, highlighting their capacities and limitations regarding application on masonry.

The third chapter will provide a partial overview of historic masonry structures in Portugal, based upon former studies and gathered information. The structures will be divided into three major groups: (a) the rural, (b) the urban and (c) the military type structure. Each typology will be described and examples will be given.

The fourth, fifth and sixth chapters will offer methodology for the inspection of rural, urban and military constructions. This, by utilizing conclusion gained from previous chapters, as well as additional relevant considerations. The methodologies will address different tasks of the diagnostic process as damage, mechanical, morphologic and geometric surveying.

The seventh chapter will present a validation attempt for the military developed methodology, in a testing campaign carried out in the Guimarães Castle. Results of the campaign will be given and post execution conclusions related to the methodology will be discussed.

The last chapter will argue the main realizations drawn from all previous chapters, as well as final conclusions of the work and recommendations for further studies.

2. ASSESSMENT OF HISTORICAL STRUCTURES

This chapter will present the state of the art of the assessment of historic masonry walls. Different approaches to evaluation of mechanical properties of existing structures will be presented, particularly in the discipline of non-destructive and minor destructive tests, which are advantageous to heritage constructions. In addition, the scientific field of data fusion will be presented and its possible contribution to the diagnosis practice of historic masonry.

2.1 Introduction

Historical heritage can be found in architecture, in landscapes, in buildings of all types, from grand monuments to vernacular constructions. This historical heritage is living evidence and a tangible documentation of the life and traditions that are in the base of our society. Therefore, it must be preserved and safeguarded taking the most careful measures.

The task of preservation of historical structures is a very convoluted and delicate craft, and demands a body of knowledge from restorers, engineers and architects working in the field. Restoration works in the past 50 years in Europe and around the world have contributed to the accumulation of this body of knowledge. Several international committees, particular for the task of structural conservation have been established, as ISCARSAH committee of UNESCO, which published guidelines that were adopted by UNESO in 2003.

The guidelines present the main ideas as were specified in the Venice charter of 1964, and include:

(i) Importance of context and environment,

(ii) Reversibility,

(iii) Authenticity,

(iv) Importance of maintenance.

In light of these guidelines, all actions taken must be minimized only to guarantee safety and durability of the structure, with the least harm to heritage values. All planned actions must be demonstrated as indispensible, all techniques must be proven successive and all materials used for the work and their compatibility to the existing materials must be fully established.

These ideas and principles apply to all stages of the conservation process, from diagnosis to the chosen intervention. Therefore, the diagnosis stage must be planned very carefully and to be tailored to the specific needs and demands of the structure surveyed.

2.2 Investigation and Diagnosis

One of the most meticulous tasks of historical conservation in the initial phase of diagnosis of the state of the structure, its state of damage, mechanical properties, materials, structural stability, etc. The onsite investigation must be as non-destructive as possible and provide information with a high level of precision (Binda, 2006). This demands an articulated diagnosis procedure, consisting of different and complimentary techniques.

In the beginning of the 21-century a project called: "The ONSITEFORMASONRY project" was carried out, involving 15 international partners in the development and improvement of methodologies for the evaluation of structural and material properties. A major conclusion of the project was the necessity of careful preparation of the investigation, together with a precise description of the problem addressed. The operations of the diagnosis process should be carefully designed, bearing in mind that each and every investigation has its cost, and should be optimized to obtain the desired results (Binda, 2006).

Since conventional techniques for diagnosis in the field of civil engineering cannot be used in the case of historical structures due to their invasiveness, different approaches are continuously being developed and practiced. Non-destructive and minor destructive testing methods, often originated in other fields of engineering, are being applied and adapted for assessment of historical masonry structures. These techniques as, complementary tests, can be reliable useful on site, provided that reliable interpretation of the data is made (Binda et al, 2001). Results of these methods can sometimes be unsatisfactory due to inappropriate exploitation and adaptation of the techniques (McCahn et al, 2001). Thus, relying on previous studies, and using complimentary tests for a complete assessment is essential.

A key issue, as mentioned, is to undertake a systematic and holistic investigation, using not one, but several inspection methods, including visual inspection, historical research and the appropriate non-destructive, minor-destructive and destructive testing techniques.

2.3 Non Destructive Testing (NDT) Methods

Non-destructive tests should be generally preferred to answer questions of stability and performance avoiding invasive intervention and destruction of historical heritage. Non-destructive methods show satisfying results in different fields of investigation, as detection of voids and cracks, presence of moisture or salts, finding hidden element of the construction and others. The following pages will showcase several NDT techniques that have been proven to be applicable in historical structures.

2.3.1 Visual Inspection

A preliminary in-situ survey is useful in order to provide details on the geometry of the structure, the visible damages (cracks, out of plumb, material decay) and in order to identify the points where more accurate observations have to be concentrated. A visual inspection should be carried out as a first measure and as a base for planning further investigation and verbalizing the questions to be addressed in the process. Visual inspection should be done with some complimentary tools as a crack meter, a flashlight, a tape measure, and an orientation plan for marking the inspection results.

2.3.2 Geometrical Survey Techniques

The geometrical documentation of an historical structure is a very crucial step in its assessment and analysis. In fact, it is almost always a necessary first step in the investigation process, which allows the designer to conduct other, more in depth testing on its basis. A geometrical survey can be executed manually or by advanced systems. Manual techniques can be very tedious to perform. They include direct visual documentation, manual measurements by tape measures or by laser meters. The information gathered manually on site is later entered into digital software, to create a workable database.

2.3.3 3D Laser Scanning

The development of reliable and affordable methods for computed documenting historic structures is viable. 3D laser scanning is an exponent of the evolution of the non-contact techniques for built up structures survey and documentation. The information gained by detailed documentation is particularly important in structural modelling, allowing a practice on the base of the real geometry instead of on idealized geometry for getting more reliable results (Cheng, 2012).

A typical laser scanner can be subdivided into the following key units: laser ranging unit, optic mechanical scanner (as seen in Fig 2.1) and control and processing unit. Developed laser scanners can reach a very high accuracy and be activated from a distance to the examined structure. Recent studies and practices exploit the benefits of 3D laser survey for the production of damage maps and for identification of crack patterns and other surface deteriorations. An example of the method is presented in Fig 2.2.


Figure 2. 1- Mechanical scanner in archeological survey in Egypt. Figure 2. 2- 3D Laser Scanning of Palac Potockich Radzyn Podlaski, Poland.
(From: http://www.topcon.co.jp/,http://www.3deling.com/)

Location of scanning unit should be planned and calculated to maximize available results. An integrate scanning work has to be planned for the whole object from several different scanner stations which can combine a set of order of multiple view (scanning worlds). For a 3D scan that supports 360 degrees field-of-view, the scanner has to move around the scanned objects to complete exterior scan views with registration targets.

2.3.4 Sonic / Ultra-sonic Methods

Sonic / ultra-sonic testing methodology is based on the generation of sonic or ultra-sonic impulses at a chosen area of the structure. An elastic wave is generated by percussion, by an electrodynamics or by a pneumatic device (transmitter) and collected through a receiver, usually an accelerometer, which can be placed in various positions.

The elaboration of the data consists in measuring the time the impulse takes to cover the distance between the transmitter and the receiver. Appliance of the method and its principles can be seen in Figures 2.3 and 2.4. The use of sonic tests for the evaluation of masonry structures has the following aims (Binda, 2005):

(i) to qualify masonry through the morphology of the wall section,

(ii) to detect the presence of voids and flaws and to find crack and damage patterns,

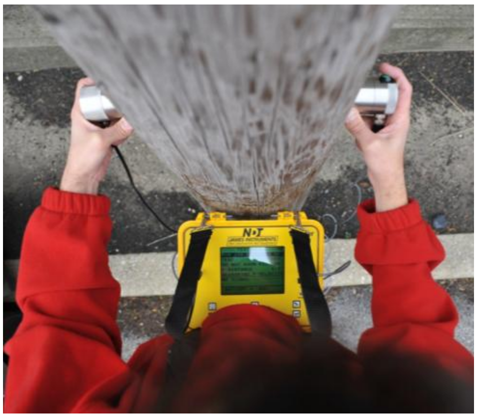
(iii) to control the effectiveness of repair by injection technique and others which can change the physical characteristics of materials.

The method is based on the fundaments of wave propagation through solids. The velocity of a stress wave passing through a solid material is proportional to the density (ρ), dynamic modulus (E), and Poisson's ratio (ν) of the material.

Resolution in terms of the smallest recognizable features is related to the dominant wave-length (as determined by the frequency) of the incident wave and also to the size of the tested element.

As frequency increases the rate of waveform attenuation also increases, limiting the size of the wall section which can be investigated. The optimal frequency is chosen considering attenuation and resolution requirements to obtain a reasonable combination of the two limiting parameters.

In general it is preferable to use sonic pulse with an input of 3.5. kHz for inhomogeneous masonry.



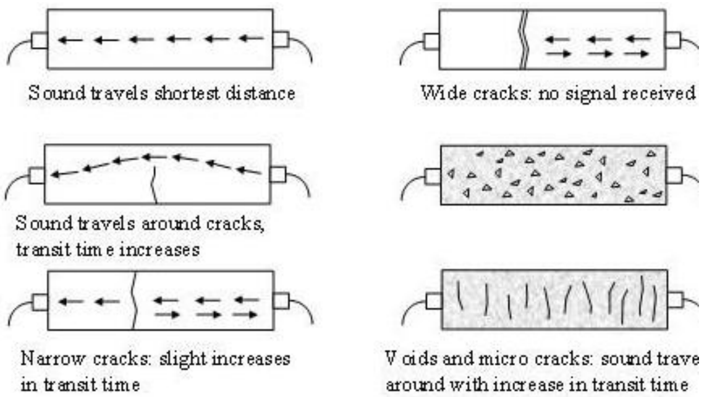


Figure 2. 3- Submission of sonic velocity testing on a timber column, Figure 2. 4- Principles of Sonic Velocity in Solids

(From: http://www.ndtjames.com/,www.theconcreteportal.com/)

Measurements obtained by the sonic and ultra sonic testing are qualitative and cannot be generalized globally. The pulse sonic velocity is characteristic of a specific masonry typology and it is impossible to generalize the values. The tests then have to be calibrated for the different types of masonry directly on site. Efforts have been made by researchers to correlate the sonic parameter to the mechanical characteristics of the material, but a fitting correlation has yet to be satisfied.

2.3.5 Impact Echo Reflection

Impact-Echo is a method for nondestructive evaluation of concrete and masonry, based on the use of impact-generated stress (sound) waves that propagate through the structure and are reflected by internal flaws and external surfaces.. It can be used to determine thickness or locate cracks, voids and other defects in masonry structures where the brick or block units are bonded together with mortar, and is not adversely affected by the presence of steel reinforcing bars.

The methods is activated by a short-duration mechanical impact, produced by tapping a small steel sphere against surface, which produces low-frequency stress waves (up to about 80 kHz) that propagate into the structure and are reflected by flaws and/or external surfaces. Multiple reflections of these waves within the structure excite local modes of vibration, and the resulting surface displacements are recorded by a transducer located adjacent to the impact. The piezoelectric crystal in the transducer produces a voltage proportional to displacement, and the resulting voltage-time signal (called a waveform) is digitized and transferred to the memory of a computer, where it is transformed mathematically into a spectrum of amplitude vs. frequency. Both the waveform and spectrum are plotted on the computer screen (Tikalsky, 2006). The dominant frequencies, which appear as peaks in the spectrum, are associated with multiple reflections of stress waves within the structure, or with flexural vibrations in thin or delaminated layers. The work principle can be seen schematically in Fig.2.5.

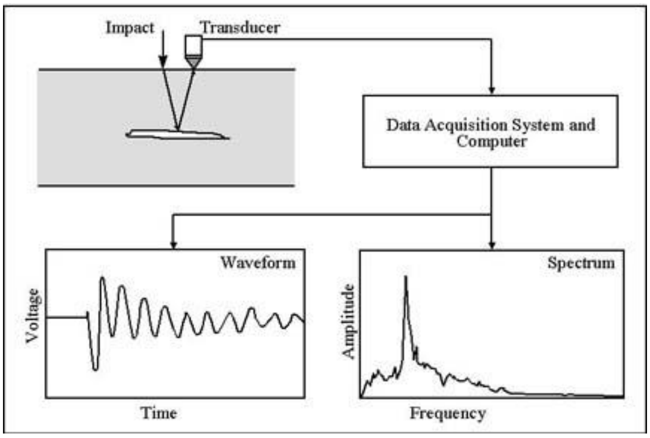


Figure 2. 5- Work principle of the Impact Echo Method

(From: http://www.impactecho.com/)

The fundamental equation of impact-echo is $d = C/(2f)$, where d is the depth from which the stress waves are reflected (the depth of a flaw or the thickness of a solid structure), C is the wave speed, and f is the dominant frequency of the signal. The frequency f is obtained from the results of a test.

To determine thickness or depth of a flaw, the wave speed C must be known. It can be measured by observing the travel time of a stress wave by direct sonic testing of known thickness (Schuller, 2003).

2.3.6 Infrared Thermography

Infrared thermography analysis is based on the thermal conductivity and emissivity (electromagnetic radiation) of materials. The method can be applied in passive or active radiation. The passive application analyses the radiation of a surface during thermal cycles due to natural phenomena of insulation and subsequent cooling. The active analysis, on the other hand, uses appliance of forced heating to the surfaces analysed (Drdacky et al, 2006).

A camera sensitive to infrared radiation collects the thermal energy, and the result is a thermo-graphic image in a coloured scale. Each tone corresponds to a temperature range. Usually the differences of temperatures are fractions of a degree. In the presence of moisture, the camera will find the coldest surface areas, where there is continuous evaporation. For masonry structures the method can be used for (Binda, 2005):

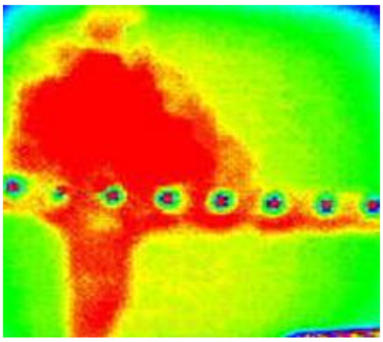
(i) Survey of cavities,

(ii) Detection of inclusions of different materials (Fig. 2.6),

(iii) Detection of water and heating systems,

(iv) Moisture presence. (Figs. 2.7, 2.8)

One of the limitations of this method is that in the diagnosis of old masonries, thermo-vision allows analysis of only the most superficial layers, and cannot provide information regarding the inner sections of the walls. For plastered, frescoed or decorated walls, infrared thermography can be particularly applicable and efficient.



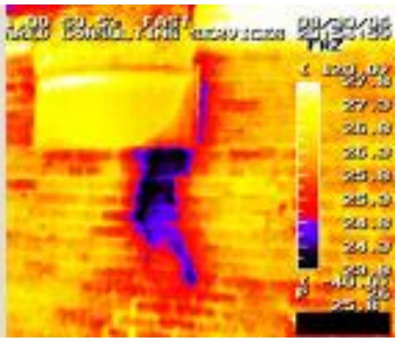


Figure 2. 6- Detection of interior metal bars via infrared thermography, Figure 2. 7-Inspected wall geometry, Figure 2. 8- Moisture detection of the inspected wall via infrared thermography

(From: http://www.ndt-ed.org/,http://www.irtest.com/)

2.3.7 Ground Penetration Radar

Called also surface penetration radar and Geo-radar, the ground penetrating radar (GPR) uses reflections of wave energy to identify internal abnormalities in the wall thickness. Data is analysed in time domain, throughout a scanned section. The equipment for the test includes a radar control unit, an antenna, which transmits the waves as well as receives them and a data storage device (Fig. 2.9). The results of the scan are radargrams that are produced when the antenna passes along the surface of the object under investigation. Radargrams can be in colour or grayscale.

The method is taken from the field of geology and archeological surveys. When applied to masonry, the purposes of radar procedures can be (On Site for Masonry, 2005):

(i) to locate the position of large voids and inclusions of different materials, like steel, wood, etc. (Fig. 2.10);

(ii) to qualify the state of conservation or damage of the walls;

(iii) to define the presence and the level of moisture;

(iv) to detect the morphology of the wall section in multiple leaf stone and brick masonry structures

Wave energy, as opposed to sonic or ultra-sonic waves can travel well through air spaces and can provide information beyond the first crack or hole. Measuring the dimensions and locations of inner elements of the walls can be calculated from the scans measuring the time range between the emission and the echo.

Limitations of this method lie in the high influence of moisture level in the masonry, which can alter results. Another disadvantage is the low readability of the results, scans are very complex and interpretation must be done by an expert.

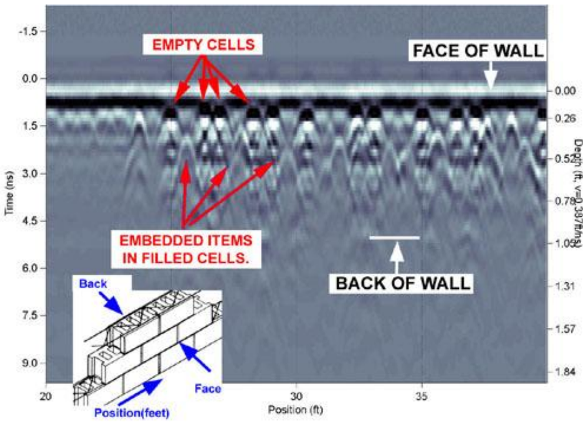
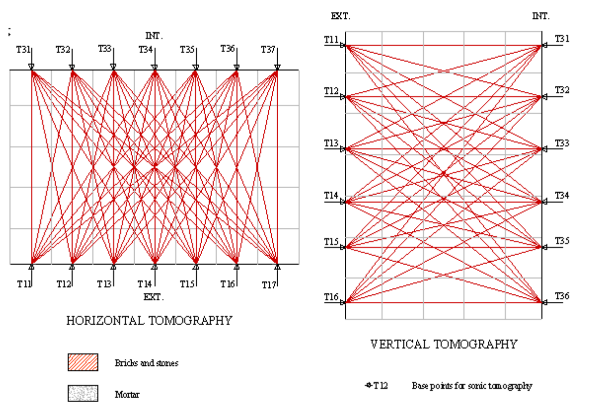



Figure 2. 9- GPR testing equipment, Figure 2. 10- Radargram showing voids and material change in concrete blocks (From: www.fkceng.com/,www.pensacolatesting.com/)

2.3.8 Tomographic Imaging

Tomography is the practice of reconstructing a cross sectional image of an object from transmissions of energy through the object. Data from ultra-sonic, sonic or radar testing can be used as input for tomographic reconstruction algorithms, which provide a cross sectional representation of internal properties (Schuller, 2003).

The method was developed originally for the field of Geophysics, but has been adapted for the use of analysis of masonry and stone, and has shown reasonable approximations of size and extent of internal abnormalities. The tomographic analysis methods require a large amount of data acquisition in order to portray results of entire cross sections. Location and size of hidden cracks, voids and other deterioration processes can be tracked in the output data. Explanatory output is presented in Figures 2.11 and 2.12.



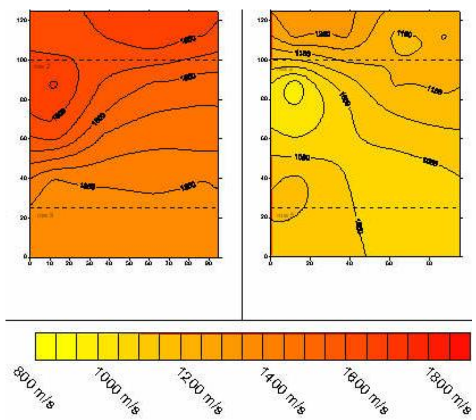


Figure 2. 11- Vertical and horizontal sonic tomography of a masonry wall, Figure 2. 12- Contour sonic tomography of a masonry wall

(From: www.ndt.net)

2.3.9 Hardness Tests- Schmidt Hammer Rebound

Rebound methods are founded in the base of the elastic theory. The rebound response of a material is a function of its dynamic modulus and its damping properties.

The "Schmidt Hammer" is an example of a test that correlates direct rebound results. The Schmidt rebound hammer is used to provide an indication of surface hardness. Identifying differences in hardness may indicate deficiencies in the material. With careful laboratory calibration, it is possible to relate rebound hardness to the elastic properties of the masonry and its compressive strength (Schuller, 2003).

Although not a highly accurate method, it can be a good instrument for comparing different results of a single material in several testing points. The test is conducted very easily and quickly, and can be affected by a variety of factors, as non-homogeneity of the tested material, element size, moisture, operator and others. Thus, it must be carried out in a large number of samples which will allow detecting any factors that may be affecting results. Specific type and orientation of the testing device (horizontal, vertical, diagonal) also has an effect on results, and must be considered when correlating rebound results to mechanical properties (Tikalsky, 2006).

Results should be converted from rebound values to strength by a corresponding table (for example, Fig. 2.13). As the device is designed for concrete these correlating tables are calibrated for concrete. When testing masonry, further calibration must be done.

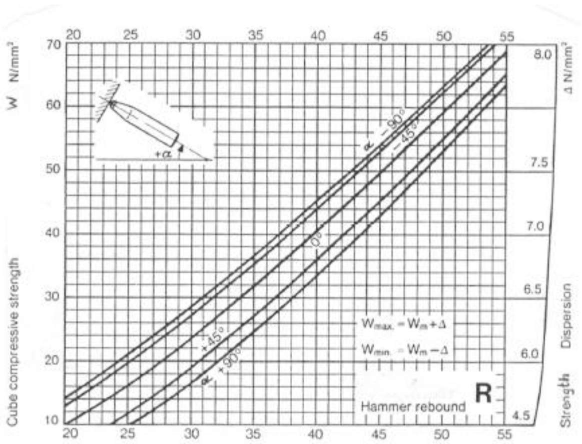


Figure 2. 13- Concrete compressive strength relation with rebound values.
(From:www.ndtjames.com)

2.4 Minor Destructive Testing (MDT) Methods

2.4.1 Boroscopy

Also mentioned as endoscopy, the boroscopy test allows the investigator to get an interior look of the section of the wall, with relatively minimal destruction. The procedure includes small diameter hole drilling done usually in the mortar joints, and insertion of a boroscope device. Boroscope devices incorporate fiber optics and an external light source to illuminate the internal space. Rigid and flexible boroscopes are available for use.

The technique can allow to (Schuller, 2003):

(i) observe identified abnormalities and defects,

(ii) observe internal wall components (flashing, ties, drainage cavities),

(iii) provide information of section morphology.

Figure 2.14 shows the execution and the possible output of the boroscopy test.

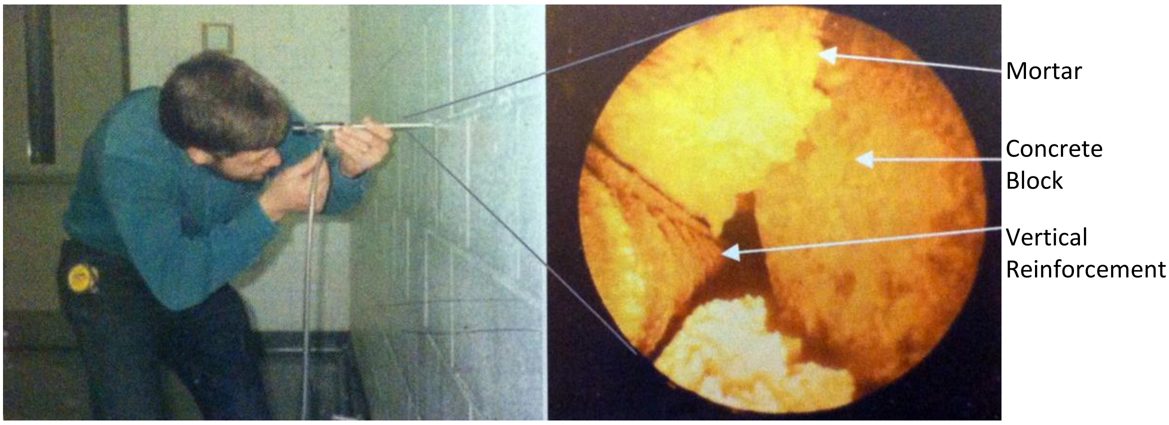


Figure 2. 14- Boroscopy test execution and real-time graphic output

(Adapted from: Schuller, 2003)

2.4.2 Coring

Drilling of larger diameters may allow extracting cores of the masonry to be tested for compression bending and shear in the laboratory. This technique facilitates the ability to get site specific local results regarding the examined masonry mechanical properties, to reassure presence of voids and discontinuities and to learn of the inner morphology of the masonry wall.

Figure 2. 15- The coring process**,** Figure 2. 16- Drilled core from a masonry wall

(From: www.expin.it)

Coring extraction is done by a drilling saw activated with water (Fig. 2.15). Thus, it can be somewhat harming for the masonry and this should be considered before application. As the operation is complex and involves both in situ and laboratory work, protocol must be followed to avoid confusion and misinterpretation of results. All cores shall be submitted to the laboratory for examination regardless of whether the core specimens failed during cutting operation. The laboratory shall report the location where each core was taken, the findings of their visual examination of each core, identify which cores were selected for shear testing and the results of the shear tests (Californian building code, 2010). A drilled core can be seen in Figure 2.16.

2.4.3 Micro Sampling Techniques

When working with complimentary NDT techniques, there is often a need for additional in-situ and laboratory testing for comparison of the obtained results with real mechanical measurements on specimens. As the investigated object is of heritage value, these tests cannot be conducted on other than small-micro samples. The complementary of micro sampling helps to evaluate the accuracy of the NDTs for the specific masonry and its damages.

The testing of non-standards samples was studied in the ONSITEFORMASONRY project, developing techniques to evaluate and test micro samples. Eventually, the research showed that testing mechanical properties in bending on non-standard mortar samples which were supplemented symmetrically on both ends with two “prostheses"(see Fig.2.17); the influence of prosthesization was negligible (Drdacky et al., 2004).

Figure 2. 17- Micro samples of mortar with wooden prosthesization

(From: www.arcchip.cz)

Further study has shown that small samples from masonry materials are advantageously taken as drilled cores. Therefore, a portable testing frame has been designed and a first prototype has been produced. The device was designed as portable, durable and independent of external electricity supply, and can be used on site for immediate results.

2.4.4 Flat Jack

The flat jack test is a method that allows determining the local state of stress of the masonry. The determination is based on the stress relaxation caused by a cut perpendicular to the wall surface. The stress release is determined by the partial closing of the cutting, e.g. the distance between two points prior to cutting and following. The test is carried out by insertion of a cut perpendicular to the wall, and placing a thin jack inside it (see Fig. 2.18). Subsequently, pressure is applied through the jack and increased gradually, until obtaining the distance measured before cutting. Distances between the points of reference are measured before, during and after the sequence of the test.

The equilibrium relationship is the fundamental requirement for all the applications where the flat-jack are currently used (Binda, 2005):

$$S_f = K_j K_a P_f$$

Where S_f is the calculated stress value, P_f is the flat-jack pressure, K_a is the slot/jack area constant (<1), and K_j is the jack calibration constant.

Flat jack tests have given fairly good results and are a valid and preferable choice in the case of mechanical assessment of historical heritage. Alongside, the method has some disadvantages; it can be applied easily only on regular masonry. Irregular stone and joints placement cause difficulty in appliance; in multi leaf walls the results obtained refer solely to the exterior leaf. Internal leafs cannot be tested; the method is almost inapplicable in low structures (lower than 2 floor) due to low stress levels.

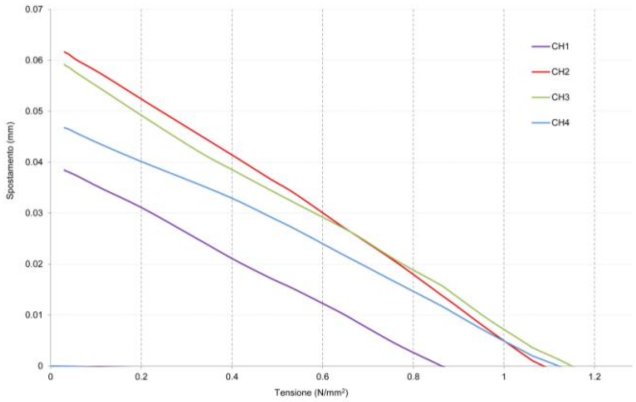


Figure 2. 18- Single flat jack inserted into cut**,** Figure 2. 19- Deformation stress diagram presenting results of single flat jack tests

(From: www.controls-group.com, www.expin.it)

Another drawback may be the interpretation and elaboration of results. The reliable determination of the equilibrium pressure is a fundamental requirement for the test. In some cases, a significant amount of subjective judgment is necessary for interpretation. Displacement measurements can be questionable. Measurements carried out in the four chosen points of measurement will never give the same value and very seldom the original distance will be attained in all the four measuring points (Binda, 1999). Fig. 2.19 exemplifies the dissimilarity in results between the different testing points.

2.4.5 Double Flat Jack

Another possibility that the flat jack provides is the measurement of deformability. By making another cut, 40-50 cm below the first one, a sample of masonry is isolated and can be tested in uniaxial loading. The test configuration is shown in Fig. 2.20. Loading cycles are performed in increasing rates and deformations are measured. A deformability modulus of the masonry related to the stress levels can be obtained. Results from testing are presented as a stress strain diagram (see Fig. 2.21) from which the Elastic Modulus (E) of the masonry can be obtained by constitutive law.

Limitations of the technique relate to maximum stress levels; The applied stresses should all be lower than the measured stress of the single jack, in order to avoid crushing of the masonry; It is almost impossible to apply the method in low rise buildings due to lack of stress response in the upper masonry.

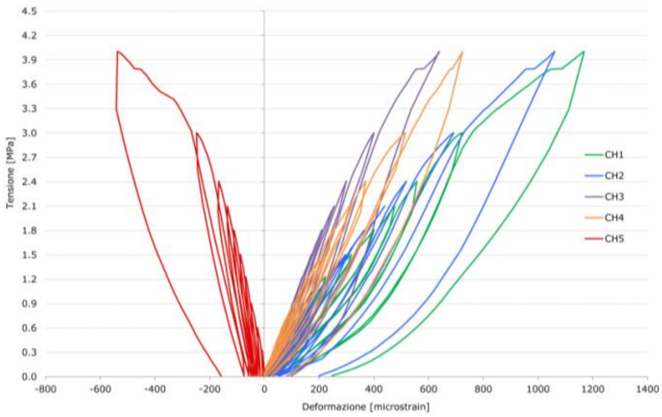


Figure 2. 20- Double flat jack test configuration on a brick masonry wall**,** Figure 2. 21- Stress strain diagram presenting results of double flat jack tests

(From: www.expin.it)

2.4.6 Tube Jack

In order to overcome the limitations of applying a flat jack test on irregular masonry walls, the tube jack technique is now being developed at the University of Minho, Portugal. The tube jack test is carried out by insertion of a series of cylindrical hydraulic jacks into the inspected masonry wall, instead of the flat jack (presented in Fig. 2.22). With the fruition of this system, significant improvements in the in situ evaluation of the mechanical properties of masonry walls are expected.

Figure 2. 22- tube jacks implicated on a masonry wall in laboratory at Minho University.

2.4.7 Laboratory Moisture and Salt Content Tests

Several complimentary laboratory tests can be conducted to complete the diagnosis process. Moisture content and presence of salt anions can be detected in direct laboratory analysis from samples collected on site or by indirect in situ measurements.

(i) A chemical analysis can be performed with the goal of measuring the salt anions content on the material samples. The method includes crushing and grinding samples into powder, drying it to constant weight and later suspending it in distilled water. After the preparation of the sample it is tested for the presence of salt anions, conductivity and pH levels.

(ii) Numerous techniques are available for the detection of moisture content of stone and mortar. Among them are the Mobile Microwave Moisture measurement and the Gravimetric method. The Mobile Microwave Moisture measurement processes are dielectric measurement processes where the ratio of the dielectric constant (DC) of water and the material is determined. Even small quantities of water can be easily detected due to the great difference between these two values. The Gravimetric method, on the other hand, consists of determining the water content in a material by using the ratio of the mass of water present to the dry weight of the material.

Indirect methods, executed by moisture meters can determine moisture content by measuring the electric resistivity. This is a function of the moisture content and every factor that influences the electric conductivity of the materials as salts, composition, etc. Thus, the method is only applicable if all other parameters, besides moisture are invariable. There are no precise and direct calibration laws between resistivity and each material, so that the moisture content must be verified in laboratory by e.g. powder drilling technique. Thermohygrometer, that registers temperature, relative humidity, moisture content and dew in the air to determine the ambient conditions and its evolution, is necessary as supporting technique for the interpretation of data of moisture meters. (On site for masonry, 2005)

2.5 Conclusion

This chapter provides an introduction to the task of evaluation of masonry walls. Several non-destructive and minor destructive methods are nowadays proven to be efficient and are being used in the field of historical constructions worldwide. These tests provide the foundation for the design of diagnosis procedures as well as interventions. Some available tests provide direct, straightforward results and can be interpreted easily, but most techniques, however, require proper planning and execution. The operator experience is essential for appropriate employment of the test and for result analysis.

When planning an intervention for a historical monument the designer must consider numerous factors. The mentioned tests are available for his dispense but many other factors must be taken into consideration during the decision making process. These factors may regard the building under consideration, as the type of the building (private housing, public or civic, religious etc.), its size, uniqueness, and even level of significance to the cultural heritage. This must be considered as the available tests often have elevated costs, and complicated execution processes. In addition, several testing methods involve long term monitoring. Figures 2.23 and 2.24 present indicative relative costs and complexity of execution.

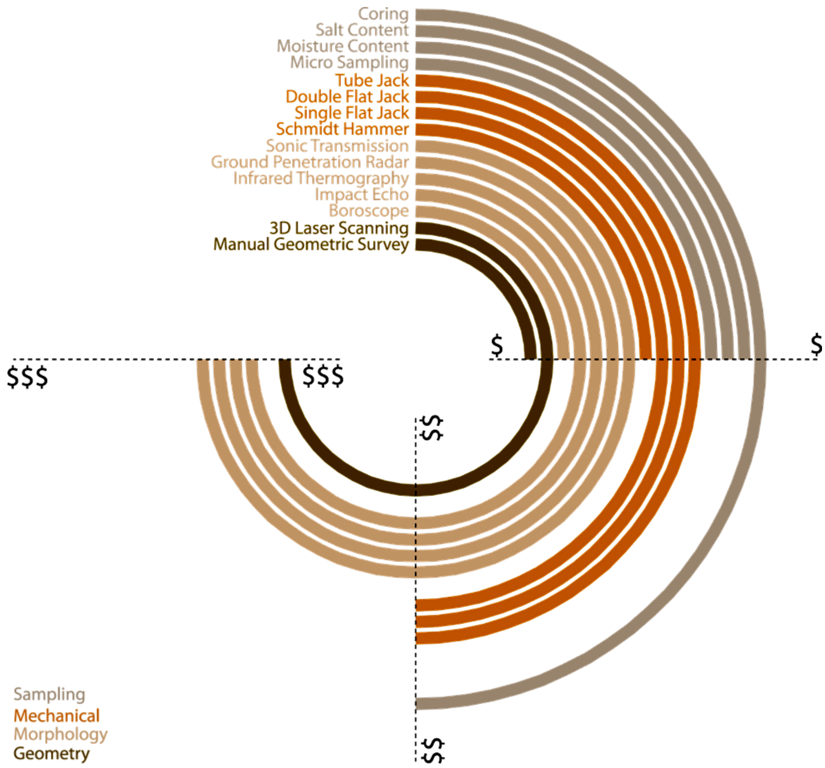


Figure 2. 23- Estimated relative costs of NDT/MDT
(Adapted from: Harvey et al., 2010)

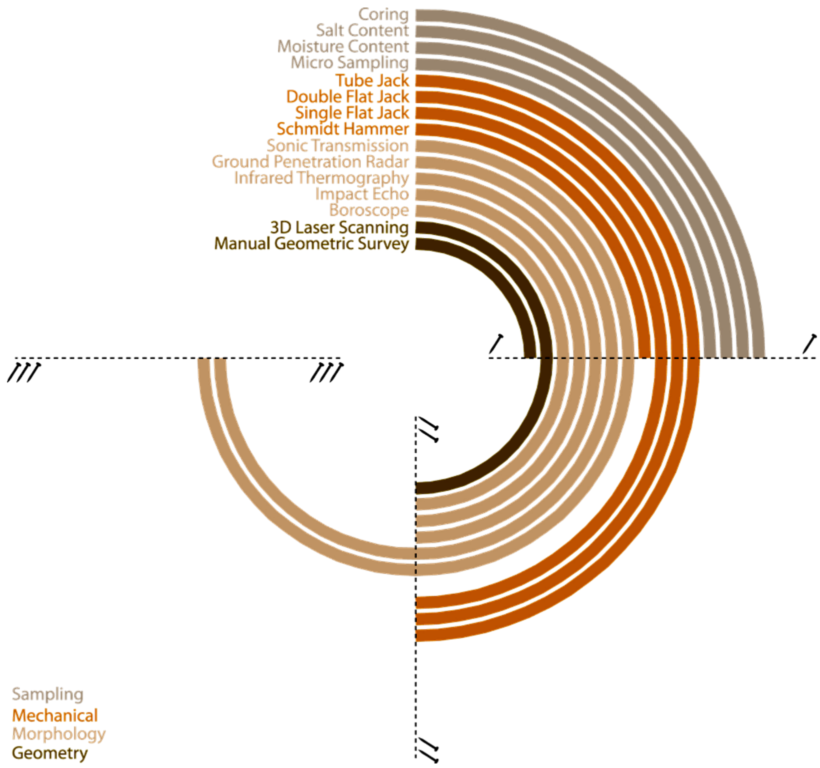


Figure 2. 24- Estimated relative execution complexity of NDT/MDT
(Adapted from: Harvey et al., 2010)

Factors may also regard the typology of the masonry under inspection, type of stone and mortar, assembling technique and its characteristics as number of leaves, regularity, connecting elements between leaves and others. This must be considered due to the fact that not every test is suitable for correct measuring and interpretation for the different masonry typologies. In other cases, some testing methods may be unnecessary for some typologies as they can only give us redundant information about them. Table 2.1 provides some information regarding capacity of the tests and their compatibility to some common typologies.

Table 2. 1- Compatibility of NDT/MDT to masonry typologies
(Adapted from: On site from masonry, 2005)

NDT	Masonry Typology
Sonic	+ in-depth, up to 100 cm analysis - small stone units, irregular texture
Infrared	+ plastered sections - in-depth analysis
GPR	+ in-depth, up to 150 cm analysis - highly fragile plaster -thin walls
Hardness	- mixed systems, as can only indicate on single element

MDT	Masonry Typology
Boroscopy	+ regular geometry - dry stone
Coring	- thin wall
Micro sampling	- mixed systems, as can only indicate on single element
Flat Jack	+ regular geometry - multi-leaf walls - irregular geometry
Double FJ	+ regular geometry - multi-leaf walls - irregular geometry
Tube Jack	+ regular and irregular geometry - multi-leaf walls

Finally, factors must regard the question or problem under consideration. Different objectives relate to different courses of action. When studying damages the test selection will be different then when studying an un-given morphology. Often the typology will have an influence on the question of study. This and further in depth study of compatibility of typology and testing will be presented in the following chapters.

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3. MASONRY TYPOLOGIES IN PORTUGAL

This chapter will describe the role of typology in the mission of performance assessment of a historical structure. The current state of research of masonry typologies in Portugal will be presented and common masonry typologies in Portugal will be portrayed. Typologies will be divided into three categories related to the size of the structures and their purposes. These three categories will be elaborately characterized and studied in following chapters.

3.1 Typology and Performance Assessment

The structural performance of a masonry wall structure can be understood provided the following factors are known (Binda et al., 2001):

(i) Geometry,

(ii) Masonry texture (single or multiple leaf walls, connection between the leaves, joints empty or filled with mortar),

(iii) Physical, chemical and mechanical characteristics of the components (bricks, stones, mortar),

(iv) Characteristics of masonry as a composite material.

A survey of these factors in masonry sections allows defining additional secondary influential parameters, such as: (a) the distribution of stones and mortar in percentage; (b) the ratio between the dimensions of the different leaves and that between the dimension of each leaf and the whole cross section; and (c) the dimension and distribution of voids in the cross section. These parameters, together with the chemical, physical and mechanical properties of the materials give the possibility to better describe the masonry and constitute a fundamental basis of any conservative intervention.

Different typologies of the masonry exhibit different behavior under loading in different mechanical properties. Previous studies (as Binda, 2002 and others) have shown that a relation can be found between masonry morphology and geometry to its mechanical properties and structural behavior. Thus, surveying these typologies has a great prospective in achieving better assessments and higher accuracy in masonry testing.

3.2 Study of Masonry Typologies

In Portugal, little research has been conducted surveying types of stone masonry walls (geometric characterization, material and mechanical behavior). The available research is mainly local and does not give an overview of the whole country. Broader researches can be found regarding building typologies, but those do not address masonry typology per se. The available resources are seldom, particularly resources in English.

The most recent study has been done by Almeida (2013). The work focuses on one-leaf granite walls, common in the historical center of Porto and uses identification tools developed in earlier studies in Italy. Another available study is the work of Casella (2003) on the survey of building typologies in various regions of Portugal. The work contains references to general characteristics of the walls, including the geometry, the type of construction equipment, the construction process and the physical and mechanical properties of stone and mortar. Another two studies from 2004 should be mentioned; the work of Pagaimo, gathering information on limestone walls of the village Tentugal in the district of Coimbra. Twelve residential buildings were investigated - geometry and materials of walls were surveyed in elevation and cross-section in order to identify predominant patterns; and the work of Teixeira, dedicated to historic buildings of Porto.

On the contrary, very extensive studies on typologies of historic masonry walls were developed in Italy by Professors Binda and Mannoni in 2006. Their study initiated due to the significant number of buildings of stone masonry in Italy, suffering from recurrence of seismic activity in the Italian region. The aim of the study was evaluating the quality of the different masonry typologies for the estimation of the vulnerability of buildings and the definition of intervention procedures to be applied in a post-earthquake phases. The statistical character of results yielded valuable information about the characteristics of the masonry in Italy by region, and was gathered and stored in a database format. This study will be presented in detail in chapter 3.7 of this work.

When studying the following chapters, it should be considered that the scientific assessment of the Portuguese heritage sites still cannot be considered inclusive as in Italy. All conclusions and results obtained by this study will inevitably be partial or generalized, and will be based on former or similar studies or on few case studies that were examined within the scope of this thesis.

3.3 Masonry Building Typologies

Masonry construction was very widely practiced in historic Portugal, and the country is very rich with monuments and structures built with different construction techniques and using various types of stones. The kinds of stone traditionally used in the construction throughout the country are granite, shale (schist) and limestone. These can be used in different construction techniques, depending on local deposits and the tradition of knowledge. Basalts, due to their hardness and low workability, are less used (Casella, L, 2003). Characterization of the mentioned stones is listed in table 3.1:

Table 3. 1 - Characterization of common stones for construction in Portugal

(Adapted from: Casella, 2003)

Origin	**Rock type**	**Density**	**Resistance Kg/cm2**	**Workability**	**Adhesion of the mortar**
Igneous	Granites	2.5 to 3.0	1500 to 2700	Variable	**Very good**
Eruptive	Basalt	2.8 to 3.3	3000	Difficult	Bad
	Melaphyre (Basalt)	2.8 to 3.0	1800	Variable	Acceptable
	Tufts	0.6 to 1.7	35 to 600	Variable, from very brittle to very abrasive	Acceptable
Sedimentary	Calcareous	1.8 to 2.6	600 to 1500	**Good**	Variable
	Loopholes	1.8 to 2.7	800 to 1700	**Good**, but sometimes fragile	Variable
Metamorphic	Sandstones		300 to 2700	Variable	Variable
	Marbles	2.4 to 2.8	1100 to 1800	**Good**	**Good**
	Shale	2.5 to 3.0	800 to 1300	Variable	Variable

As other European countries, the architecture in Portugal was greatly influenced by the cultural currents that have characterized the various eras of its history, leading to a highly enriched architectural prospect. The diversity of shapes and materials in traditional Portuguese architecture is related to many factors, including geography, economy, social issues, history and culture, and the type of needs and available goods in each region. For example, buildings in granite dominate the northern region of the country, Schist constructions are principal in the central region and limestone is found in Southern region constructions (Almeida, 2013). Figure 3.1 shows a geological map of Portugal from 1994, which clearly presents the governing rocks of the different regions.

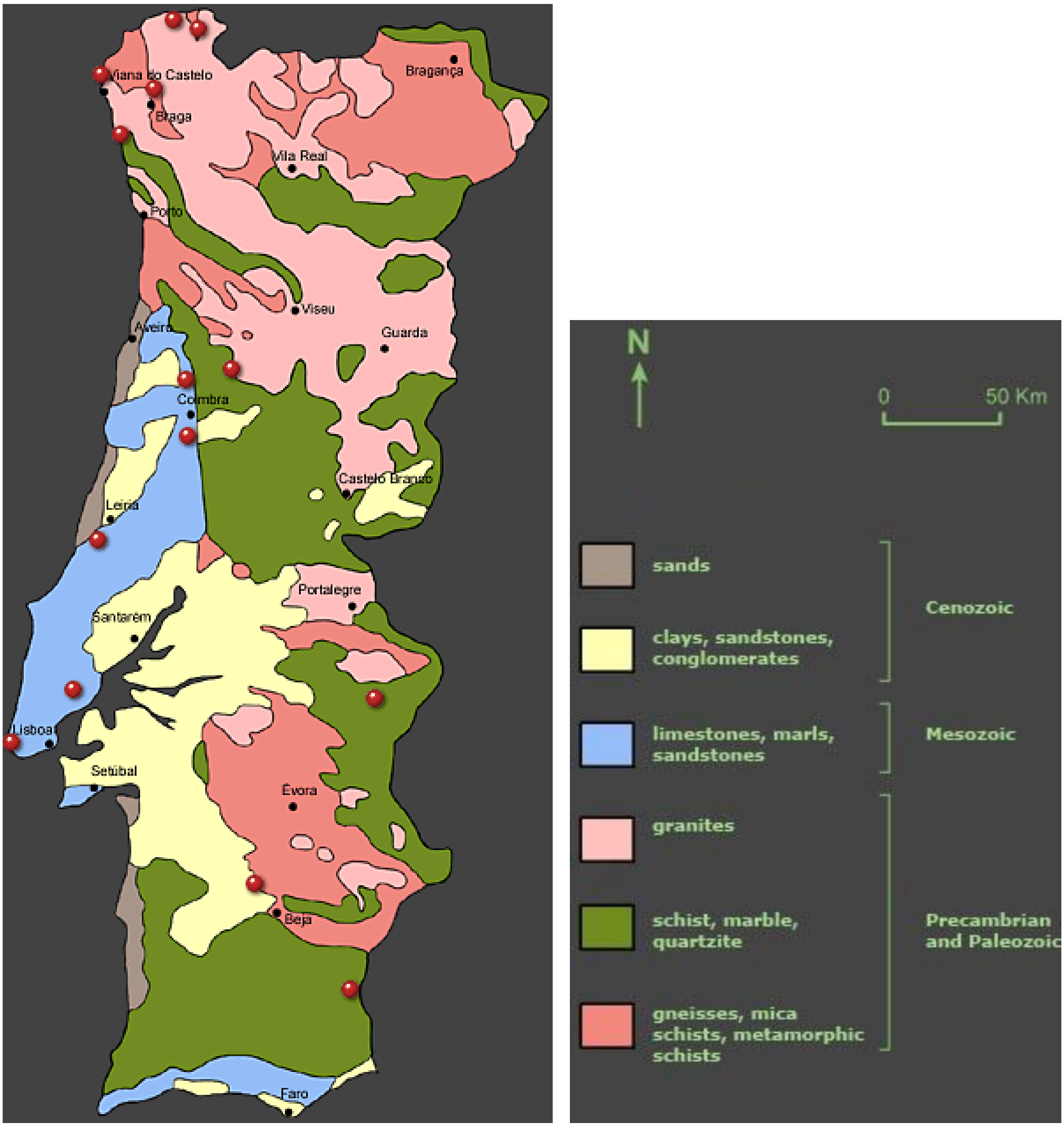


Figure 3. 1- Geological Map of Portugal

(Adapted from: Pimentel, 1994)

As can be seen above, limestone can be found namely in the south and in the Lisbon area, while the north is predominated by mostly granites and shales. Shales can also be found in other regions and are quite widespread.

One major consideration in masonry construction must always be the potential damages. Stone, as any other organic material, is subject to degradation by climatic and atmospheric agents. In the case of stones, it appears that the action of the weather (rain, wind and temperature) has a major effect on the disaggregation and deterioration process. However, stone used for construction in an area where it was previously extracted from, still holds properties of its natural geological cycle. Accordingly, its deterioration process will be minimized (Casella, 2003).

In broad-spectrum, it can be stated that the function of a particular structure as well as the materials available locally, will influence its constitution. By knowledge of the type of wall, its typology, materials, texture, etc. it is possible to expect a certain numbers of parameters as morphology, damages, and others. For this purpose, three typologies were chosen for a more refined research and for the application of a diagnostic method which will be described in following chapters.

The three building typologies which were chosen for the research are: (a) the rural, vernacular masonry homes, (b) the urban or civil building, which naturally shows better masonry properties, and (c) military constructions, which employ the use of much more massive constructions than the first two typologies.

3.4 Rural Building Typologies

The most important and unique aspect regarding a rural architectural typology is that it was primarily built by the inhabiting family itself. Many decisions such as what type of stone to use, the size and shape of the stones, the type of mortar and the height of the walls was derived by the limited abilities of the builders. Building materials were gathered, prepared and even assembled by the family. Thus, in the rural constructions we find merely no ashlar stone elements, a medium to small stone size etc.

3.4.1 Materials and Structural Techniques

As mentioned before, materials of rural structures are generally chosen by the physical location and conditions, and not as a decorative or design choice. A broad survey of the field of rural stone structures was conducted by Casella (2003). The study finds primarily that typologies recur in different geographic areas, demonstrating the existence of a common matrix in the logic of construction, always on the pragmatic needs. The choice of the material, she concludes, concerns mostly with the geological characteristics of the soils which, as she refers, "raise" the structures (Casella, 2003).

Regarding building techniques, they can be classified roughly into three major systems, which can vary with the different skill level of the executer or with the specific functionality of the wall (structural vs. decorative, ground vs. first floor etc.), as listed in table 3.2:

Table 3. 2 - Classification of rural building techniques in stone

(Adapted from: Casella, 2003)

Classification	Description
Masonry cut stone	Regular stones laid in mortar, facing stones with better regularity. Edges were improved not only for appearance but for revoking the major irregularities which can cause concentrated stresses. This technique is employed often in the rural landscape in bordering walls and in basements.
Ordinary stone masonry	Irregular stones set in mortar, less planned and therefore distributed more easily and quickly. This masonry type was usually performed to be coated with plaster, however in defining walls is often left uncoated. In this type of technique the stones should be laid avoiding empty spaces. The irregularity of the stones and often necessary, for the stability of this system is given by the weight of the stone and mortar supplied by adherence (it may be clay and sand or lime).
Dry stone Masonry	A technique that avoids the use of the mortar between the stones developed mainly in areas where lime was scarce. It is commonly associated with irregular stone masonry. To remedy lower cohesiveness of the wall, this technique requires good execution in catching stones together through the careful fitting of stones and utilization of small filling stones.

These techniques are showcased in many types of building typologies of the rural landscape, as bordering walls, house walls, barns and others. The most common typologies are certainly the houses.

Regarding the bedding or coating material, different types of mortar can be found, varying from lime or simple earth mortar to dry non-mortar walls. Finishing of the walls can range from un-plastered to white washed plastered structures, dependent on the area of construction.

3.4.2 Architectural Characteristics

An article regarding rural architectural typologies in Portugal was published by Oliveira et al. (2003). They portray a general description of the rural Portuguese house. The next few paragraphs are based on their findings.

In very general terms, and while overseeing numerous variants, the rural Portuguese house can be divided into two architectural categories, namely the Northern house and Southern house typologies. They are roughly associated with areas separated by the line connecting Leiria (in the west) to Castelo Branco (in the east) (Oliveira et al., 2003). There are apparent differences between these two regions; the north suffers continuous rain months and mountainous geography, while the plane built south enjoys an easier and sunnier climate.

The Northern House

The typical Northern house consists of two floors (first and ground floor) of a rectangular plan. In rural areas the ground floor is intended solely for agricultural activities, while the raised floor has the function of housing. The house is usually built with stonewalls with mortared joints, a sloped roof, exterior stairs to the upper floor also in stone, which may end in a porch (wood or stone) that serves as a public space. Alternatively, a single inner ladder or staircase comprises the access between the floors. Depending on local resources, granite and schist are the most frequent type of stone, and stone arrangement varies between regular alignment to a completely random arrangement.

In areas where granite was predominant, independent walls are commonly two leaved of outer and inner veneers promptly connected together by transversal stones, or alternatively, the walls consist of a single block stones throughout the thickness, which are arranged in horizontal rows. This type of wall is commonly referred to as “perpianho” (see Fig 3.2).

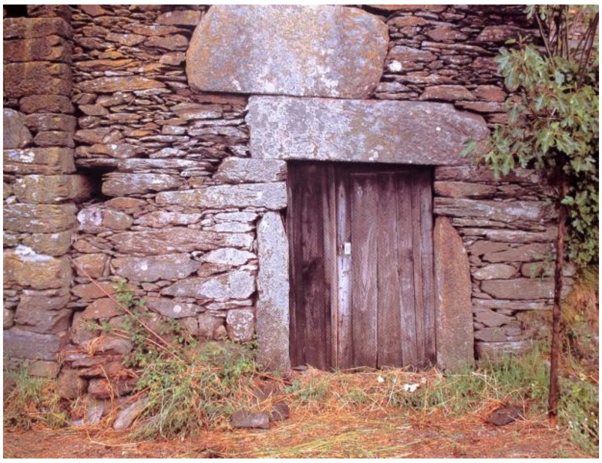


Figure 3. 2- Northern house built in granite. Figure 3. 3- Northern house built in mixed schist and granite

(From: Casella, 2003)

In shale predominant areas, walls are built by overlapping laminar stones. Wooden beams or granite blocks are occasionally placed near the openings to increase stability (see Fig 3.3). Similarly, wherever possible, the corners are carried out with large stone blocks arranged alternately to ensure stability. In certain areas of the country, the roofs and eaves are also made with plates of shale, which accentuate the originality.

The Southern House

In typical houses in the South, ground floors and are intended for housing. Agricultural necessities are habituated in independent buildings (Oliveira et al., 2003). The materials used in these constructions range from adobe, rammed earth, brick and limestone (see Figures 3.4, 3.5). The simplicity of molding these materials allowed obtaining various architectural forms such as chimneys. The marginal construction in stone is related to the scarcity of the material in these regions. The walls are usually whitewashed and roofing can be gabled or flat.


Figure 3. 4- Southern house built in limestone and earth, Figure 3. 5- Southern house built in limestone and brick. (From: Casella, 2003)

3.4.3 Geometry and Morphology

Geometry and morphology of the walls are closely related to the type of stone. In the case of schist constructions for example, walls are constructed of two leaves, as can be seen in Figures 3.6 and 3.7. In these cases, the schist stones are neatly arranged and wood or stone connectors can be found throughout the section and play a fundamental role for the monolithic behavior of the walls (Barros et al., 2010). In other cases, such as granite rural constructions, walls are generally single leaved. Thickness of the walls can range from 40-80 cm, and elevation is normally not higher than 5m and is often lower (Casella, 2003).

Regularity properties are also ranged and are dependent on the type of stone and its plasticity as well as the abilities of the constructor. On the other hand, stone sizes are often similar and range from 5-25 cm in hieght, demonstrating the pragmatic limitations of the execution.


Figure 3. 6- Section of a double leaf schist masonry wall with connectors, Figure 3. 7- Elevation of a schist masonry wall (From: Oliveira, 2003)

3.4.4 Loading

According to Tubi and Silva (Tubi et al., 2006) the walls are intended to provide a robust and safe casing, resisting to the vertical loads (live loads of horizontal elements as pavements and roofs), their own dead load and horizontal actions. But the walls have also to accommodate openings for lighting, ventilation and of course accessibility. In that sense, masonry corners play an important role in the building structural performance, since they ensure the connection between perpendicular walls and simultaneously accommodate larger stresses which tend to concentrate in the corners, due to the horizontal loadings induced by wind and earthquakes, as well as the resulting thrust from the roof structure (Barros et al., 2010).

In many rural houses, larger stone elements are used to strengthen corners and spans, as seen in Figures 3.8 and 3.9.


Figure 3. 8- Supporting granite elements in corners of schist constructions, Figure 3. 9- Supporting granite elements over openings. (From: Casella, 2003)

Regarding external loading, it can vary depending on the geographic location. In northern Portugal, external loading can include mostly wind loads (horizontal loads mainly) and heavy rain loading, whereas the south of Portugal is considered seismically active, yet much less exposed to rain.

3.4.5 Foundations

Foundations are normally shallow, built up to an average of 0.3 m deep, their stones being 0.1 m wider to each side than those of the wall (Freitas, 2012). These foundations could be completely continuous or lay between existent exploited bedrocks.

3.4.6 Typical Damages

The preservation of this fragile heritage, of its diversity and of its landscape value, faces considerable threats. The loss of use of most rural buildings due to the local agricultural abandonment of the territory reduces significantly maintenance and repairs of its structures, leading ultimately to their ruin and destruction. Progressively, the lack of memory and the loss of vernacular construction knowledge open the way to the substitution of vernacular models and construction materials for industrial ones, making them natural in the collective memory (Oliveira et al., 1992).

Other damages, in still habituated structures, correspond namely to lack of maintenance and to late, unplanned alterations that modify and jeopardize the structural behavior.

Expected damages are highly affected by the construction material. For example, schist stone presents a high water absorption capability and thus sensible to moisture from the surrounding environment, furthermore, schist stone has a sensibility to salt crystallization and climate damage. Likewise, dry stone constructions have a low waterproofing ability and thus show similar weaknesses. In addition, dry stone constructions suffer from a lower traction resistance. Earth constructions show on top of that a disadvantage in durability.

A general expected damage in rural constructions may be a high presence of salts in the masonry resulting from the high exposure to animals along with moisture content in the stone, as well as the water from the ground, the presence of salts in mortars, etc.

3.5 Urban Architectural Typologies

The building typologies found in the urban centers in Portugal poles apart from the rural building properties namely due to the elevated funds and intricate skills invested in them. Even though many of the urban buildings were not constructed with very elevated budgets and resources, they still enjoyed better conditions than the rural constructions. First, urban buildings were constructed by master-builders and not by the inhabitants. Secondly, construction materials were often transported into the building sites from quarries, and were not gathered only from the close surrounding. Furthermore, various construction equipments were available in the cities. Therefore, the urban typologies show more ashlar stone alignments, and many repeated elements that were ordered from the quarries. Often one can find recurring dimensions of facades and sizes of elements, derived from the industrialized fabrication.

3.5.1 Materials and Structural Techniques

Portugal has several urban centers, most of which were functioning as civic cores also in the past. They include the larger cities, Lisbon and Porto, and also smaller municipalities as Braga in the north, Coimbra in the country center and others. The historic masonry construction that can be found in these centers varies among them, mostly in regards to building materials chosen for construction. Overall, these structures show a higher construction level then found in the countryside, and rises much higher, up to 6-7 floors.

Pinho (2000) offers a categorization of the masonry typologies found in the cities (as seen in Table 3.3):

Table 3. 3 - Designation of the walls of old buildings

(Adapted from: Pinho, 2000):

Nature and type of device	Designation
Freestone with faces properly rigged, based on mortar, or just superimposed and juxtaposed.	Masonry walls (ashlar)
Irregular stones rigged on one side, based on ordinary mortar.	Masonry cut stone
Rough stones of irregular shape and dimensions and connected with ordinary mortar.	ordinary masonry
Brickwork and stonework; masonry and brick; masonry with wooden frames, etc..	mixed walls

The urban typologies can be classified into common housing buildings, and more intricate typologies as churches, civic buildings, monuments etc.

3.5.2 Housing Typologies

Regarding urban housing typologies, Pinho gives a general description. He defines the "urban dwelling" (ordinary masonry) type walls as walls constituted by rocks of medium dimensions (for a possibility of manual handling in some cases), bonded together by a mortar of lime and sand, given the relative abundance of these materials. Pinho also distinguishes them from what he names the "ashlar" walls which are built by larger stones and were mostly used for monuments and churches.

Housing Buildings in Lisbon

In his book, Pinho (2000) mentions that the case of the Lisbon houses can be generalized to the whole country. Old masonry buildings in Lisbon are mainly composed by thick masonry walls arranged in perpendicular planes with relatively flexible wooden floor diaphragms. In older times, mostly before the great earthquake of 1755, the bearing capacity of masonry walls was mostly guaranteed by the internal compressive stresses and by the friction generated between the masonry elements. The mortar was usually made with good quality sand, and air lime in a ratio of approximately one part to the double (1:2, 2:5, 5:9) or even stronger (3:5) (Appleton, 2005). The exterior masonry walls have a decreasing thickness from bottom to top, and, over the centuries the general wall thickness was also reduced.

The solution for the interior structure diverges with the different construction phases. As a convention in this type of building, the ‘frontal’ walls were generally parallel to the main façade wall regarding the support of the floor beams, while the ‘tabique’ walls were considered as partition walls without other structural function. On the older masonry buildings, ‘frontal’ walls were composed by an irregular timber structure filled by rubble masonry.

'Pombalino' Buildings

The new, so-called ‘**Pombalino**’ buildings resulted from the effort of engineers to answer the necessity of rebuilding Lisbon after the 1755 earthquake. Most of the downtown built environment was destroyed by the devastating actions of the earthquake and the resulting tsunami and fires. In response to the need to rebuild with a construction type less vulnerable to seismic events, engineers invented a structural design that combined the flexibility of a timber frame with the bearing capacity of masonry walls. During the first half of the nineteenth century there were few changes on the urban landscape as the city of Lisbon continued to grow accordingly with the 'Pombalino' reconstruction plan. The perimeter of the reconstruction plan is presented in Figures 3.10 and 3.11:

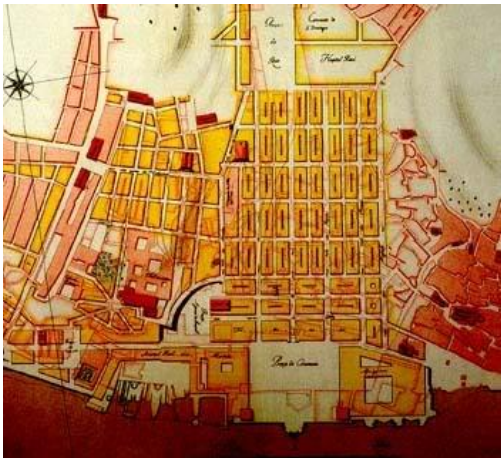



Figure 3. 10- Historical map of the Pombalina reconstruction plan of Lisbon, Figure 3. 11- Aerial view of the Pombalina construction area.

(Adapted from: arteemtodaaparte.wordpress.com)

The new buildings were supported on a timber grid laid on short timber piles intended to stiffen the alluvial soil and to create a working platform above the water level (Appleton, 2003). The general foundation system consisted of continuous masonry walls covered by a group of arches. The building ground floor was entirely built in stone masonry, and covered by vaults and arches supporting the first floor (see Figure 3.12), while the upper floors were composed by timber beams usually placed perpendicular to the rubble stone masonry façade walls.

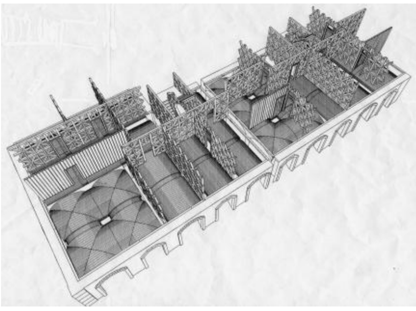
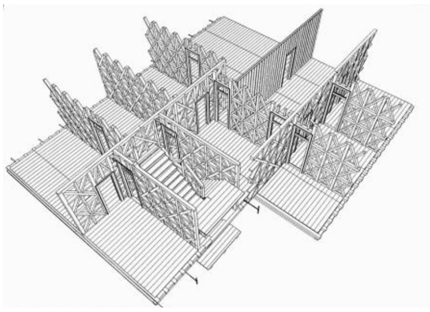
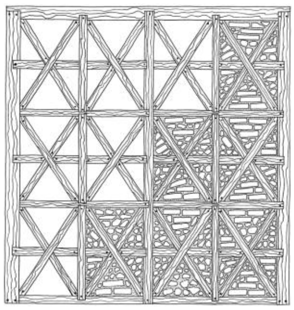




Figure 3. 12- Schematic axonometric representation of a typical masonry basement, Figure 3. 13- Schematic axonometric representation of a typical floor, Figure 3. 14- Detail of a Pombalino system wall.

(Adapted from: Cóias, 2007)

This typology of buildings is characterized by a three-dimensional timber structure (named 'gaiola-pombalina') enclosed to the front walls above the first floor. The conception of 'frontal' walls improved to a uniform and repetitive system composed by vertical, horizontal and diagonal wooden joists, filled by rubble masonry (see Figure 3.13).

The interior structure was composed by timber-masonry walls, timber floors and roof, linked to the exterior walls by timber connecters partially embedded on the masonry and reinforced by metal straps (Simões et el., 2012). The most traditional solution for the partition walls is made of timber laths nailed to vertical joists, filled afterwards by rubble masonry and mortar (see Figure 3.14). These walls have a deformable and light structure.

In these buildings, floors were composed by wooden beams, usually placed perpendicular to the façade walls and braced by smaller beams that prevent the transverse deformation of the main beams. The floors were supported on the interior walls and embedded on the masonry walls. (Simões et al., 2012)

The geometric and morphologic properties of the masonry in the 'Pombalino' buildings can vary. In some cases, the masonry is a rather crude, formed by coarsely chopped rocks that need plastering, or large ashlars, which in some cases show a volume of 1 m^3. On the other hand, also stones of more regular dimensions can be found in some walls, which corresponds to greater equality in the height of the rows or at least on alternate equidistant. In other cases, mixed walls are found in which ashlar stonework applies to lintels, corbels, columns, cornices, gables, etc…

'Gaioleiro' Buildings

In 1864, a commission was nominated by the Ministry of Public Works to develop a program of urban improvements and expansion of the city to the north and in 1888, a new plan was developed introducing a less complex and more economical alternative to the 'Pombalino' buildings. The ‘Gaioleiro’ buildings were planned as aggregated quarters with interior courtyards surrounded by a grid of secondary streets, which were wider than the streets of the ‘Pombalino’ downtown. This typology of buildings and is related flats were aiming to sustain the development of the city and the housing needs of an increasing population. (Simões et al., 2012)

The new typology was very flexible compared with the ‘Pombalino’ plan. There were no standards for the buildings height or depth, neither for the architectural design of the façade walls. The floor plan proportions are usually longer in the lateral dimension and tighter in the façade walls, but these proportions may vary. The plans originally had two flats per floor. Light wells providing natural light and ventilation to the interior rooms are often located on the lateral walls. The ground floors are constructed of ventilated masonry boxes, preventing the rising of moisture from the soil.

The construction was often carried out by private bodies, and therefore the quality of the buildings is very variable.

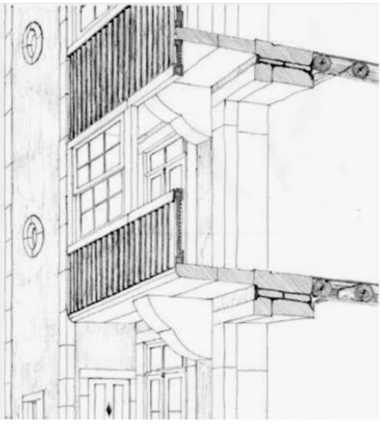
During the nineteenth century, the cage structure characteristic of the ‘Pombalino’ buildings was progressively simplified. The diagonal elements from the ‘frontal’ walls started to be removed, conditioning the bracing of the timber structure. The rubble infill between the timber elements was then replaced by brick masonry (see Figure 3.15), solid on the lower floors and hollow on the upper, or by ‘tabique’ walls (see Figure 3.16), originally used on ‘Pombalino’ buildings as partition walls. The thickness of the brick masonry walls decreases along the height of the building by changing the position of the bricks. The variation of strength of the walls is also related with the transition between solid masonry bricks in the lower floors and hollow bricks on the upper floors or the replacement of the brick masonry walls by ‘tabique’ walls. The light wells and side walls, originally built in rubble stone masonry, were also replaced by brick masonry walls.

Figure 3. 15- Brick masonry between timber elements in Gaioleiro walls, Figure 3. 16- 'Tabique' exterior walls with no diagonal timber frame, (From: forumdacasa.com, sjoaohostel.wordpress.com)

The ‘tabique’ walls obtain a structural role on the ‘Gaioleiro’ building typically in the upper floors. This fact points a major vulnerability of these buildings related with the variation of the type of interior walls along the elevation of the building. As a result, the masonry walls are not continuously laterally supported by the interior structure and are, therefore, prone to out-of-plane failure. (Simões et el., 2012)

Housing Buildings in Porto

Typical construction techniques widely used in Porto during the 19th century, were making use of available local materials, such as granite stone and wood. The structural system is characterized by an envelope of granite masonry bearing walls including the façades and the lateral walls, having a thickness of 60 cm and 30 cm respectively, interlocked by ashlar granite units and supporting the horizontal wooden elements of floors and roofs (see Figures 3.17 and 3.18). The lateral walls (see Figure 3.19) are single-leaf walls laid with lime mortar, permanent in thickness and structurally shared with the adjacent buildings, whereas the façades are double-leaf walls, decreasing in thickness from the bottom upwards. (Betzer et al., 2013)



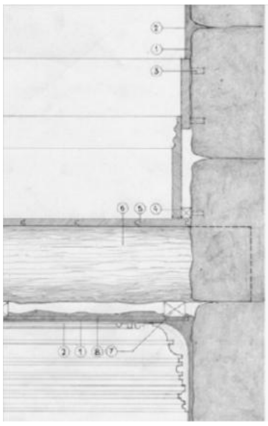


Figure 3. 17- Schematic axonometric representation of a typical 19th century Porto House's façade,

Figure 3. 18-Picture of a typical wooden beam pavement, Figure 3. 19- Connection between wooden beams and the lateral granite wall

(Adapted from: Teixeira, 2004; Betzer et al., 2013)

The typical plan is rectangular, with a short façade (typically 6 to 7 meters long) and a longer lateral dimension (typically 45 m). The rectangle in frequently perforated by 2 light wells adjacent to one of the lateral walls (Figure 3.20). Although built with good quality material, the main fronts of the building suffer a reduction of load-bearing capacity due to the presence of a great number of openings. This fragility was solved by framing the openings with reinforcements in dressed factory-made modular granite elements and connected to the masonry of the façade itself. In some cases, openings were reinforced with timber framing as well. (Betzer et al., 2013)

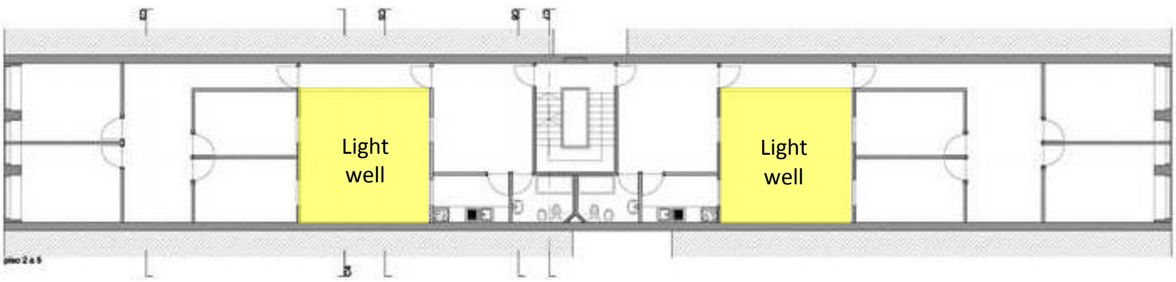


Figure 3. 20- Typical Floor Plan of a Porto Housing Building

(Adapted from: Betzer et al., 2013)

The horizontal structural system was composed of wooden beams embedded into the lateral walls and connected to each other with bridging in order to prevent lateral movement. The stairs core was built as a timber frame system as well as the roofs.

Many of these buildings over gone various alterations throughout the years, and currently have concrete structural elements that replace some of the original timber features.

3.5.3 Typical Damages to the Masonry

A survey conducted by Prof. Luis Ramos from Minho University in 2000 of a Pombalino compound in Lisbon, indicated that (Ramos et al., 2003):

(i) More than 80% of the structure of the buildings that compose the block suffered changes. 54% of these are major changes, modifying the original structural system;

(ii) The new materials (steel and reinforced concrete) and the older materials (stone masonry and timber truss) are incompatible from the mechanical point of view;

(iii) Bracing elements could not be found in several parts of the block, meaning that the ability of the structure to resist considerable horizontal forces is compromised.

Thus, the main damages to this building typology was caused by the vast amount changes and intervention conducted in them. Incompatibility between the old and new materials led to both material deterioration and structural weaknesses.

The structural failures that are common to building typologies in Porto are quite similar and generally the results of three main sources:

(i) Structural failures that originate from the construction design done by 19th century 'standards', followed by 1937 RC alterations, both of which do not comply with current standards.

(ii) Structural failures that originate from the construction phases and quality.

(iii) Structural failures that originate from lack of proper maintenance.

In many cases an extensive vertical crack can be found in the masonry wall, located on the sixth level of the building, its highest floor. Possibly, the cause of this common pattern is a concentrated load, which comes from a wooden beam (Betzer et al., 2013). In other cases this type of cracking appears in other locations where wooden beams are supported by the masonry wall. this is due to change of use and, consequently, increase of the live load, as well as the deterioration of masonry due to concentrated loads. Besides the structural damages, some non structural problems can come about in the masonry, such as chromatic alterations, deposits and disintegration, which can be classified as layering, detachment, loss of cohesion between materials and biological growth. These problems are mainly induced by poor water isolation of light wells.

3.5.4 Foundations

Foundations of these buildings usually consist of direct foundations formed by simple extension of the masonry wall to the ground with the same width or with its enlargement, depending on the characteristics of the land. The constitution of the foundation is similar to that of the shear walls of the structure. It should be noted that these over width foundations are only applied in situations where the foundation soil has a lower the resistance than that of the walls. In cases where the terrain is very sturdy foundation (Granitic rocks, limestone and basalt) this over-width may not exist (Andrade, 2011).

3.5.5 Churches, Monasteries and Urban Monuments

As mentioned previously, Pinho in his book on traditional masonry walls in Portugal classifies several types of masonry walls in the cities. Among them are those he titles "ashlar walls". His definition points out their regular rigged and relatively large dimensions (Pinho, 2000).

It must be taken into consideration that yet again, this typology represents larger and better quality resources than the former typologies introduced. These monumental structures built in the cities were planned to be long-lasting and often public or private funds were invested in them. The structures are generally unique in plan and configuration, and were planned and executed by master builders. The materials used, the assembling techniques and the details also exhibit a larger selection that was available to the builders, and more fertile basis for architectural trail.

From the structural point of view, many of the buildings are sustained by bearing walls or pillars consisting of solid or leaved masonry. The buildings materials are mostly local (granite in Porto, limestone in Lisbon etc.) and the configuration plan can vary, depending on the purpose of the structure and its specific site. The structures are often supported by masonry vaults or arches and covered by timber roofs. This building typology, although considered in this work as one, shows very diverse technologies and morphologies, as well as many possible configurations and is still being studied and realized.

One example is the **Church, Nursery and Tower of Clérigos in Porto**. The structure was built in the 18th century in the historical center of the city close to the Sao Bento train station (see Figure 3.21). The tower, Torre dos Clérigos, can be seen from various points of the city and it is one of its most characteristic symbols. The stretched plan includes the tower on one hand and the elliptical nave on the opposite (see Figure 3.22).

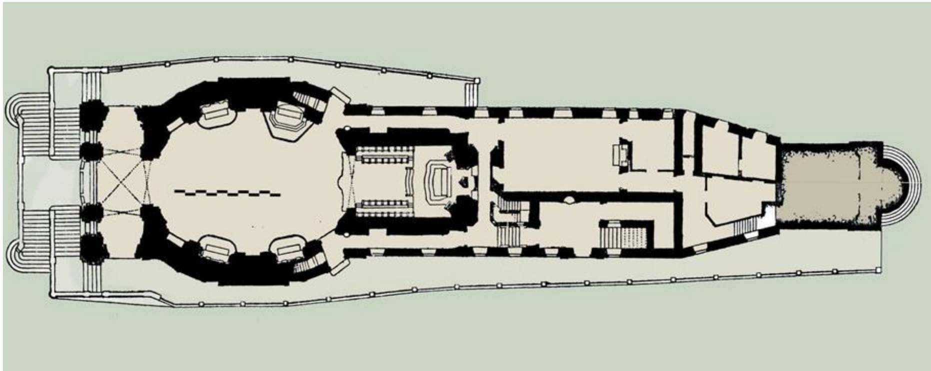



Figure 3. 21- Clérigos complex in aerial view (Adapted from: www.portopatrimoniomundial.com), Figure 3. 22- Plan of Clérigos complex (Adapted from: coisasdaarquitetura.wordpress.com)

The structural scheme of the building is articulated by a system of bearing walls built in Porto granite (both yellow and blue granite), with very thick lateral walls in multiple locations. In the church for example, these walls have a gallery inside them that separates the wall, at least locally, into two parts. This led researchers that studied the building to the conclusion that the walls might have been realized in two layers with a rubble filling. The same can be said of the walls of the tower, realized in the same material, which similarly have a significant thickness and need to be further investigated.

The church has three vaults, the largest of them in the elliptical nave. Their thickness and technique of execution cannot be determined without further inspections. The floors are built with timber elements, as well as the original roofs. Iron elements were typically used for the joints, particularly for the trusses of the roof (Mordanova, et al., 2014).

Another example is the **Monastery of Jerónimos** in Lisbon, which is considered the crown asset of Portuguese architectural heritage dating from the 16th century. The monastery is quite large in its perimeter, with a plan of about 300x50m^2. It exhibits the Portuguese adaptation to the gothic style architecture, also known as the "Manueline" style. The monastery complex includes a church, two cloisters and towers up to 50 meters high. Façade and the main cloister are showed in Figures 3.23 and 3.24.

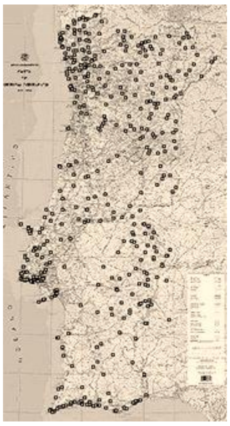
Figure 3. 23- Monastery of Jeronimos (from: www.openbuildings.com), Figure 3. 24- Cloister of the monastery (from: www.historvius.com)

The monastery church exhibits different typologies in masonry; the south wall has a thickness of around 1.9 m and possesses very large openings. Three large trapezoidal buttresses ensure the stability of the wall; the north wall is extremely robust (with an average thickness of around 3.5 m) and includes an internal staircase that provides access to the cloister. The chancel walls are also rather thick (around 2.5-2.65 m) (Lourenço, et al., 2004). The masonry used is well cut ashlar stones with a vast amount of decoration elements carved in stone (see Figures 3.25, 3.26). The bright stone, typical to the southern Portugal architecture, is local golden Limestone.

Figure 3. 25- Detail in Limestone (from: http://en.wikipedia.org/wiki/Jer%C3%B3nimos_Monastery), Figure 3. 26- Detail in Limestone (from: www.thebrooklynscribbler.blogspot.com)

3.6 Military Architectural Typologies

Military architecture and fortressing has been a common building typology in Portugal from Medieval times, originating in the time of the Christian Reconquista. The country exhibits a broad assortment of fortified castles and cities, spreading throughout the landscape from North to South. The early spread of fortifications defending land broadened in the 11th century from the North, progressing further south, contributing to consolidate new territories and thus pushing away the Muslim enemy. Military constructions were being built in Portugal up until the 18th century. Typologies of these fortified castles fluctuate both throughout the years, as their function and threat changed as artillery was introduced into the battlefields, and dependent on location. Figure 3.27 shows a map of the various locations of castles and fortresses in Portugal.



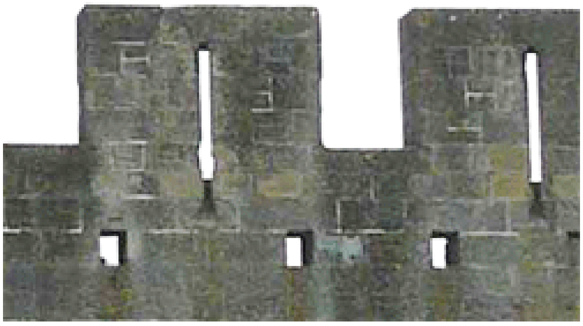


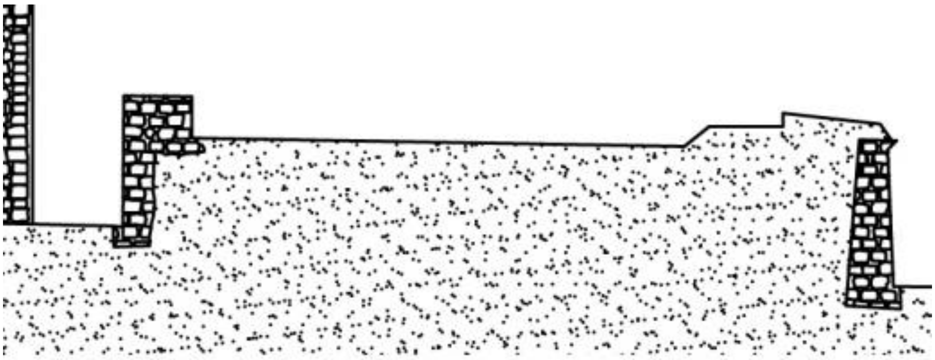
Figure 3. 27- Map of fortified sites in Portugal, Figure 3. 28- Figure of batters, Figure 3. 29- Figure of battlements.

(From: http://www.castlesandmanorhouses.com/)

3.6.1 Architectural Characteristics

Military architecture is very rich in its elements and details, most of them an inherent part of the combat strategy. These elements can include: high thickness of walls, changing section of the walls (also called batters, shown in Figure 3.28), basements, towers, battlements and crenellations (see Figure 3.29) and others. Therefore, fortresses can be an intriguing case study in the assessment of historic masonry walls due to their particular features. The affluence of elements is inevitably related to the public importance and character of these structures. Substantial funds and resources were invested in their constructions, from the vast shape and configuration to the very last detail of construction and combat.

Military structures also introduce the design of multiple leaf masonry retaining walls. This typology was developed for defence purposes, exploiting the soil of the plot to create a large section wall, having external masonry leaves and a wide internal earth filling. These walls have sections rising up in some cases to 10 m. The external leaves of the retaining walls are often composed of several leaves themselves. A typical section and a picture of a retaining wall can be seen in Figures 3.30 and 3.31.



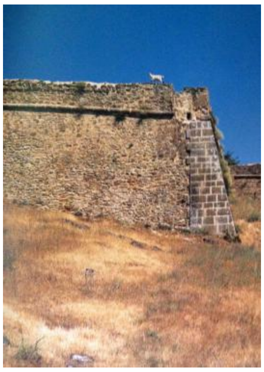


Figure 3. 30- Section scheme of a masonry earth wall, Figure 3. 31- Picture of retaining wall in Alentejo region.

(From: Author, Casella, 2003)

3.6.2 The Northern Fortress

The military bulwarked structures illustrate the state of science and technology in Europe at the time in which they arose. The north of Portugal, particularly the Minho region, experienced a fair amount of warfare throughout history and conceals many fortresses from different periods using adapting construction techniques and developing technologies.

An important example of a regional medieval military structure is the Guimarães Castle, which dates back to the 10th century and the battles against the Moors in the Iberian Peninsula. The masonry work of the castle consists of single and three leaf walls with granite stone ashlars on the external. The masonry features horizontal courses and is relatively regular, despite the fact that the height of the courses is not constant and that the length of the units is rather variable (see Figure 3.32). Several investigation and research works were carried out in the castle, including laser scan survey, which allowed the documentation of the regularity and assemblage of the masonry.

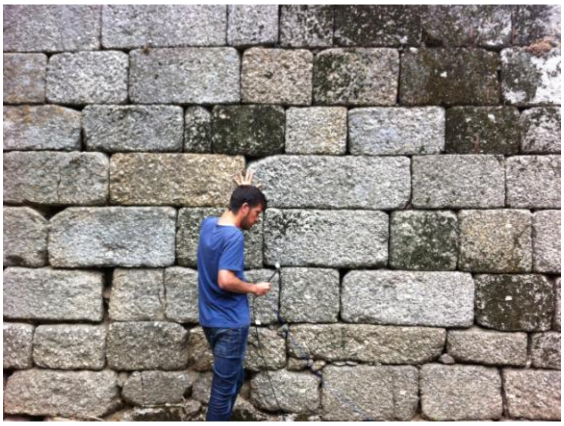


Figure 3. 32- Masonry of Guimarães castle, Figure 3. 33- Guimarães castle current condition

Throughout history, the structure over gone several alterations. Between the 12th and 14th centuries, the castle was enlarged and the defence capacity was improved. Later, the castle was abandoned and suffered damage caused by time, and by the subsequent changes of use. In the 20th century, important restoration works have been carried out. The current condition is shown in Figure 3.33, where the pentagonal perimeter of the castle can be identified. The castle is surrounded by eight square towers, which delimit the main square, with a main tower in the centre (Lourenço et al., 2013).

Further study of the morphology and state of the stone masonry has been done within the scope of this thesis, and will be elaborated in chapter 6.

Other regional examples, similar in materials and technology, include:

The fort of Leça de Palmeira - Bulwarked granite fort built in the 17th century in order to reinforce the sandbar of the mouth of the Douro. The fort has a four pointed star plan, protected by sloping curtains and watch towers (see Figure 3.34).

Bragandelo Fort - Rurally located fort that was made up of ditches and embankments, using earth and granite blocks. Granite used is essentially small to medium in size, and not perfect in shape. The plan is almost a square, with some angularity in the corners, with a 40 m corridor leading to the north facing entrance (see Figure 3.35).


Figure 3. 34- Fort of Leca de Palmeira (from:http://en.wikipedia.org/wiki/Fort_of_Le%C3%A7a_de_Palmeira), Figure 3. 35- Aerial map of Bragandelo Fort (from: www.maps.google.com)

3.6.3 The Midland Fortresses

Other geographical areas show different typologies of fortresses. An example from the Mideast of Portugal is the Fortifications of Almeida, near the Spanish border. These exceptional fortifications are nominee for a world heritage classification by UNESCO.

The fortifications exhibit different architectonical periods and styles, nested in possible Muslim or Leonese origins from the 10th century, followed by recurring reconstructions and additions beginning in the 12th century and forward. The current ruins of the fortress allow recognizing an irregular quadrangular floor plan (see Figure 3.36), surrounded by a ditch with a slab pavement and with a counterscarp lined with ashlar masonry (see Figure 3.37), presenting, at the angles, the foundations of four circular towers (Campos, 2009).


Figure 3. 36- Aerial view of the Almeida fortifications, Figure 3. 37- Picture of the Almeida fortifications (From: Campus, J, 2009)

Continuing south, in the region of Lisbon we find the example of the 19th century Sacavem Fort in the mountains of Sintra. It is situated on the right bank of the river Trancão, and has an irregular pentagonal plan, surrounded by a moat and is partially buried in the soil, which makes it hardly noticeable when viewed from a lower altitude. It is built of plastered limestone masonry, with more recent additions in concrete. An aerial plan and one of the fortress walls can be seen in Figures 3.38 and 3.39.

Figure 3. 38- Aerial view of the Sacavem fortifications, Figure 3. 39- Typical walls of the Sacavem fortifications, (From: http://www.monumentos.pt/)

The construction of this fort began in 1875 and its first construction was completed in 1892. Over the years it has over gone many alterations and additions by several architects. Today, the fort serves as National Archives for the General Management of Buildings and National Monuments.

The mainland area exhibits many regions and various geological and geographical conditions and thus we find numerous types and characteristics of military architectures.

3.6.4 The Southern Fortresses

Further in the south several military architectural structures can be found. In the southwestern point of the southern region of Algarve, in the town of Sagres, a 15th century originated Fortress can be found. The fortress, built in the era of Alfonso the V in bastion style, has a long and branched history, corresponding to its strategic location. The fortress was much rebuilt in the second half of the eighteenth century, after the massive earthquake, while integrating a sixteenth century tower. Nowadays, after massive restoration works executed in the 20th century, it is open to the public as a historical monument and exhibition center.

The fortress is built with plastered limestone (see Figure 3.40), typical to the area. The plan is configured from six strategically placed batteries and watch towers (see Figure 3.41). The shore side is closed by curtain walls that extend beyond the shore to the west.

Figure 3. 40- Walls of the Fort of Sagres, Figure 3. 41- Aerial view of the Fort of Sagres

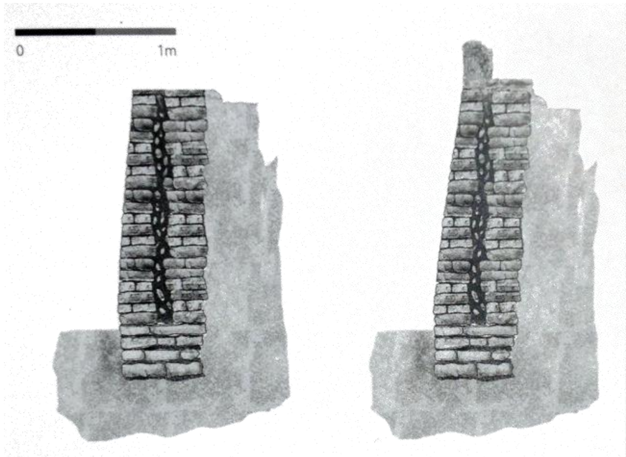
(From: http://www.igespar.pt/)

Other southern examples are found in the large region of Alentejo. The Fortress of Evoramonte, shown in Figure 3.42, and the Fortress of Estremoz, constructed both with limestone and not plastered. The fortresses walls are built from different stone techniques varying from irregular to highly regular cut. Walls can have a thickness of up to 3-4 m in towers and retaining walls.

Figure 3. 42- The fortress of Evoramonte in Alentejo.

(From: Casella, 2003)

Construction techniques include three leaf retaining walls with ruble filling as a middle leaf, which are part of a larger system of walls with earth filling (see Figure 3.43), and assembly of different regularity stones for the creation of horizontal alignment (see Fig 3.44).



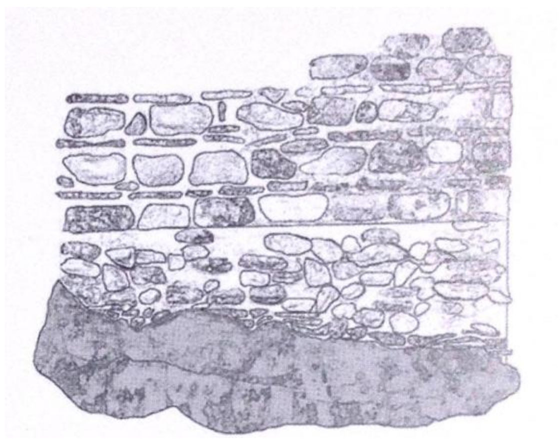


Figure 3. 43- Section scheme of retaining wall in Estremoz, Figure 3. 44- Elevation scheme of the base assembly of the fortress tower in Evaromonte.

(From: Casella, 2003)

3.6.5 Materials and Building Techniques

As seen in the simpler architectural typologies, the type of rock chosen for the construction is constantly dependent on the local environment and setting. In the case of military constructions we can find a difference in typology and technique of building and architectural style, mostly deriving from the different conquerors and invading influences. The builders were often non local, or at least guided by foreign supervisors, and thus the techniques introduced in one part of the country were often introduced in another as well, and both regions can exhibit similar building habits. Retaining walls for example are a country wide occurrence in this typology.

Regardless, we can also find many examples of exploitation of the local conditions and techniques as was mentioned in the cases of the plastered Sagres fort or broader use of the ground in the southern areas where the earth is easier to cultivate. Additional evidence of the use of local materials can be found in the shale areas where remaining fortresses are barely found, as they have deteriorated and became ruins throughout the years. One example is the Sertã castle in the region of Castelo Branco, which was a schist medieval construction, ruined in time and then rebuilt in 1998.

3.6.6 Typical Damages

Typical damages for fortresses often include corresponding damages of earth leaf walls, as cracking due to root loads, due to remaining roots which have grown in the earth supported by the masonry, as well as high moisture content that can be caused due to leakage of the fortified system. Other problems may be local damages in small elements exposed to significant loading, or material deteriorations due to moisture and erosion caused by wind.

Unfortunately, research of fortified sites of Portugal is currently insufficient. Thus, we must bear in mind that only little information is available regarding these building techniques and much wider and comprehensive study must be carried out before a global and valid conclusion can be drawn. Conclusions offered in this study should be considered merely as primer.

3.7 Comparison and Conclusion

As mentioned in the exposition to this chapter and constantly in its body, the fundamental differences between rural, urban and military building typologies in Portugal (as in the rest of the world) lie in the basic questions of the original designated function of the construction and practice of its execution.

As far as the function, the typology names speak for themselves; on one hand, the rural and urban housing typologies were designed for dwelling purposes, and oriented for their inhabitants' needs and economic abilities. The monuments and military typologies, on the other hand, were generally intended for much more durable functions, as battle defence or long-lasting religious spaces. As a direct result, the typologies show diversity in durability and masonry quality. This is in complete accordance with the execution techniques and abilities, as increasing substance of function lead necessarily to growing funds and resources. The execution quality is of course linked to the available resources and its influence enhances the noted differences.

3.7.1 Former Studies- The Case of Italy

The broad study conducted in Italy by Binda et al. (2002), takes these issues into reflection for the design and appliance of correct intervention methodologies for the different recognized typologies. The study focuses on a wide range of scales, considering both building typologies and wall and masonry typologies.

In the larger scale of building typologies, comparing between different case studies in the Umbria and Liguria regions, they find that the mechanical behavior of the stone is better in monument structures, showing higher results of elastic modulus (E). This indicates the elevated stone quality used in this typology. Moreover, they find higher elastic modulus in civic buildings, and low results in rural structures. Results are presented in the Figure 3.45.

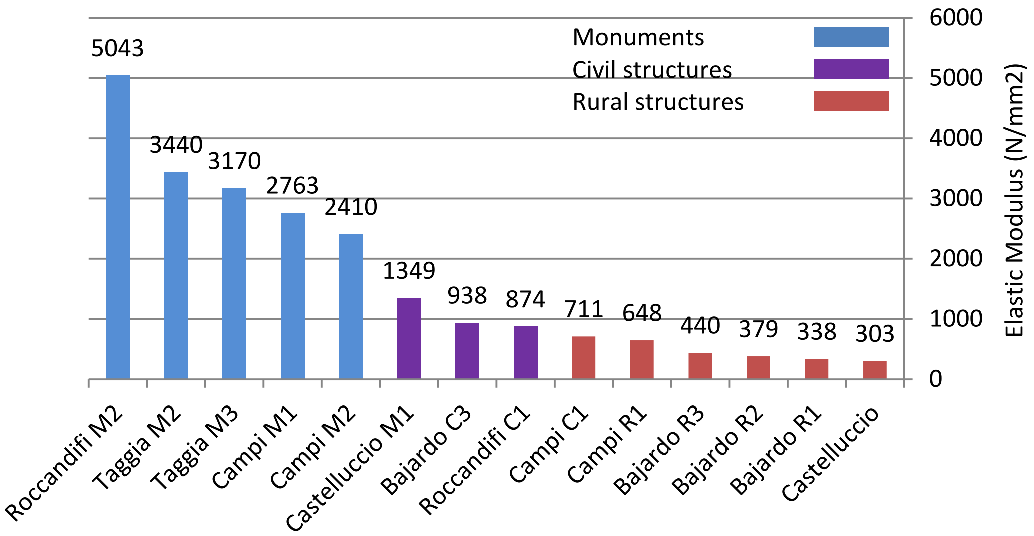


Figure 3. 45- Elastic Modulus related to different building typologies

(Adapted from: Binda, et al., 2002)

In the smaller scale, relating to wall and masonry typologies, they introduce the idea of classes of buildings. They propose that the approach for restoration should be done by classes of buildings and structures (Giuffrè, 1991), (Doglioni et. al., 1994), (Binda, 2002), and mention that it is frequently impossible to apply techniques of intervention equal for every building class. For this classification they attempt to distinguish mean types and classes of masonry walls found in Italy. They ultimately categorize four mean classes, as can be seen in Fig. 3.46:

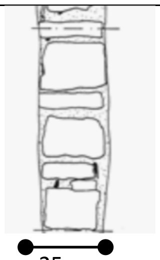
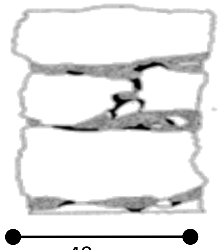
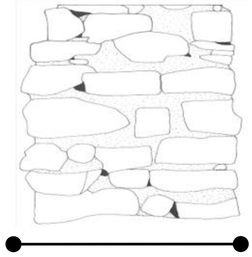
(i) one leaf solid wall,

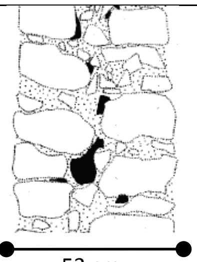
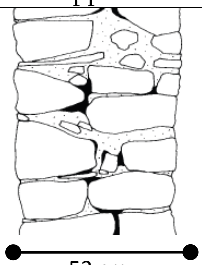
(ii) two leaves,

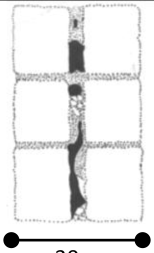
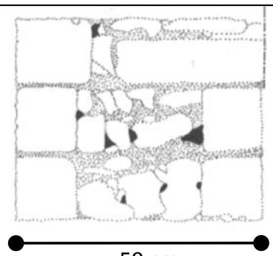
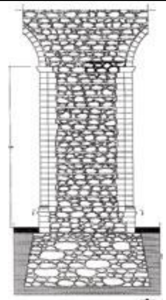
(iii) three leaves,

(iv) dry wall.

In addition, they note that each class can be further subdivided into two subclasses or even more (Binda, 2002).

Class A- One leaf solid wall	
Single Stone	Thick Wall
 	

Class B- Two Leaves		
Two Leaves with no Connection	Two Leaves with simple Connection made with Overlapped Stone	Two Leaves with Transversal Connection made with Long Regular Stone
		

Class C- Three Leaves		
Three Leaves with a Thin Internal Leaf	Three Leaves with a Thick Internal Leaf	Three Leaves with a Thick Internal Leaf referred to Pillars of Churches and Cathedrals
		

Class D- Dry Wall


Figure 3. 46- Classes of masonries common in Italy

(Adapted from: Binda, et al., 2009)

The importance of the characterization of connectors in the masonry is pointed out, as their presence in the morphology has a crucial role in the stability of the section. In figures 3.47 and 3.48, adapted from their former studies, different levels of connectors are showcased, and typical masonry sections are presented, relating to connector presence.

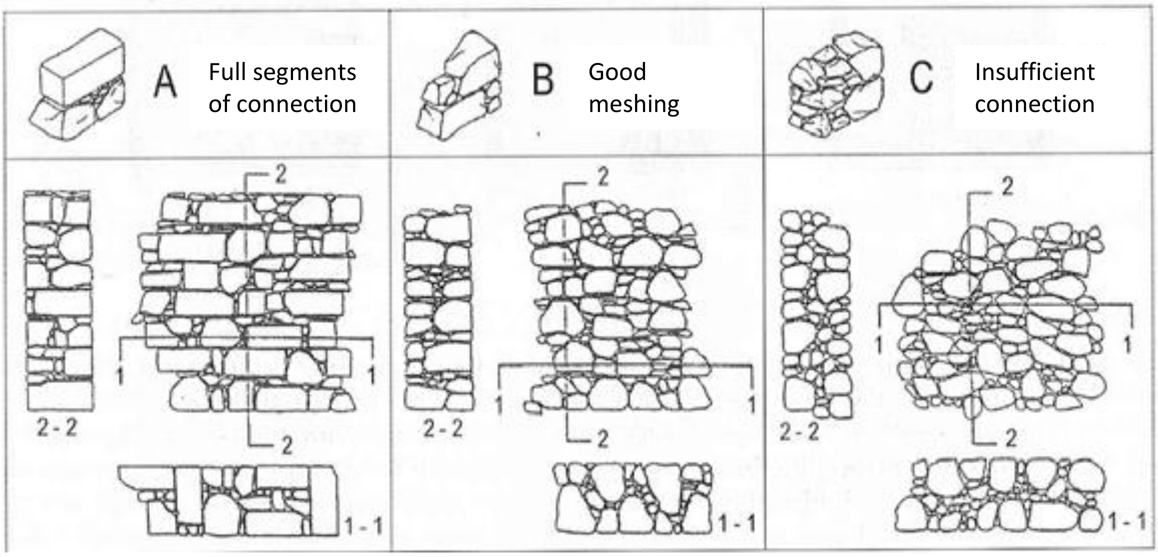


Figure 3. 47- Good to poor quality connections in masonry

(Adapted from: Giuffrè, 1993)

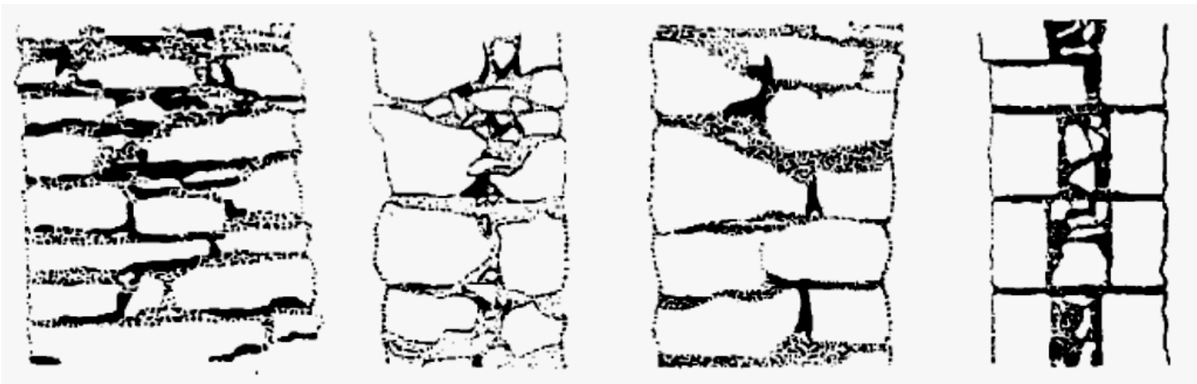


Figure 3. 48- Typical masonry cross sections- single leaf; two leaves without connection; two leaves with connection; three leaves

(From: Binda, 1994)

The study further concludes that building and structure typology is of great importance. Sequentially, a reliable approach to preservation should engage in the choice for the most appropriate techniques corresponding to the special type of building and materials (Dolce, 1999), (Binda, 2002).

3.7.2 The Case of Portugal

Subsequent to the noted study, it can be concluded that the stone masonry construction in Portugal can be analyzed within the chosen classification of typology by building type and size, as the found techniques in each field of construction showed similarities within the typologies and dissimilarities between them. For example, rural structures almost always exhibit small scale stones, irregularity and double leaf morphology, whereas the urban structures showed larger segments of stone and various possible morphologies and geometries.

Simultaneously, other possibilities of classification were found to be valid, as location and geography. These were found to necessarily have an effect on the type of stone used for the construction, allowing differentiating a type of northern structure, likely built from non plastered granite, from a southern structure built from limestone or adobe brickwork and often plastered and white washed.

It can be generally noted that several mechanical properties are related to typology, as regularity, thickness and morphology, whereas other properties tend to be dependent on material and thus are more related to the geographical character. Concluding tables will be presented in the following pages.

A summary of the surveyed typologies and their mechanical properties is given in Table 3.4:

Table 3. 4 - Summary of surveyed masonry structures relating to typology

	Rural structures	**Urban Structures**	**Military Structures**
Construction technique			
Elevation	Max 5.5 m	Max 25 m (3.5 m between floors)	Max 10 m
Thickness	0.3-0.6 m	0.3-1 m	Max 10 m
Foundations	Shallow- up to 30cm deep	Masonry basements Continuous foundations	In many cases- Retaining walls
Morphology	Mostly double leaf	**Varies** Single/ triple leaf	**Varies** Single/ triple leaf/ retaining walls
Connections	**Varies**	**Varies**	**Varies**
Regularity	Irregular	**Varies** Dependent on material	Mostly regular
Size of units	Small to medium	Medium to large	Medium to large
Mechanical effects			
Loading	Selfweight, weight of the floors and roof	Selfweight, weight of the floors and roof	Selfweight, live loads as pedestrians on roof. loading by root penetration stress
Typical damages	Deterioration due to lack of maintenance, change of use, Leakage of draining system.	Deterioration due to lack of maintenance, change of use, Leakage of draining system.	Cracking due to root loads, leakage- moisture content

A summary of the geographic location (see Figure 3.1 in chapter 3.2 of this thesis) and its influence on the mechanical characteristics is given in table 3.5:

Table 3. 5 - Summary of surveyed masonry structures related to stone type:

	Limestone areas	**Granite areas**	**Shale areas**
Material properties			
Type of Stone	limestone	granite	schist occasionally: Granite strengthening units
Type of Mortar	Air lime / clay	Dry stone/ air lime	Dry stone/ air lime
Type of Plaster	lime	none	None
Mechanical effects			
Typical damages	Although very durable, limestone absorbs water and is highly reactive when exposed to acids and it can suffer substantial deterioration.	Granite suffers mainly physical damages as blistering, chipping, stone cracking. May also suffer from continuous rising damp.	Inferior hardness and lamellar internal structure lower the resistance performance. (not long lasting) Leaf separation due to morphology

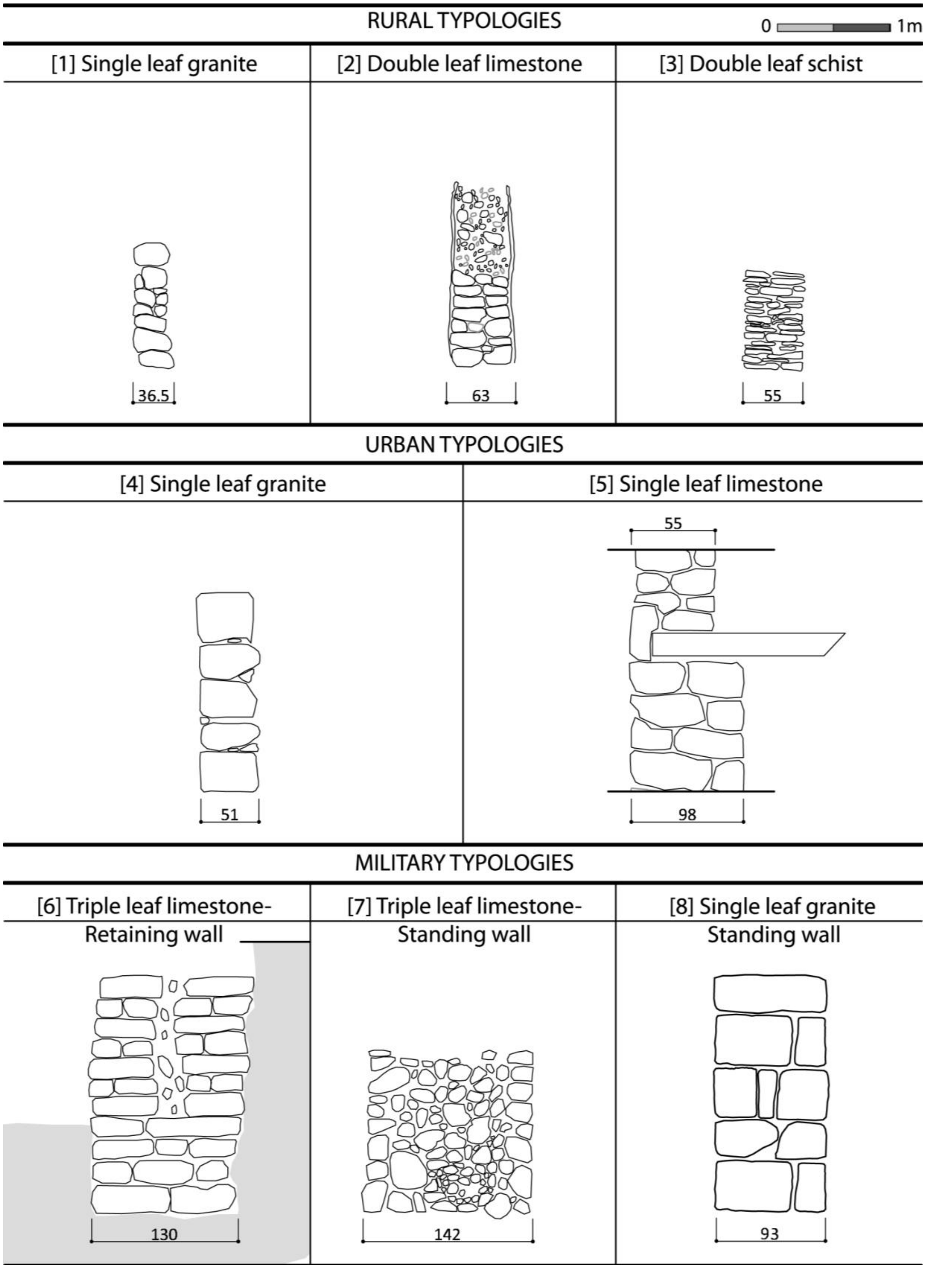
Table 3.6 showcases several examples of specific typologies obtained from previous studies in Portugal:

[1]- **Rural single leaf granite wall, found in Vila Real**. Dry stone construction with large units, especially over openings. (Casella, 2003)

[2]- **Rural double leaf limestone and earth construction, found in Algarve**. (Casella, 2003)

[3]- **Rural double leaf schist wall, found in Alentejo**. Semi cut stone with air lime mortar. (Casella, 2003)

Table 3. 6 - Common masonry typologies in Portugal



[4]- **Urban single leaf granite wall, found in Porto**. Is approximately 50 cm thick and has a distribution of dispersed voids. The stones have an irregular shape and height of between 23 to37 cm. Presence of small stones in the shims. Percentages of materials obtained at this section were 88% with respect to stone, 10% to mortar and fine stones and 2% for voids (Mota, 2009).

[5]- **Urban single leaf Limestone wall, found in Lisbon**. Thick wall typology as defined by Binda (2002). Wall thickness decreases with height increasing, corresponding to the loading (Pinho, 2000).

[6]- **Military triple leaf limestone retaining wall, found in Setubal**. Thin ruble middle leaf with thicker exterior leaves (Casella, 2003).

[7]- **Military triple leaf limestone standing wall, found in Alentejo**. Ashlar and cut stone construction with air lime mortar (Casella, 2003).

[8]- **Military single leaf granite standing wall (thick wall), found in Guimarães Castle**. Ashlar construction with nearly empty joints. Regular horizontal courses in different heights, uneven vertical joints.

3.7.3 Conclusion

In the next chapters, the gathered information will be utilized in creating a general methodology for the inspection and diagnosis procedure of each of the typologies. The methodology will be prescribed on the typologies and taking into consideration three fundamental factors they regard:

(i) The essential questions of the diagnosis typically raised by the discussed typology.

(ii) The physical factors of the typology, including morphology, geometry, materials and others, and their affect on the process.

(iii) The significance of the typology under discussion to the global and local heritage, influencing the amount of funding and time resourced into the diagnosis practice.

Taking these factors into consideration will initiate different approaches of methodology for the diagnosis of each typology, as their level of significance and as well as the dilemmas they arise can be fundamentally different. These considerations will be combined with the knowledge of the mechanical properties of each typology obtained by the study, and type specific methodologies will be developed.

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4. METHODOLOGY FOR DIAGNOSIS OF RURAL TYPOLOGIES

The following chapters will present proposals for inspection and diagnosis of historical structures of rural, urban and military typologies. The proposals will relate to typical problems of the typologies and their inherent properties. For each diagnosis procedure a coherent approach to the diagnosis will be developed and detailed into practical decision making tools of a general nature, and a specific case will be exemplified.

4.1 General Methodology Recommendations

The case of historic rural structures raises an elementary issue in the field of conservation. On the one hand, these are historic structures, built in historic construction techniques and therefore must be considered as cultural heritage and worthy of documentation and preservation. On the other hand, these structures are generally owned by private owners, often non wealthy, not culturally proficient and with only little or no resources, who see the structure as a dwelling solution and no more. In many areas, the absence of operational quarries, the lack of master builders with experience in masonry building, along with the excessive specialization of local construction industry in non-traditional and concrete solutions, increases the costs of building and conservation of such kind of walls (Barroso et al., 2014). Alongside that, the rural typology walls are often simpler to recognize, the construction techniques are straightforward and undemanding and the structure itself is at many times small in dimension. This makes the task of conservation of these structures accordingly less intricate than a complex monument.

The mentioned considerations demand a simple, frugal and accessible approach to conservation. The diagnosis procedure must be a smart, compact utilization of the possible practice, suggesting only what is necessary and efficient. It must be based on existent requirements and on the characteristic question of the diagnosis of the rural typology.

4.1.1 Questions of the Diagnosis

The survey conducted by Casella (Casella, 2003) found that many of these historic structures are in very good shape, and are potentially very simple to preserve. Nonetheless, the idea of continuous deterioration must be considered, proclaiming that lack of maintenance for a long time can be as destructive as exceptional events in a long range (Binda, 2014). This binds the designer to intervene and stop the decaying process. Hence, the main question of the diagnosis is:

(i) Damage Survey- What is the level of damage and its sources?

Other questions that may rise in more intricate typologies as morphology detection, mechanical properties of the masonry, or how to conduct a complex geometrical survey can be considered as a part of one total diagnosis process in this case, as the rural typology is fairly simple and easier to asses.

The methodology for answering these questions is to be dictated using the available tools mentioned in the previous chapters, considered together with the questions and considerations presented above. The possible methodologies can still vary according to the physical aspects of the walls. The rural wall can be of many characters and therefore, the right tools for its diagnosis may change.

4.2 Inspection and Diagnosis

4.2.1 Testing Compound

In light of the listed above, Table 4.1 shows a proposal for the different techniques that are useful in the task of damage and mechanical survey of rural masonry walls:

Table 4. 1 - Recommendations for damage and mechanical survey of rural masonry walls

*Geometrical classification from Casella, 2003

geometry	**material**	**morphology**	**finish**	visual	infrared	Hardness	Boro	MS	MC	Salts
cut stone	granite	single leaf	none	■		■	■	■	■	■
		double leaf	none	■		■	■	■	■	■
	limestone	single leaf	plastered	■	■		■	■	■	■
			none	■		■	■	■	■	■
		double leaf	plastered	■	■		■	■	■	■
			none	■		■	■	■	■	■
ordinary stone	granite	single leaf	none	■		■		■	■	■
		double leaf	none	■		■		■	■	■
	schist	double leaf	none	■		■		■	■	■
			plastered	■	■			■	■	■
	limestone	single leaf	plastered	■	■			■	■	■
			none	■		■		■	■	■
		double leaf	plastered	■	■			■	■	■
			none	■		■		■	■	■
dry stone	granite	single leaf	none	■		■		■	■	■
		double leaf	none	■		■		■	■	■
	schist	single leaf	none	■		■		■	■	■
		double leaf	none	■		■		■	■	■

Compound and hard to execute methodologies will often not be recommended for the diagnosis of the rural structures, as they will not be applicable or practical for that type of wall. For example, jack tests may not be useful due to low loading, as well as the wide-ranging irregularity often found in the texture of the walls. Another example can be seen in GPR testing that is not recommended, as the thickness of the walls is fairly narrow, and better results can be obtained by simpler test methods. Sonic tests may also not be practical due to the large amount of voids in the walls, which is an outcome of the construction technique. Non recommended applications can be as a result of both impracticality due to the physical properties of the wall (type of stone, its size, morphology or other properties) as well as high funds or the high level of knowledge needed for the correct execution of the tests, which is not always available in rural conservation.

4.2.2 Recommended Tests

Visual inspection

Visual inspection is the chief test that should be conducted in diagnosis of rural walls. During the inspection typical damages should be checked:

(i) Damage caused by lack of maintenance- biological attack, moisture presence,

(ii) Damage due to change of use that may cause additional loading, or a change in the structural scheme,

(iii) Chemical attacks due to animal residue,

(iv) Disassembly of external leaf due to lack of cohesion or adequate connectors.

Visual inspection may also be a part in other diagnostic tactics, for example in the case of local dismantling of stone units in order to detect morphology. In this case, dismantling must be conducted up to 75% of the wall thickness, and after internal visual inspection the units should be put back into place.

Boroscopy

Usually used as a complementary technique, recommended in order to control the extension of the results of other tests or to validate them. In the case of rural constructions it can stand alone as a methodology for morphology detection. Limitations of the method include its minor destructive nature, and the fact it can be conducted solely on regular masonry walls. It must be stated that the test can obtain only local results, thus preliminary information is needed in order to choose the localization of the boroscopy.

Moisture content and salt presence testing

Moisture can be detected in masonry in two main ways – direct laboratory measurements of samples extracted from site, or indirect in situ measurements which are correlated to laboratory results. In the case of rural structures, both methods are applicable, yet if the material is very inhomogeneous (as rural masonry tends to be often), the interpretation of data from indirect in situ measurements is more difficult (On site for masonry, 2005). Condensation of water inside the structure can disturb the measurements, thus the location must be considered before chosen. Damaged locations, pointed out in preliminary visual inspection should also be considered as one. In plastered typologies, both the masonry components and the plaster should be tested.

As for salt detection, samples should be collected from hazard spots like wet masonry or walls that are closely located to animals and their residues. For both moisture and salt detection it is advised to carry out measurements in different heights of a tested wall in order to detect or rule out effects of rising damp, roof leakages, etc.

Hardness tests

Hardness testing with a Schmidt hammer is a very simple method to achieve immediate mechanical properties. These properties relate solely to superficial surface resistance. In the case of rural masonry walls, Schmidt hammer can be applied on suspected damaged areas, and complimented by moisture and salt content tests. Likewise, it is advised to carry out measurements in different heights.

A few cases of rural walls will not allow using Schmidt hammer – very rough textures seen in non plastered small stone walls, plastered walls (as the test is superficial the rebound results will correspond to the plaster not the masonry). The rebound test is a local method applicable on individual elements and not on a composite material. Therefore, results will testify only on the nature of the stone or mortar elements tested. In walls of mixed stone (such as limestone and brick) as well as in walls with large mortar joints, the results for the stone elements will be harder to calibrate.

Infrared Thermography

Infrared thermography provides near surface information of a few cm deep. It can be useful for both damage survey of plastered walls, and for 2D distribution of moisture on an explored surface. For the application the surface should have uniform structure (roughness), which is not necessarily a characteristic of the rural masonry walls. Execution is recommended outside, as the small interior spaces may not be practical for the equipment configuration and because the exterior suffers maximum weathering exposure. This can be a limitation, as measurements outside require constant environmental conditions - the area measured should be windless and not directed to south or south-west (On site for masonry, 2005). Furthermore, Infrared needs constant flow of energy, therefore, cannot be applied on every location.

The interpretation of results requires some experience and a detailed documentation of the measured surface quality, at the best by means of usual photography, which should be collected along the process.

4.2.3 Implementation Example

In Table 4.2 following, recommendations for the damage survey procedure of a double leaf schist masonry wall are introduced. Additional implementation tables for different rural typologies can be found in Annex 1.

Table 4. 2 – Practical tool for inspection and diagnosis of a rural masonry wall

DAMAGE SURVEY		
SCHIST DOUBLE LEAF		
Visual Inspection	Compulsory	Visual inspection is the chief test that should be conducted in diagnosis of rural walls. During the inspection typical damages should be checked: ▪ Damage caused by lack of maintenance- biological attack, moisture presence. ▪ Damage due to late alterations that cause additional loading, or change the structural scheme. ▪ Chemical attacks due to animal residue. ▪ Disassembly of external leaf due to lack of cohesion or adequate connectors.
NDT	Recommendation	**Appliance**
Moisture testing	locally recommended	Can be applied in areas of special interest where damaged stones are found, in order to estimate the severity of damage. Test can be applied on adjacent stones in different heights for recognizing the peak level of the damage, by comparing results.
Hardness test	Locally recommended	Can be applied in areas of special interest where damaged stones are found, in order to estimate the severity of damage. Test can be applied on adjacent stones in different heights for recognizing the peak level of the damage, by comparing hardness results.
MDT	Recommendation	**Appliance**
Micro sampling	Locally recommended	Samples can be taken for the measurement of moisture content and salt presence. Samples can be obtained from adjacent stones in different heights for recognizing the peak level of the damage, by comparing results.

Main characteristics of the wall dictate the usability of different methods, and demand certain application techniques. Even though in the conceptual level similar resources should be invested in all rural typologies, often the physical restrictions themselves limit us to non-uniform methodologies for the same typology.

4.3 Conclusions

In an article published this year in Portugal regarding rural masonry walls, Barroso et al. (2014) address the importance of their conservation. They note that the study of these existent masonry typologies, which is often vernacular, is very relevant in the process of protecting and even regaining lost knowledge. The goal of the intervention in the rural habitat structures is to safeguard their preservation. In light of these, the diagnosis procedure should be:

(i) By examining closely the necessity and usefulness of the constitute methods of the diagnosis routine, reassembling them in a refined typology fitting manner is possible.

(ii) Simple, reachable methods can be applied for both the diagnosis and the intervention of rural structures. These methods can and should be appropriate for the use of local builders and property owners. More intricate approaches are often unnecessary.

(iii) The desired simplicity of the diagnosis procedure is often in accordance with the typology itself and its basic characteristics.

(iv) The availability of knowledge is fundamental to assist technicians to make more effective preservation interventions with proper materials and techniques, and thus, documentation and publication of knowledge is essential.

5. METHODOLOGY FOR DIAGNOSIS OF URBAN TYPOLOGIES

5.1 General Methodology Recommendations

Investigation at urban level initiates different doubts than those of the rural or the military field. The urban typology presents a necessarily denser surrounding, which obligates a wide diagnosis procedure originating in the scale of a neighborhood, street or block, and not focusing immediately on a single structure. As a first step of the diagnosis, the larger scale should be learned, its events or evolutions, its structural behavior, etc (Binda, 2014). Only after understanding the larger scale, the single element can be diagnosed. This of course said relates to housing typologies in the urban landscape of Portugal. Other stand-alone urban typologies such as churches and monasteries have been presented earlier, but these are less of an issue of study in this work.

Historical centers of three cities were inscribed as world heritage sites in Portugal: Porto, Guimarães and Évora. Furthermore, the historic center of Lisbon exhibits construction typologies that are of a heritage nature. Hence, the subject of the conservation of these centers is of great importance to the cultural identity of the country.

This stipulates a coherent diagnosis methodology for both the urban and the building scale. The historic centers exhibit aggregate structures sharing the lateral supporting walls. These walls are usually masonry walls of single leaf morphology. The type of stone, mortar and their shapes and relation can vary, but the evident advantage of the conservation practice of these structures is the deduction processes possible due to the similarities.

5.1.1 Questions of the Diagnosis

The fundamental question of the urban diagnosis regards the evaluation of safety condition of the structure and its structural assessment. Addressing these topics includes the elevation of the level of knowledge of the geometry, the materials, the building techniques, the cracking patterns, the structural damages, etc. These can be recognized with the assessment tools available. The process can be further utilized by learning from similar cases and choosing the correct tools by processing existing data and results from similar cases.

The testing procedures can be divided into three fundamental classifications of query:

(i) Damage survey,

(ii) Mechanical properties of the masonry,

(iii) Geometry and Morphology detection.

Having satisfied all these inquiries, a comprehensive assessment of the structural state can be reached.

5.2 Damage Survey

5.2.1 Testing Compound

In order to conduct an effective damage survey of an urban masonry wall, a proposed methodology with the recommended techniques is shown in Table 5.1:

Table 5. 1- Recommendations for damage survey of an urban masonry wall

*Geometrical classification from Pinho, 2000

geometry	material	morphology	finish	visual	sonic	infrared	GPR	Hardn	Boro	MS	MC	Salts
(1) Ashlar	granite	single leaf	plastered	■	■	■				■	■	■
			none	■	■			■		■	■	■
		multi-leaf	plastered	■		■	■		■	■	■	■
			none	■				■	■	■	■	■
	limestone	single leaf	plastered	■	■	■				■	■	■
			none	■	■			■		■	■	■
		multi-leaf	plastered	■		■	■		■	■	■	■
			none	■				■	■	■	■	■
(2) Cut stone	granite	single leaf	plastered	■	■	■				■	■	■
			none	■	■			■		■	■	■
		multi-leaf	plastered	■		■	■		■	■	■	■
			none	■				■	■	■	■	■
	limestone	single leaf	plastered	■	■	■				■	■	■
			none	■	■			■		■	■	■
		multi-leaf	plastered	■		■	■		■	■	■	■
			none	■				■	■	■	■	■
(3) Ordinary stone	granite	single leaf	plastered	■	■	■				■	■	■
			none	■	■			■		■	■	■
		multi-leaf	plastered	■		■	■		■	■	■	■
			none	■				■	■	■	■	■
	limestone	single leaf	plastered	■	■	■				■	■	■
			none	■	■			■		■	■	■
		multi-leaf	plastered	■		■	■		■	■	■	■
			none	■				■	■	■	■	■
(4) Mixed masonry	granite & brick	single leaf	plastered	■		■				■	■	■
			none	■				■		■	■	■
		multi-leaf	plastered	■		■	■		■	■	■	■
			none	■				■	■	■	■	■
	limestone & brick	single leaf	plastered	■		■				■	■	■
			none	■				■		■	■	■
		multi-leaf	plastered	■		■	■		■	■	■	■
			none	■				■	■	■	■	■

5.2.2 Recommended Tests

Visual inspection

The first stage of any type of damage survey must start with a visual inspection, with a purpose of recognizing viewable damages, abnormalities and possible points of interest for further investigation. In the case of urban housing buildings visual inspection must be conducted anticipating the typical damages as the leakage adjacent to light wells or cracking due to overloading on the top floors. Furthermore, typical material damages (for granite, limestone and others) should also be studied prior to the inspection, to induce an efficient procedure.

The visual inspection may be executed in several intervals with progressing tasks. For example, direct documenting of crack patterns or damage maps can be useful for further analysis of the structure after inspection.

Sonic Transmission

Being a local testing method, sonic transmission should be planned and carefully located prior to execution. Moreover, as the results provided are generally qualitative, the test excels when used in comparative study, if in calibration with other testing methods or in itself.

Some possible applications for the detection of damage by sonic transmission can be - mapping of void positions, mapping of areas affected by cracks by transmission or by travel time and attenuation tomography (both with a resolution from 20 to 70 cm depending on sonic velocity and size of the masonry structure) and others. Crack pattern mapping is recommended only for regular brick and stone masonry. Otherwise, the results may be only qualitative. Another application possible with ultrasonic transmission is estimation of crack depth – which is possible in the case of cracks orthogonal to the surface and applicable only on single blocks because mortar joints produce high attenuation (On site for masonry, 2005).

GPR

GPR can contribute to damage surveying in the identification of hidden crack patterns or voids in the masonry. Urban walls with smaller sections may not be suitable targets for the method. In many cases, the diagnosis procedure will turn to GPR after exhausting other possible methods completed with insufficient results.

The methods abilities can be detection of main fractures by reflection, mapping of areas affected by diffused cracks by reflection or by attenuation tomography with a resolution from 10 to 40 cm, depending on radar frequency and size of the masonry structure. (On site for masonry, 2005)

Sampling, moisture content and salt presence testing

Complimentary in-laboratory tests are an inherent part of the diagnosis procedure. In the case of damage survey, moisture content and salt anions presence is a vital piece of data for the assessment of the masonry condition. In the case of urban structures samples can be collected for laboratory testing or collected in situ and calibrated.

Condensation of water inside the structure can disturb the measurements, thus the location must be considered before chosen. Damaged locations, pointed out in preliminary visual inspection should also be considered as one. In plastered typologies, both the masonry components and the plaster should be tested.

Hardness tests

In the task of damage survey, hardness tests can serve as a complimentary test to confirm deterioration of single masonry elements or even of whole structural elements. After identifying potentially damaged locations, Schmidt hammers rebound measurements can be taken from it and compared with additional measurements obtained from "healthy" masonry. Moreover, when a structural element is suspected to be deteriorated samples can be acquired from it and compared with other structural elements with the same material. For example, in the light wells of housing typologies where the masonry walls often suffer an accelerated deterioration process due to moisture, rebound measurements should show lower results than other parts of the building.

Infrared Thermography

A very efficient method for the task of damage survey is the Infrared thermography. It can provide data of the distribution of moisture on an explored surface, up to a few cm deep. Its limitations are mostly due to constant environmental demands which may not be easily satisfied in every case. On plastered walls, practicing the method allows detection of de-laminations between masonry and plaster, presence of inclusions and crack patterns and voids.

The measurement depends namely on physical characteristics of the surface as well as of the substratum layers and on the surface qualities – namely reflectance and surface damages. The interpretation of results requires some experience and a detailed documentation of the measured surface quality, at the best by means of usual photography.

Boroscopy

In specific cases, where damage is suspected to be leaf detachment or hidden voids, boroscopy can be used as a local verification method. As it is partially destructive it should be considered only if non destructive efforts have failed.

5.2.3 Implementation Example

Table 5.2 following, presents the recommendations for the inspection and diagnosis procedure of damage survey of an urban single leaf granite masonry wall found in Porto. Additional tables for the diagnosis procedures of other typology walls can be found in Annex 1.

Table 5. 2- Practical tool for damage diagnosis of a Porto single leaf granite urban wall

DAMAGE SURVEY		
Porto single leaf granite wall		
Visual Inspection	**Compulsory**	Search for typical damages: ▪ Cracking on top floors ▪ Light wells stone deterioration
NDT	**Recommendation**	**Appliance**
Infrared thermography	**Highly recommended**	For hidden crack patterns, inclusions and moisture detection. Should be done in early stages in order to guide further testing efforts as sampling, sonic and others.
Sonic / ultrasonic transmission	**Moderately recommended**	Should be applied in specified locations, preferably in comparative study. Crack pattern mapping is recommended for regular brick and stone masonry. Estimation of crack depth – possible in the case of cracks orthogonal to the surface and applicable only on single blocks.
GPR	**Moderately recommended**	Recommended implicitly if other methods failed. Should **not** be applied on sensitive plaster.
Hardness test	**Moderately - locally recommended**	As a complementary method. Should be applied in specified locations and in a comparative method. (samples from both damaged and healthy sources)
MDT	**Recommendation**	**Appliance**
Sampling, Moisture and salt anions content	**Highly recommended**	Sampling for comprehensive data acquisition. Sampling must be made in specified, possibly damaged locations with comparative samples. Must be documented strictly.
Boroscopy	**Moderately - locally recommended**	In the suspicion of external leaf detachment can be applied locally.

5.3 Mechanical Properties of the Masonry

5.3.1 Testing Compound

The recommended procedures for a survey of different types of urban masonry walls are presented in table 5.3:

Table 5. 3- Recommendations for mechanical diagnosis of an urban masonry wall

*Geometrical classification from Pinho, 2000

geometry	material	morphology	finish	visual	sonic	Hardness	coring	MS	FJ	DFJ	TJ
(1) Ashlar	granite	single leaf	plastered	■	■			■			
			none	■	■	■		■	■	■	■
		multi-leaf	plastered	■			■	■			
			none	■		■	■	■			
	limestone	single leaf	plastered	■	■			■			
			none	■	■	■		■	■	■	■
		multi-leaf	plastered	■			■	■			
			none	■		■	■	■			
(2) Cut stone	granite	single leaf	plastered	■	■			■			
			none	■	■	■		■	■	■	■
		multi-leaf	plastered	■			■	■			
			none	■		■	■	■			
	limestone	single leaf	plastered	■	■			■			
			none	■	■	■		■	■	■	■
		multi-leaf	plastered	■			■	■			
			none	■		■	■	■			
(3) Ordinary stone	granite	single leaf	plastered	■	■			■			
			none	■	■	■		■			■
		multi-leaf	plastered	■			■	■			
			none	■		■	■	■			
	limestone	single leaf	plastered	■	■			■			
			none	■	■	■		■			■
		multi-leaf	plastered	■			■	■			
			none	■		■	■	■			
(4) Mixed masonry	granite & brick	single leaf	plastered	■				■			
			none	■		■		■	■		■
		multi-leaf	plastered	■			■	■			
			none	■		■	■	■			
	limestone & brick	single leaf	plastered	■				■			
			none	■		■		■	■		■
		multi-leaf	plastered	■			■	■			
			none	■		■	■	■			

5.3.2 Recommended Tests

The evaluation of the parameters of resistant masonry is a complicated task, since it is a heterogeneous material having a broad range of properties due to assembly, composition of the mortars and relation between the different composite materials (Andrade, 2011). Thus, the recommended tests are oriented both to composite and single material scale. The tests recommended for the procedure are oriented for mechanical estimation, and their usefulness may vary according to the characteristics of the typology:

Visual inspection

Visual inspection is a fundamental stage in each type of diagnosis procedure. Visual inspection will allow the researcher to focus his efforts to an area of interest that may be representing of the entire structure, or on the contrary, seems to be an important spot for the investigation due to excessive loading or damage.

Hardness tests

Hardness testing with a Schmidt hammer is a very simple method to achieve immediate mechanical properties. These properties relate solely to superficial surface resistance, but can be a starting or reference measurement for further testing. As the walls are typically of single leaf morphology, in stone units that are not damaged, rebound results may be an indication for the resistance of the whole cross section. However, hardness tests are limited to providing individual element information and not of the masonry composite as a whole.

Application is limited on plastered walls as the rebound results correspond to the near surface material solely.

Coring

Coring can be a practical method for collecting data of inner leaves in multi leaf walls. In single leaf walls samples can be collected from surface and even micro-samples may be sufficient for crushing tests. In multi leaves, however, coring can be both a method to detect morphology and to extract distant samples for testing of mechanical properties. The properties provided by the tests are local and should be determined across the wall section in different places. Furthermore, it offers information on the elastic properties only of the single material. Reliable relationships between the behavior of the masonry components and those of wall are not established in the research (On site for masonry, 2005).

Particular attention should be directed to the sampling modality and quantity. The cores should be extracted in the direction of the load applied because the behavior of masonry is not isotropic. This can be a major limitation due to accessibility issues in multi leaf walls. Other restrictions yield from the fact that the method is locally destructive, and the sample is rarely allowed, and from the sampling process in which the stress decrease and the transportation phase often damage the sample itself.

Micro Sampling

Micro Sampling is another method that can provide mechanical properties of individual elements of the masonry, and not those of the composite material. In the case of single leaf walls it can be a very compensating method. Extraction of samples must be closely documented as results are local and should be mapped correctly on the masonry surface.

Single Flat-Jack

Single flat jack can provide quantitative information regarding the state of stress of the masonry as a composite material. The measurement is local and is related with jack dimension. In case of multiple leaves, the measurement is limited to the external leaves. The choice of the flat-jack dimensions and of the cut position should take into account the masonry texture dimensions and characteristics. For example, in the case of irregular stone wall the cut should preferably be carried out in the stones.

The method has several restrictions including its partial (minor) destructive nature and the fact that flat jack tests are not applicable on low stresses stone masonry if the cut is carried out on stiff stone elements, as the measurable released strain is of 20 μ# limited by the accuracy of the mechanical extensometer. Furthermore, the test does not give precise results on masonry subject to low stresses.

A previous control of the masonry by sonic test or other techniques is recommended. This would avoid carrying out the test in correspondence to unknown masonry defects or voids that could affect the reliability of the test. For a complete interpretation of test results, they should be compared to reference values obtained from more or less complex structural analysis (expected stresses) or material strength (for comparison of existing stresses). (On site for masonry, 2005)

Double Flat-Jack

The measurement is local being related to jack dimension. In case of multiple leaves, the measurement is limited to the external leaves. The dead load on top of the flat jack must equilibrate the induced state of stress.

The test is partially destructive. In case of rubble stone masonry walls, the stones must be cut. The choice of the cut position is very important. The test cannot be carried out when stresses on masonry are very low due to lack of contrast. Eventually only low stresses can be inducted in order to calculate the modulus. In laboratory some problem might occur because of the nonsufficient reaction of the testing frame or the use of unsuitable constraints. If double flat jacks are used to determine local elastic modulus (secant), it is necessary to multiply the modulus by a certain calibration coefficient. Its value depends on strength of mortar and height of masonry clamped between the two flat jacks. (Other influences come from the measurement itself and they are the geometry of flat jacks and the cut space for insertion of flat jacks.) In laboratory such coefficients are possible to obtain by calibration and comparative testing.

A preliminary control of the masonry by sonic test or other techniques is recommended. This would avoid carrying out the test in correspondence of unknown masonry defects or voids that could affect the reliability of the test. The main purpose of the method is its use in-situ; however the calibration coefficients have to be determined to obtain results comparable with standardized laboratory tests.

Tube-Jack

Tube-jack is a method currently under development which can be very efficient in the case of irregular masonry. The aim of the test is to achieve the same information as obtained in flat jack tests, with less morphology limitations. To drill the holes for the jacks, one can simply follow the path of the joints and make the desired holes in proper spots, regardless of straightness of the path. In other words, tube-jack testing is closer to a non-destructive state than the existing flat-jack method.

The method should be applied on single-layer, irregular walls. This comprises of a step forward from existing flat-jack, yet, nearly all historical buildings contain many multi-layer walls. In multi-leaf walls, the bed joints of different layers usually do not align. In performing a tube-jack test, the jack needs to penetrate horizontally through the entire thickness of the wall in order to prevent the introduction of any lateral pressure to the wall (Ramos et al., 2010).

Pulse Sonic Velocity Testing

In the field of mechanical properties surveying, sonic testing can be utilized as a complimentary method. As results of other, more specific tests as flat jacks can give varying results; sonic results can be an important addition of information and a validation. It is also necessary in the pre-testing stages to define the correct location for further tests. Sonic testing can provide qualitative indication of the density properties of the different areas. The resolution depends on masonry texture and on the test points' grid, (20 cm is the minimum). (On site for masonry, 2005)

Several studies including that of Riva in 1997 (Binda, 2014)have shown correlation between elastic modulus obtained from double flat jack tests and values of pulse sonic velocity measured in transparency in the same area, as can be seen in Figure 5.1:

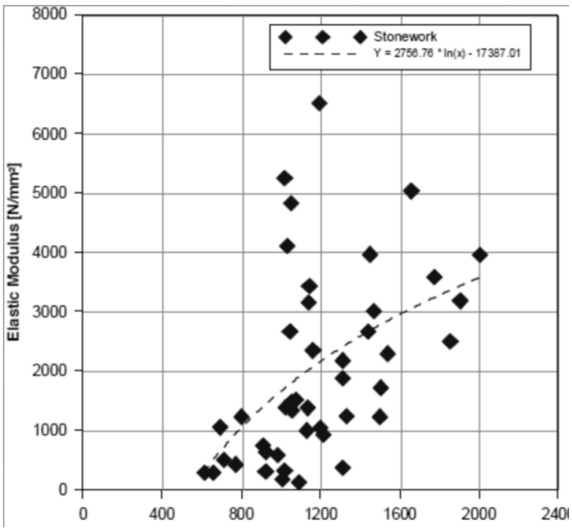

Figure 5. 1- Comparison between elastic modulus obtained from double flat jack tests and values of pulse sonic velocity measured in transparency in the same area in case of stonework.
(Adapted from: Binda, 2014)

Sonic testing cannot be applied on frescoes and historic mortar that is not in a solid condition, and thus cannot always be applied.

5.3.3 Implementation Example

Table 5.4 following, presents the recommendations for the inspection and diagnosis procedure of mechanical properties survey an urban single leaf granite masonry wall found in Porto. Additional implementation tables for the diagnosis procedures of other walls can be found in Annex 1.

Table 5. 4- Practical tool for mechanical diagnosis procedure of a Porto single leaf granite urban wall

*Geometrical classification from Pinho, 2000

MECHANICAL SURVEY		
Porto one leaf granite wall		
Visual Inspection	**Compulsory**	Search for areas of interest: ▪ Representing section ▪ "Special" section- damaged/ overloaded
NDT	**Recommendation**	**Appliance**
Sonic / ultrasonic	**Moderately recommended**	As a complementary method. Should be applied in same location as quantitative testing. (Flat Jack etc.)
Hardness test	**Moderately - locally recommended**	A very simple method to achieve validation of homogeneity of mechanical related properties of the near surface.
MDT	**Recommendation**	**Appliance**
Coring	**Not recommended**	Not recommended in single leaf walls, only for the purpose of cylindrical sample testing.
Micro sampling	**Highly recommended**	Destructive tests for compression, tension and bending can be conducted and results can be obtained in situ. Allows finding resistance of the stone or mortar units and not the state of stress or modulus of elasticity of the masonry as a composite material.
Flat Jack	**Moderately recommended**	Local results can be obtained. Location of test to be determined by sonic testing and preferably within a stone unit.
Double flat jack	**Moderately recommended**	Local results can be obtained. Location of test to be determined by sonic testing and preferably within stone units. Results should be correlated and compared to standardized lab results.
Tube jack	**Highly recommended**	As the masonry is normally irregular and consists of one leaf, the tube jack can be a good appliance for measurement of local state of stress. General configuration of the tubes can derive from natural joint texture and correlated.

5.3.4 Expected Results- Reference Values

The following Table 5.5 presents values of the resistant characteristics of masonry walls of irregular stone obtained by Flat Jack and Double flat jack tests in different studies in Portugal and Europe. These can provide a general expected result of the diagnosis, although it is important to note that these results do not show a direct correlation between them and should be interpreted only according to the building where they were performed. However, they are relative results to the value of the stress, modulus of elasticity and the value of disruption of irregular stone masonry walls.

The values are presented in the table, referring also to the bibliographic reference where they were obtained, the location of buildings, the number of tests conducted, the type of masonry and the number of floors.

Table 5. 5- Results of other studies performed in stone masonry walls

(Adapted from: Andrade, 2011)

Location	Lisbon	Tentúgal	Bragança	P.Delgada	Porto	Ljubljana
authors	Manning, Ramos (2010)	Pagaimo, Lourenço	Roque, Lourenço	Mesquita, Lança	Guedes, Miranda	Tomazevic
Number of trials	3 single 5 double	2 single 8 double	3 single 3 double	3 single 3 double	1 single 1 double	-
No. Floors	2	2	2	2	3	-
Type masonry stone	Composite- brick and stone	limestone	shale	basalt	granite	limestone
State of Stress [MPa]	0,05 - 0,2	0,08 - 0,15	0,08 - 0,13	0,02 - 0,09	0,4 - 0,7	-
Min E [GPa]	-	0,21	0,8	-	-	
Max E [GPa]	1,3	0,38	1,2	-	-	
Module deformability [GPa]	-	0,3	1,0	-	1,0	2,6
Min tensile strength [MPa]	-	0,65	0,60	0,48	-	
Max tensile strength [MPa]	-	0,74	0,80	0,96	-	
Tensile strength [MPa]	-	0,7	0,7	0,7	0,7	0,8

In the cases described, the stress state of the masonry varies considerably and may have values between 0.08 and 0.7 MPa. The modulus of elasticity also shows variation, with values between 0.3 and 2.6 GPa In relation to the rupture of masonry. Stress value of 0.7 MPa is identified in four studies, changing only the last study 0.1 MPa (0.08 MPa). The values presented were taken from other studies show no descriptions of each case, with the necessary bibliographic said to be able to make a coherent critical assessment of results.

5.4 Morphology and Geometry Detection

The shear walls of housing typologies in Portugal cities are as described generally single leaved. Nevertheless, other morphologies are common in the urban centers in facade walls as well as in monuments.

5.4.1 Testing Compound

Table 5.6 presents the recommended procedures for geometry and morphology survey of an urban masonry wall.

Table 5. 6- Recommendations for morphology detection of an urban masonry wall

*Geometrical classification from Pinho, 2000

geometry	material	morphology	finish	visual	sonic	Infra	GPR	Boro	coring
(1) Ashlar	granite	single leaf	plastered						
			none						
		multi-leaf	plastered						
			none						
	limestone	single leaf	plastered						
			none						
		multi-leaf	plastered						
			none						
(2) Cut stone	granite	single leaf	plastered						
			none						
		multi-leaf	plastered						
			none						
	limestone	single leaf	plastered						
			none						
		multi-leaf	plastered						
			none						
(3) Ordinary stone	granite	single leaf	plastered						
			none						
		multi-leaf	plastered						
			none						
	limestone	single leaf	plastered						
			none						
		multi-leaf	plastered						
			none						
(4) Mixed masonry	granite & brick	single leaf	plastered						
			none						
		multi-leaf	plastered						
			none						
	limestone & brick	single leaf	plastered						
			none						
		multi-leaf	plastered						
			none						

5.4.2 Recommended Tests

Visual inspection

Visual inspection in the case of morphology detection is naturally in the mantle, as its purpose is namely detection of correct positions for more invading tests and inspections. The method can also be used for local visual inspection after dismantling, yet the number and the positions of the inspection should be accurately chosen being locally destructive.

Sonic Transmission

Sonic transmission can be quite proficient in detecting multiple leaves in masonry wall. However, it was found to be mostly efficient when the external leaves are of regular stones and the internal is weak rubble. The test by transmission can seldom recognize the presence of 2 leaves and presence of detachments could only be supposed by low velocity and should be confirmed by other tests. This is namely because the method can fail when there are no elastic property variations between the leaves. In any case, a calibration procedure and a direct control are recommended.

The test offers a resolution from 20 to 70 cm deep depending on velocity and size of the masonry structure and is not very accurate for smaller structural elements. Besides that, use is restricted on delicate surfaces, as the testing itself may be harmful for them.

GPR

GPR allows exploring large thicknesses of walls, up to 1.5 m. Indication on the presence and dimension of leaves with a resolution of 5 cm (in reflection) and a resolution from 10 to 40 cm (in tomography) is possible, depending on radar frequency and size of the masonry structure. The use of a steel plate opposite the antenna is recommended in order to find wall thickness.

The method is quite expensive and complex to execute and interpretation, and is thus recommended mostly in cases of large sections where other detection methods are not sufficient. Possible failure can occur when moisture or salt content is high or when there is multiple scattering from inhomogeneous materials. Thus, Limits are given by very high moisture and salt contents as well as by very inhomogeneous structures. Interpretation is particularly difficult in case of leaves made with the same materials, as there may be no electrical property variations between the leaves. Another limitation of use can be on delicate or high value plaster, as the antenna can leave linear marks on the tested surface.

A calibration procedure and a direct control are recommended, and the elaboration procedure should be very accurate and done by experts.

Coring

Although its destructive nature, coring can be a practical method for collecting morphological data. Cores of various diameters can be extracted (average size 40 mm) from masonry depth up to 1m. The core, which is extracted as one continuous element can provide us with information about number of leaves, their depth and their material properties. It is useful mostly for diagnosis of multi leaf walls. After careful measuring and documenting the core can be used for further tests, as chemical analysis of the sample and others.

Limitations of the application can be found in the fact that the procedure is executed with water, which can be difficult to carry out in the populated urban environment. Other disadvantages are the destructive nature of the test as well o as the locality of results.

Boroscopy

Boroscopy can provide us with some visual data regarding morphology. In deeper wall sections (those which are usually the target of inspection) it may not be very efficient as it is limited in length. Nevertheless, it is widely recommended in order to control the extension of the results of other tests or to validate them. Limitations of the method include its minor destructive nature, and the fact it can be conducted solely on regular masonry walls. Furthermore, obtained image can be hard to understand and may lead to wrong conclusions if not interpreted by an expert.

Infrared Thermography

Infrared is a very useful technique for complementing other methods by providing information in the shallow depth, whilst some techniques give information at a higher depth. In the case of mixed masonry systems (which can be mixed stones, mixed stone and brick, mixed stone and timber etc.) it can be especially compensating, allowing to detect pattern and placement of the different materials. In combination with numerical simulation, estimation of the thickness of plaster can also be detected.

For correct execution surface should have uniform roughness, which is quite common in plastered surfaces. The executions requires energy flow, and thus, this method is not applicable everywhere, and must be done at precise moments of the day.

5.4.3 Implementation Example

Table 5.7 following, presents the recommendations for the inspection and diagnosis procedure of morphological survey an urban single leaf mixed masonry wall typically found in Lisbon. Additional tables for the diagnosis procedures of other typology walls can be found in Annex 1.

Table 5. 7- Practical tool for morphologic diagnosis of a Lisbon single leaf mixed masonry urban wall

MORPHOLOGY SURVEY		
Single leaf mixed masonry wall- Lisbon		
Visual Inspection	Compulsory	▪ Positioning further testing ▪ Local inspection after dismantling
NDT	**Recommendation**	**Appliance**
Sonic / ultrasonic transmission	**Moderately recommended**	Can provide evidence on wall thickness. Generally more efficient in multi leaf walls. If practiced, location should be verified in regards to material.
Infrared thermography	**Highly recommended**	Detection of mixed system characteristics and layout. The method is very superficial and will provide only shallow information. In-depth analysis will demand other, complimentary techniques. Should be applied in an un-windy environment
GPR	**Moderately recommended**	Should be approached implicitly, if other methods are not satisfactory or possible (as boroscopy or coring) Should be applied on undamaged plaster. The use of a steel plate opposite the antenna is recommended in order to find wall thickness.
MDT	**Recommendation**	**Appliance**
Coring	**Moderately recommended**	If no information is available as for the type of masonry and timber, coring can be a sampling method for detection. Location must be chosen after preliminary information is gathered of the location of the different composite materials. Furthermore, it can provide info regarding the assembly of the masonry units, one or 2 leaves.
Boroscopy	**Highly recommended**	Can provide evidence on wall thickness. Generally more efficient in multi leaf walls.

5.5 Conclusions

The case of urban walls provides a large range of typologies, varying in both morphology, thickness, geometry and others. Generally, it can be considered a case of medium size wall sections, taking housing masonry walls as a common case study. They are similar in the relatively dense environment as well as in building techniques and architectural typology. Furthermore, they have a repeating nature that can be a great advantage to their proper assessment. The field of the inspection and diagnosis of historical urban structures can be characterized by:

(i) Previous studies of these typologies are available and can be an important tool for expecting and verifying results.

(ii) Typical damages retreat and can be anticipated, which can make inspection procedures more efficient with the proper prior preparation.

(iii) A step by step approach should be practiced in designing the diagnosis procedure, exhausting simple methods that are expected to be efficient before turning to others.

(iv) Geometry (regularity) of the masonry should be carefully taken into account in planning the diagnosis procedure, as it raises limitations to almost every testing technique.

(v) Information of studies should be collected and published in the municipal level to create a database of relatable cases to future works.

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6. METHODOLOGY FOR DIAGNOSIS OF MILITARY TYPOLOGIES

6.1 General Methodology Recommendations

Military typologies are fundamentally different from the prior typologies presented. They are monolithic, large scale structures, occupying vast areas of land and often not only of public interest but also of public use. This places them in a different position in the cultural arena and its resources. Their preservation is commonly a matter of public action and even political power, and the resources invested in them are accordingly high, both in funds and in expertise practice.

However, the differences in funding and exposure are not the only major dissimilarities found in the military structures compared with the urban or rural structures. The size of the structure and its proportions frequently sentences the difficulty and the problem needed to be diagnosed. The diagnosis issues generally include:

(i) Geometric survey and documentation of the large scale walls;

(ii) Study of the unknown morphology of the masonry walls;

(iii) Damage survey;

(iv) Mechanical properties inquiry in a specific location.

All questions may relate to the wide scale of the whole structure, or in later inspections, to precise locations that were highlighted for further study. A suitable methodology should combine global and local assessment tools available to create an efficient scheme of action. The relation between the global and local tests conducted, as well as the correct locations should be carefully studied and adjusted. The typology of military structures includes many types of masonry walls and details, from retaining walls to towers, gates, openings etc. Their common property is their massive sections.

Generally, many of the military structures were built with good quality materials and workmanship, and thus exhibit less deterioration than lower quality structures. Nonetheless, damage processes can occur, initiating mainly from the deterioration of materials due to weathering, and in phenomena related to retaining walls such as moisture and cracking due to roots in the supported soil. These can of course be considered as a starting point for the diagnosis.

Visual inspection

In large scale structures, as the military typology, visual inspection has to be accompanied by a very thorough documentation system. There must be an overall view of the procedures occurring for the diagnosis works, as in many cases they can happen in parallel times, and by different researchers. The expertise works must be managed and coordinated in the full structure scale, and information should be transferred between all working teams involved in the project. This is true for all parts of the works, but is especially important for the visual inspections which can give an overall assessment of the state of the structure, and to outline policy regarding the following steps of the works, in all fields of diagnosis; mechanical, damage, morphological etc.

6.2 Geometric-Morphologic Survey and Documentation

Usually a global task, geometric survey of these large structures is a tremendlusly important yet tedious task, that can be made more efficient if planned wisely. Generally, although the object for inspection is great in size, it is highly recommended to execute several techniques in superposed locations in order to be able to base the analysis on complimentary results and to validate the information gathered. This can be true for all sizes of buildings but is accentuated in those of large scale (Binda et al., 2004).

6.2.1 Testing Compound

Table 6. 1- Recommendations for geometric-morphologic survey of military wall

geometry	material	morphology	finish	visual	GS	laser	Sonic	infrared	GPR	Boro
Ashlar	granite	retaining wall	none							
		standing wall	none							
	limestone	retaining wall	plastered							
			none							
		standing wall	plastered							
			none							
Cut stone	granite	retaining wall	none							
		standing wall	none							
	limestone	retaining wall	plastered							
			none							
		standing wall	plastered							
			none							

6.2.2 Recommended Tests

Geometric Survey Techniques

Several manual techniques are available for the task of geometric or textural survey. The collection of this data can be essential for the correct understanding of building logic of the structure. This achievement enables the erection of more exact 3D simulation models to analyze building behavior.

As the expected dimensions of the structure are very large, manual tools can and should be used mostly for local works, specific places marked by visual inspection to be further examined. Laser meters can be efficient for initial and rough estimations of proportions and element dimensions. Photogrammetric survey can be resourceful as well, allowing recognition of stone patterns, element sizes and proportions as well as perceptive on stone/mortar relations, joint patterns and thickness.

Obtaining results involves the task of in site documentation by means of photography or hand drawing, then manually transferring the data into engineering drawings.

For the detection of morphology, local dismantling can be considered in discrete and sheltered locations, for in-depth measurements. This can achieve solely local indications. Some sites may require several morphology detection procedures, as the typology is often characterized by the existence of several types of walls (Casella, 2003). Although possible, several non destructive techniques can be practiced before turning to this destructive measure.

Infrared Thermography

The technique can be used as a complimentary method for photogrammetric stone texture survey for plastered walls. Scientific methodologies are nowadays being developed in several studies conducted in Jordan, Spain, Turkey and others (Yastikli et al., 2013)(Cabrelles et al., 2009).

3D Laser Scanning

The state of the art technology of 3D laser measuring allows obtaining almost instant digital findings of bare geometry. Results can be obtained from both 3D and 2D spheres, from general mass and space dimensioning to wall texture survey. This information can be used for creation of structural models for 3D analysis and for structural monitoring, which can also be obliging in the field of damage survey.

As a laser scanner experiences difficulty to work at buildings placed in dense areas without appropriate station-locations, military structures are very convenient objects for scanning. Moreover, the large-scale open environment is appropriate for avoiding obstruction problems and reducing the number of scanning stations. As these structures tend to have high dimensions, mobile lifts are available for the scanning units, if properly monitored and controlled both in terms of location and vibration avoidance (Cheng, 2012).

The technique can also be used for a virtual reconstruction of in ruin monuments, or moreover, to protect loss of heritage knowledge due to natural disasters, such as earthquake, fire and accident collapse by early recordings.

GPR

The specificities of the military construction make the GPR particularly well suited. The thickness of the walls, the limitation of one-sided accessibility in retaining walls, as well as the massive proportion of elements allows maximizing the abilities of this method, designed for similar conditions (Underground survey). Available antennas with frequencies of 800 and 500 MHz can be compatible for survey. 500 MHz should be used in solely in very massive sections, as its resolution is lower.

With GPR scanning diverse information can be reached regarding morphologic layers, wall thickness, element and joint shapes, as well as the presence of voids and inclusions. In the case of military structures, especially retaining walls, the task of morphology assessment is particularly intricate, and GPR profiling can allow finding concealed elements and information without damaging the wall.

Vertical profiles are carried out by lowering the antenna down the external face of the retaining wall. Horizontal profiles are useful for identifying lateral changes in thickness, particularly if a buttress type construction is suspected, and for defining the extent of a large defect. The interpreted data is used to construct elevations and sections of the wall's internal construction.

Sonic Transmission

Direct sonic testing can also be used for obtaining data of morphologic properties of standing walls, but they are limited as double sided access is often not reachable, and the execution of opposite side measurements can be hard to coordinate. If only indirect testing can be preformed, morphologic information can be gathered in relation to joints and near surface changes in sections, as in the case of cut stone geometry where regularity is formed only on surface with irregular body of stones.

Impact Echo

In both standing and retaining walls, impact echo can be a very efficient method for the detection of section width or interior information of the wall. As access is required only for one side of the wall, the technique can be very efficient. Gathered information can give light on both general dimensions of the wall, as well as its interior layering. Multiple peaks in frequency domain can point to the inner structure of the wall, reflecting back to the transmitter.

Boroscopy

Please see recommendations in Chapter 5.4- Recommended tests for the geometric morphologic survey of urban typology walls.

6.2.3 Implementation Example

Table 6.2 following, presents the recommendations for the inspection and diagnosis procedure of morphological survey of a non- plastered granite fortress standing wall. Additional tables for the diagnosis procedures of other typology walls can be found in annex 1.

Table 6. 2- Practical tool for morphologic diagnosis procedure of a granite cut stone military wall

GEOMETRY MORPHOLOGY SURVEY		
Granite Fortress Standing Wall (not plastered)		
Visual Inspection	**Compulsory**	▪ Positioning further testing ▪ Local inspection after dismantling ▪ Complimentary as reference material for localizing executed tests
NDT	**Recommendation**	**Appliance**
Laser Scanning	**Highly recommended**	Recommended for superficial and not for thickness or in depth survey. Information can be used for creation of structural models for 3D analysis and for structural monitoring, which can also be obliging in the field of damage survey.
Sonic / ultrasonic transmission	**Highly recommended**	Direct application- strongly recommended if applicable Indirect application- solely for near surface info.
Infrared thermography	**Not Recommended**	Not necessary in non plastered structures.
GPR	**Highly recommended**	Horizontal and vertical profiles should be taken, in sequential order. It is recommended to locate profiles within the courses of the stone for better contact with scanning unit. For very high thicknesses a 500 MHZ antenna can be used.
MDT	**Recommendation**	**Appliance**
Boroscopy	**Moderately recommended**	Preferably applied in existing boreholes or empty mortar joints. Otherwise, can be applied in mortar joints or, as a last resort, by drilling within the stone elements.

6.3 Damage Survey

6.3.1 Testing Compound

The recommended compound of testing techniques for a damage survey of a military type wall is presented in Table 6.3.

Table 6. 3- Recommendations for damage survey of a military masonry wall

geometry	material	morphology	finish	visual	Laser	sonic	infrared	GPR	Hardness	MS	MC	Salts
Ashlar	granite	retaining wall	none									
		standing wall	none									
	limestone	retaining wall	plastered									
			none									
		standing wall	plastered									
			none									
Cut stone	granite	retaining wall	none									
		standing wall	none									
	limestone	retaining wall	plastered									
			none									
		standing wall	plastered									
			none									

6.3.2 Recommended Tests

Visual inspection

Visual inspection should be conducted in a number of planned sessions due to large size of the architectural object. If so, the campaign must be planned before execution and standardized to all structure parts. Typical damages as moisture problems or localized crack patterns in retaining walls should be anticipated.

GPR

GPR can contribute to damage surveying in the identification of hidden crack patterns or voids in the masonry. The method's abilities can be detection of main fractures by reflection, mapping of areas affected by diffused cracks by reflection or by attenuation tomography (possible only if access is possible from at least two sides of the wall) with a resolution from 10 to 40 cm, depending on radar frequency and size of the masonry structure (On site for masonry, 2005). High or low resolution antennas can be used, for near surface or in-depth analysis accordingly.

Laser Scanning

Long term damage surveying can be obtained advantageously with utilization of laser scanning techniques. Heritage structures can be irreversibly damaged by environmental disasters or by ongoing atmospheric damages. Those damages are sometimes discovered too late. High accuracy 3D scanning, at usual times, could detect deformations and crack propagation, and initiate proper interventions in time to prevent escalation. Digital archives of scanned heritage structures can be employed as reference for monitoring of the structures and to the art of restoration of cultural heritages in general (Pieraccini et al., 2001).

Additional Methods- Sampling, moisture content and salt presence testing, Hardness tests, Infrared Thermography, Boroscopy, Sonic Transmission

Please see recommendations in Chapter 5.2- Recommended tests for the damage survey of urban typology walls.

6.3.3 Implementation Example

Table 6.4 presents the recommendations for the inspection and diagnosis procedure of damage survey of a military limestone retaining wall. Additional tables for the diagnosis procedures of other typology walls can be found in Annex 1.

Table 6. 4- Practical tool for damage diagnosis procedure of a limestone retaining military wall

DAMAGE SURVEY		
Limestone Plastered Retaining Wall		
Visual Inspection	**Compulsory**	Search for typical damages: ▪ Moisture and leakage ▪ Local crack patterns due to root loads ▪ Overloading
NDT	**Recommendation**	**Appliance**
Infrared thermography	**Highly recommended**	For hidden crack patterns, inclusions and moisture detection. Should be done in early stages in order to guide further testing efforts as sampling, sonic and others.
Sonic / ultrasonic transmission	**Not recommended**	Not recommended for plastered retaining walls, as indirect tests will only detect condition of the plaster. Can be applied if plaster is locally removed.
GPR	**Highly recommended**	For detection of voids and inclusions. High or low resolution antennas can be used, for near surface or in-depth analysis accordingly.
Laser Scanning	**Highly recommended**	For long term monitoring of damage as well as database creation for the case of destruction due to natural disasters.
Hardness test	**Not recommended**	Not recommended for plastered walls, results will only detect condition of the plaster. Can be applied if plaster is locally removed.
MDT	**Recommendation**	**Appliance**
Sampling, Moisture and salt anions content	**Highly recommended**	Sampling for comprehensive data acquisition. Sampling must be made in specified, possibly damaged locations with comparative samples. Must be documented strictly.
Boroscopy	**Moderately - locally recommended**	In the suspicion of external leaf detachment can be applied locally.

6.4 Mechanical Properties of the Masonry

6.4.1 Testing Compound

Table 6.5 presents the recommended testing procedures for survey of mechanical properties of masonry military walls.

Table 6. 5- Recommendations for the diagnosis of mechanical properties of a military masonry wall

geometry	material	morphology	finish	visual	sonic	Hardness	coring	MS	FJ	DFJ	TJ
Ashlar	granite	retaining wall	none								
		standing wall	none								
	limestone	retaining wall	plastered								
			none								
		standing wall	plastered								
			none								
Cut stone	granite	retaining wall	none								
		standing wall	none								
	limestone	retaining wall	plastered								
			none								
		standing wall	plastered								
			none								

6.4.2 Recommended Tests

Single Flat-Jack, Double-Flat Jack, Tube-Jack

In the case of military structures, a jack test, in both single, double and tube appliance, can only provide information regarding the exterior leaf of the wall. Even in the case of single leaf "thick wall" the section is composed of multiple layers of stones and sectional results cannot be obtained. Useful information can be achieved regarding external leaves individually. As military installations are, at times, constituted by stone external leaf and large infill with earth, the two leaves do not connect. Therefore, this possibility could be very effective.

For entire section segments, estimations of the state of stress, attained from single or tube jack tests, and elastic properties, attained by the double jack, should be collected by means of other techniques.

For application recommendations of these methods for the external leaf, please see Chapter 5.3.2.

Sonic Transmission

An alternative method for attaining mechanical properties of the masonry as a composite material can be found in sonic transmission. Velocity results of both direct and indirect appliance can be a base for calculation of the Elastic Modulus. According to the British Standard, it is possible to calculate the dynamic modulus of elasticity of an elastic, isotropic material of infinite dimensions by relationship between elastic properties and the speed of ultrasonic waves. The expression 6.1 represents this relationship.

$$V_P = \sqrt{\frac{E_d}{\rho} * \frac{(1-\nu}{(1+\nu)*(1-2\nu)}}$$

Where V_p is the P-wave velocity [m/sec], E_d is the dynamic modulus of elasticity [GPa], the ρ is material density in [kg/m^3], and ν Poisson's ratio. This expression is generally used for isotropic materials, is not completly suitable for masonry. However, when applied only to stones units, results are not as divergent (Guimarães, 2009). Even so, inaccuracy of the results should be taken into account. In the case of indirect sonic testing, R waves (V_R) are detected, and these should be correlated to P-wave measures prior to calculating the dynamic Modulus.

Additional Tests- Hardness tests, Coring, Micro Sampling

Please see Chapter 5.3.2 for recommendations for these methods.

6.4.3 Implementation Example

Table 6.6 presents the recommendations for the inspection and diagnosis procedure of mechanical properties survey of a thick wall granite standing military wall. Additional implementation tables for the diagnosis procedures of other walls can be found in Annex 1.

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MECHANICAL SURVEY		
Thick-wall Granite Standing Wall		
Visual Inspection	**Compulsory**	Search for areas of interest: ▪ Representing section ▪ "Special" section- damaged/ overloaded
NDT	**Recommendation**	**Appliance**
Sonic / ultrasonic	**Highly recommended**	Results for elastic properties can be achieved with direct and indirect applications. Method is not fully compatible for masonry and inaccuracy of the results should be taken into account.
Hardness test	**Moderately - locally recommended**	A very simple method to achieve validation of homogeneity of mechanical related properties of the near surface.
MDT	**Recommendation**	**Appliance**
Coring	**Moderately recommended**	Sampling should be done in the direction of the loading, and standardized dimensions must be considered.
Micro sampling	**Highly recommended**	Destructive tests for compression, tension and bending can be conducted and results can be obtained in situ. Allows finding resistance of the stone or mortar units and not the state of stress or modulus of elasticity of the masonry as a composite material.
Flat Jack	**Moderately recommended**	Results obtained solely for single leaf. Cannot be applied on whole wall section, yet can achieve individual indications for external leaves.
Double flat jack	**Moderately recommended**	Results obtained solely for single leaf. Cannot be applied on whole wall section, yet can achieve individual indications for external leaves.
Tube jack	**Moderately recommended**	Results obtained solely for single leaf. Cannot be applied on whole wall section, yet can achieve individual indications for external leaves.

6.5 Conclusions

Military wall typologies challenge the researcher and designer with the aspect of size. In both structural and sectional scales, size presents a major factor. Massive sections and wide-spreading of the structure impose many limitations and demand creative solutions to be thought out:

(i) Standing and retaining walls are very different in character, and should be approached differently, although part of the same structure.

(ii) Surveying must be done in several locations, and different quality of masonry can be expected within a single monument;

(iii) Mechanical characteristic survey is almost impossible to attain in the sectional-composite scale, as jack tests are not compatible for multi leaf walls. Studies can either be done for single elements, or with methods that may not provide accurate results;

(iv) Typical damages of these constructions can be anticipated, due to similar conditions of walls and layouts. This can be advantageous for attaining high affectivity in the inspection procedures;

(v) Documentation of the structures, including their geometry, morphology, testing results etc. can be advantageous for both short term management and long term monitoring. It should be widely recommended and executed in all campaigns.

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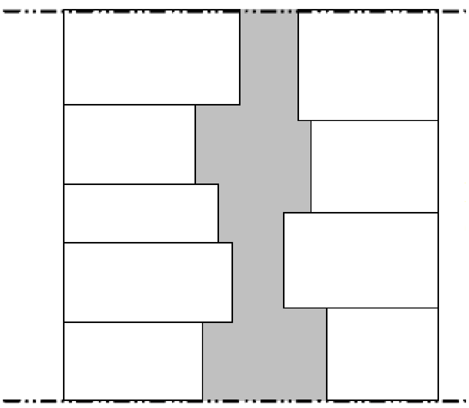
7. VALIDATION OF THE METHODOLOGY- GUIMARÃES CASTLE

A non-destructive testing campaign was held the Castle of Guimarães to complement the study of methodology for inspection and diagnosis of military constructions. This chapter will present the results of the nondestructive campaign that was conducted in several parts of the structure in July 2014, and diagnosis based on that information. The testing compound included direct and indirect sonic transmission, impact echo and GPR scanning. The chapter is organized in five sections, with the following designations and content: methodology plan, description of locations of campaigns and their geometrical properties, results of testing of the tower wall, results of testing in the battlement wall, diagnosis and conclusions.

7.1 Methodology Planning

In order to assess the morphology of the granite walls, without compromising their physical integrity, several techniques were considered. A former study of the castle, carried out in the upper part of the Alcáçova wall (the northern battlement wall), found a supposed 3 leaved morphology by means of boroscopy and sonic transmissions (see Figure 7.1). Most data collected was related to thickness of the exterior leaves, which was estimated to be 0.3-0.4 meters. However, in a visual survey conducted as a preliminary step of the present campaign, it was evident that the former tested area was not necessarily constructed in the same manner of the chosen locations for the current study. The upper part of the wall, tested before, is different in width as well as exhibits singular architectural elements (windows etc.); this can be seen in Figure 7.2. More information regarding the testing locations of the current study will follow.



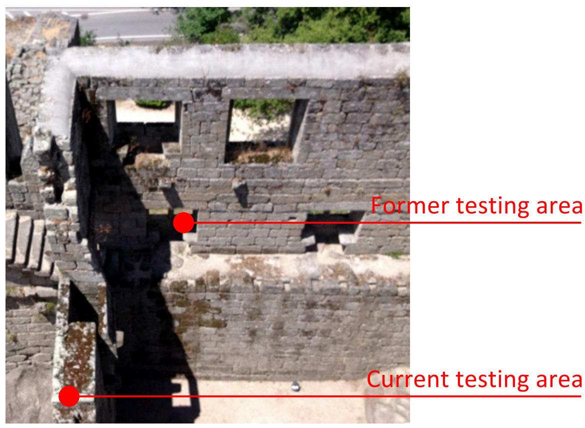


Figure 7. 1- Estimated morphology from former study. Figure 7. 2- Locations of former and current campaigns

(Adapted from: Moreira, 2010)

The site conditions were classified according to the methodology suggested in the previous chapter and was recognized as:

The testing compound deriving from the given information, prescribes a visual and geometrical survey, GPR scanning, sonic testing, impact echo and boroscopy. All these tests were conducted, excluding boroscopy, for the lack of available expert personnel.

7.2 Tested Locations

The Castle of Guimarães, as is visible in Figure 7.3, consists of a Central Watchtower which is surrounded by eight lateral towers connected by a battlement. The locations chosen for the testing process were the southern wall of the central tower, tested from the interior by GPR and indirect sonic transmission, and an interior battlement wall which allowed direct sonic testing, as well as GPR scanning and Impact Echo reflection.

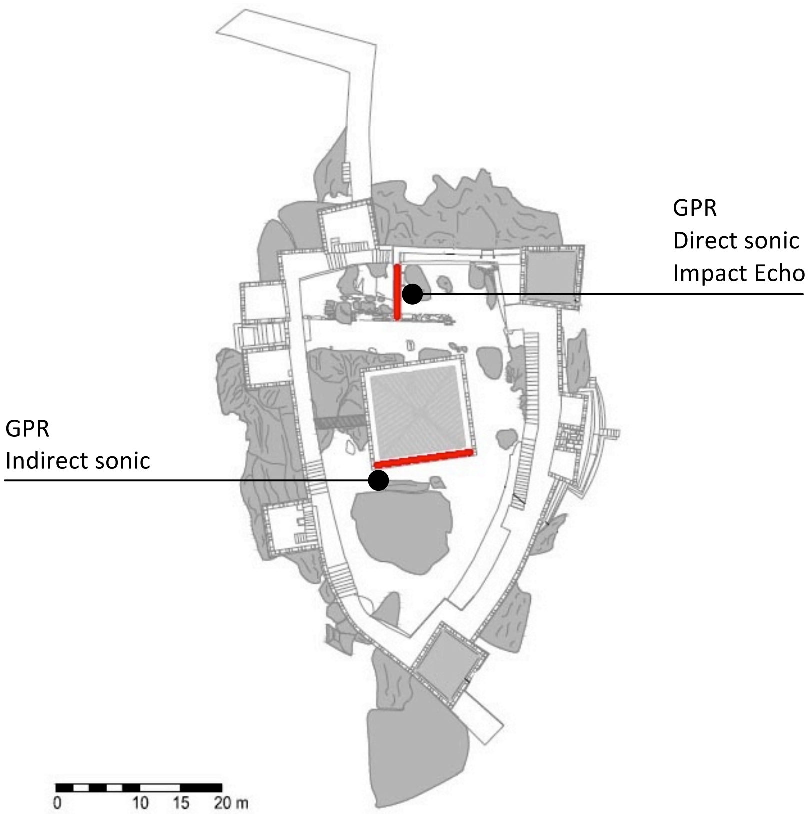


Figure 7. 3- Plan of Guimarães Castle, with marked locations of conducted campaigns

(Adapted from: Moreira, 2010)

7.2.1 Battlement Wall

The first wall to be tested was an interior battlement wall with an apparent thickness of 0.93 m (see Figure 7.4). The wall is composed of ashlar granite stones assembled in continuous horizontal courses of different heights. Its position allowed carrying out direct sonic tests which were preferable for the case of morphology detection. Figure 7.5 presents the testing areas in the wall. The aim of the campaign was to learn more of its internal structure. Testing plan included direct sonic transmission and impact echo reflection testing, as well as GPR scanning.

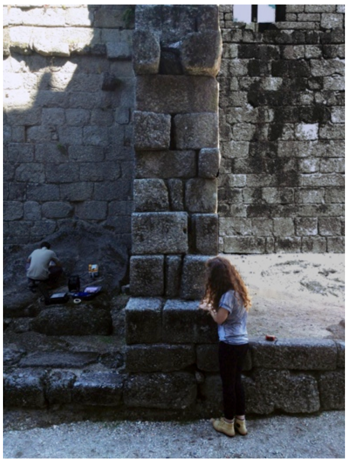


Figure 7. 4- Apparent section of the wall. Figure 7. 5- General layout of the tested wall (GPR profiles in with, sonic tested area in red)

7.2.2 Central Tower South Wall

As can be seen in Figure7.6 the wall exhibits ashlar granite stone units with thin mortar joints. The stone units share a recurring height of 40 cm, and have regular horizontal joints and irregular vertical joints. As it is perforated by windows its depth can be measured, and is approximately 1.80m. Testing plan included horizontal and vertical profiles tested both by indirect sonic transmission and for GPR scan.

Figure 7. 6- Geometric characteristics of the inspected wall

7.3 Battlement Wall Results

7.3.1 Reference Stone Sonic Transmission

As part of the preliminary study, direct sonic tests were performed on a single granite stone from the masonry wall. The dimensions of the stone are: length- 0.75m, width- 0.61m, height- 0.45m, demonstrated in Figures 7.7 and 7.8. The available dimension for the direct transmission was the width.

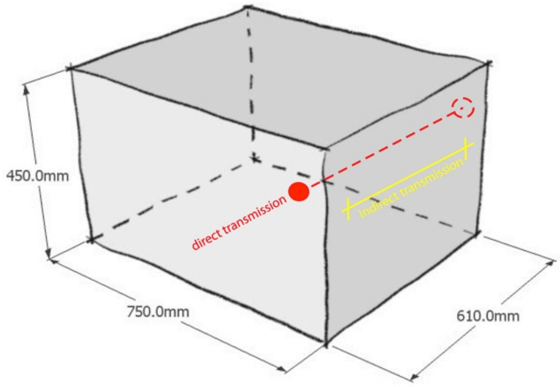


Figure 7. 7- Sketch of tested reference stone. Figure 7. 8- Picture of tested reference stone

Results

Ten measurements were acquired in the designated position to obtain an average value. The average value obtained was 2748.7 m/sec, with standard deviation of 199 and a variation coefficient of 7.2%. The measured velocity is within the range of expected velocity in historic stone (Madeira, 2010).

Indirect transmission was also obtained on the reachable surface. The average value obtained was 1557 m/sec, with standard deviation of 219 and a variation coefficient of 14%.

This data will be used as reference value in further testing operations.

7.3.2 Ground Penetration Radar

Three horizontal profiles were taken, carried out along the main axis of units, and one vertical radargram. These radargrams are illustrated in the following figures. Both execution and interpretation of the results were done with the help of Professor Francisco Fernandes.

Error! Reference source not found. illustrates the horizontal radargram obtained from the 4th row. This radargram gives significant information relatively to geometry and constitution of the wall. The hyperbolas from the surface are caused by the vertical joints between units. These signals are followed by a few others, around 0.3-0.4 m deeper, which indicate the thickness of the first layer of stone. It is not continuous along the scan, evident to the irregularity of this layer. After this signal, in parts of the radargram, only the signal from the opposite side appears while, in other parts, additional signals appear in-between. These additional signals are related to joints between units, confirming what was observed from the apparent section in the destroyed element, that the cross section of this wall is constituted by single crossing stones, as well as two and three layers of stones, in an apparently, random manner.

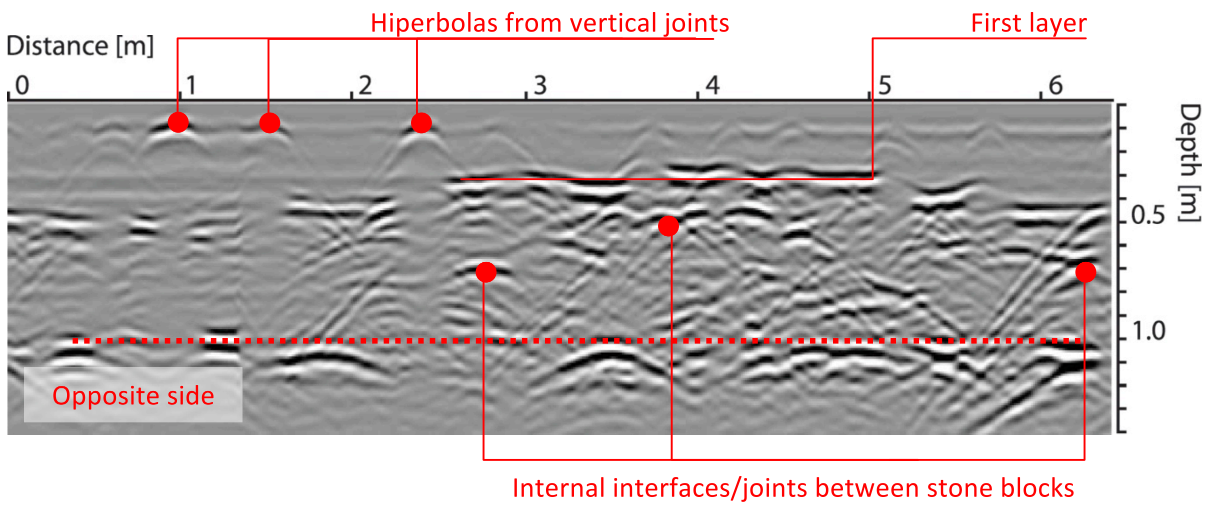


Figure 7. 9- Horizontal radargram from 4th row of battlement wall

The additional horizontal profiles that were obtained from the 5th and 6th rows of the wall showed similar results, which did point to a distinguished morphology, yet further indicated of a non-uniform section. In the vertical profile collected, illustrated in Figure 7.10, the inner structure can further be observed. A first layer is evident, with a rather irregular thickness, an inner layer, which apparently is larger than the first layer, and the opposite side. The irregularity of the leaves can suggests a certain interconnection of the units to provide stiffness to the section.

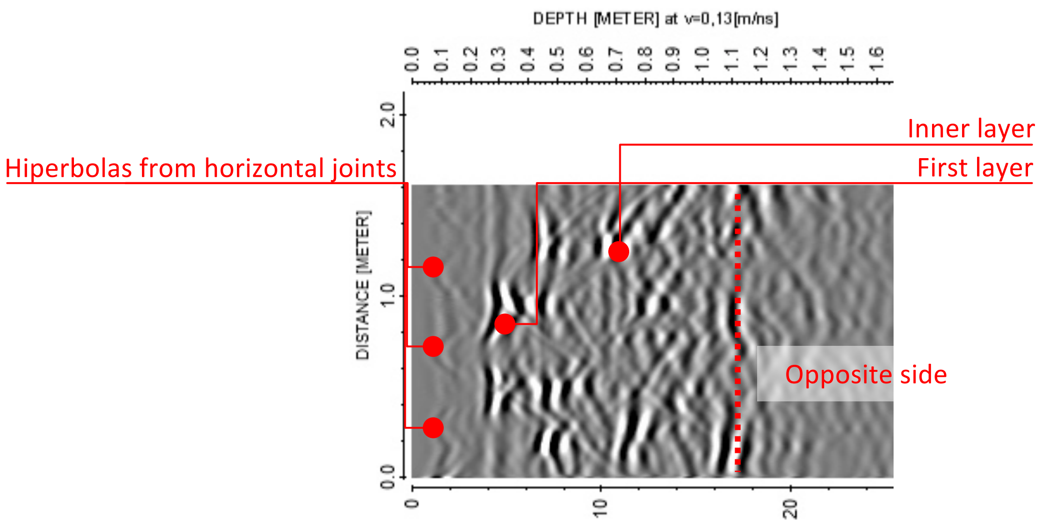


Figure 7. 10- Vertical radargram from battlement wall

7.3.3 Direct Sonic Transmission

The direct sonic test was carried out on a prescribed 3 by 3 grid of 0.7m (horizontal) on 0.4m (vertical) spacing. Two hitting points were set on the opposite side of the wall; each pulsed in sets of 10 hits, collecting receiving data from 2 accelerometers placed gradually in the 9 receiving points. Layout of the receiving grid can be seen in Figure 7.11. The Figure also shows location of impact echo tests (highlighted stones) and GPR profiles (black dashed line).

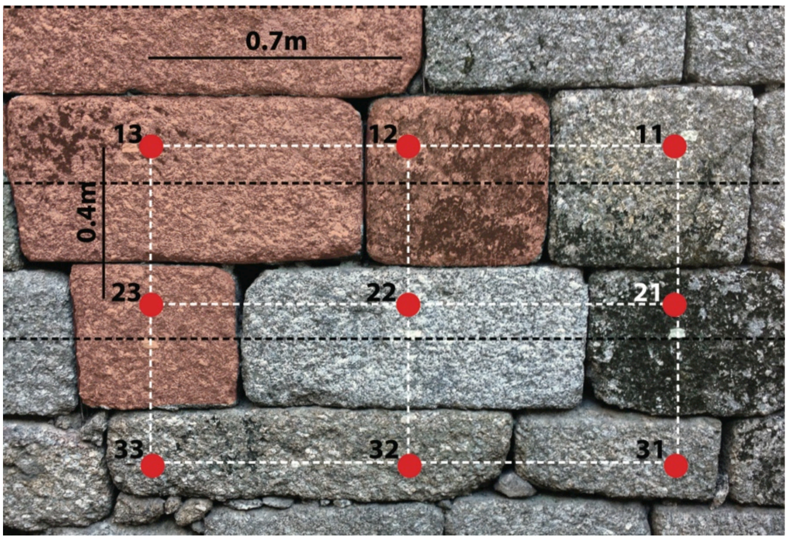


Figure 7. 11- Layout of testing grid for direct sonic testing

The acquisition and processing of the signals were performed using LabView ® software, developed by the University of Minho for acquisition and analysis of sonic tests signals, by the name of Sonic Acquire and Sonic Analyzer.

Results

Average velocity through the wall, obtained from the tests was: 533.7 m/sec, with a variation coefficient of 15%. This velocity is essentially lower than the reference velocity through a single stone (2775 m/sec, See Chapter 7.3.1), pointing at a 19% velocity capacity in the wall. This result can indicate the presence of voids and damage within the section. The stones were recognized as partially damaged in their apparent vision, and are evidently damaged also in the interior. Another possible explanation can be the shape of the masonry units; although they seem quite regular in the façade, they may be irregular in their inner surfaces. This construction method, illustrated in Fig 7.12, was widely used in historic times. Full results can be found in Annex 2.

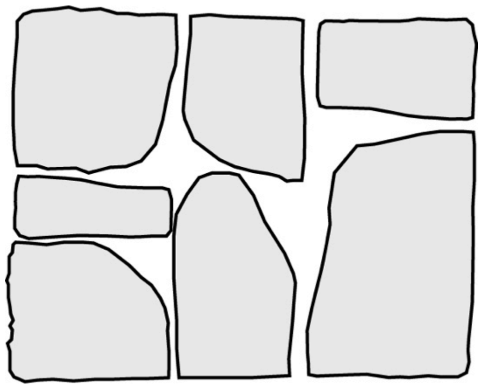


Figure 7. 12- Horizontal plan of masonry section illustrating exterior regular joints with irregular interior shape

7.3.4 Impact Echo

Impact echo reflection test was carried out in 4 stones. 2 of which were suspected to be transversal stones, and two that were obviously part of a layered section. The testing positions can be seen in Figure 7.13, which also marks boundaries of direct sonic tests (white dashed box) and GPR profiles (black dashed line) which were obtained. The work principle of the technique is based on wave propagation in a structure, reflecting as it encounters an interface. The reflected wave repeatedly rebounds back to the surface and reflects again into the interior of the structure. The process repeats, and multiple reflections occur between the surface and the interface until the wave fades out. The echo of the wave will form a peak in the frequency domain. The results of the measurements are taken in time signal and therefore, the conventional impact echo method applies the Fast Fourier Transform (FFT) into frequency domain.

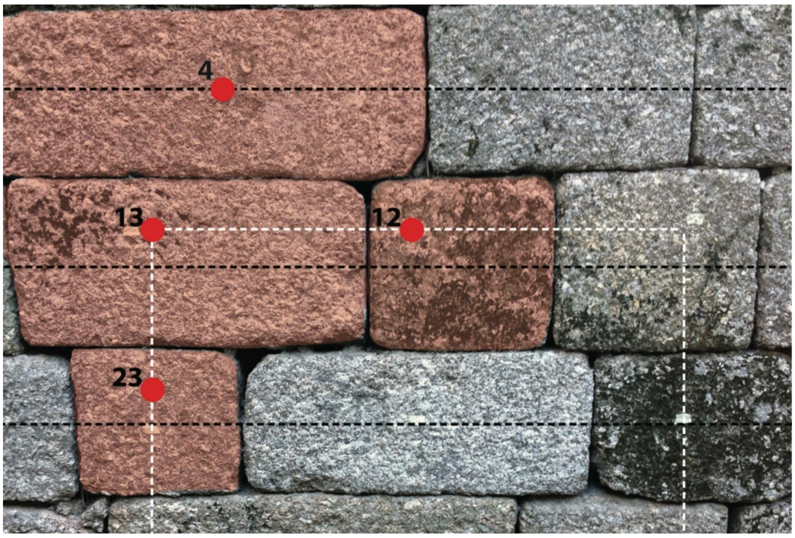


Figure 7. 13- Layout of testing position of impact echo testing,

A relation was found between dominant frequency and distance and thus, by locating the peaks in the Fourier spectrum, the size of the structure can be determined. Fourier transform was applied to the collected data in Seismo Signal software, and data was plotted in frequency domain.

Results

Plotted results of all measured positions had multiple peaks, pointing to the same assumption brought up by previous tests, that the wall was composed of multiple elements. Furthermore, stones that where suspected as transversal, showed similar results to those recognized as shallow. This can indicate that they are not section crossing after all. An example for a multiple peak frequency graph, obtained from measurement of point 23, can be seen in Figure 7.14.

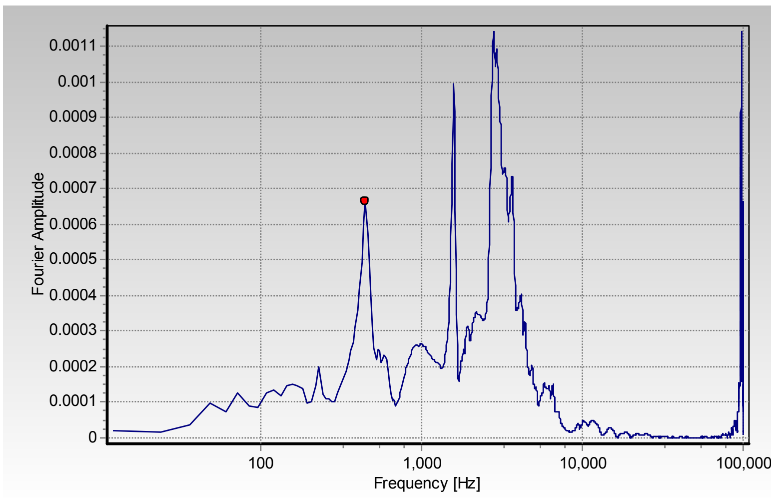


Figure 7. 14- Plot of frequency signal showing multiple peaks, result of IE measurements in point 23

Consequently, after marking dominant frequencies of each measured point, obtained frequency (f) was related to the depth of the section (d) by the following equation, where C_p is the velocity of the longitudinal wave, for which the reference stone velocity was used. (See Chapter 7.3.1):

$$d = C_p/2f$$

Results of two measured points showed results representative of wall morphology. Point 23 showed two peaks in the distances of 0.51m and 0.87m. The actual wall width, measured on site was 0.93m, which is very close to the estimated result. The closer peak can indicate existence of an inner joint or layer. Similar results were noted in point 4, showing peaks at distances 0.60m and 0.88m. All measurements showed a very low variation coefficient of less than 0.01%. Figure 7.15 illustrates this diagnose. It should further be noted that all points indicated on additional peaks, with corresponding values of 3m or more. This can be related to noises which can cause these errors. The other two points measured showed non-conclusive results. Full results can be found in Annex 2.

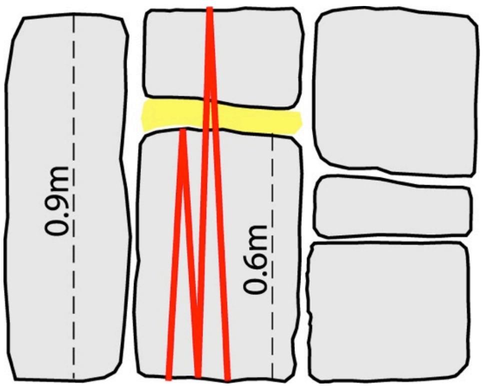


Figure 7. 15- Horizontal plan of masonry section illustrating interior interfaces with large, detectable joints.

7.3.5 Correlation of Results

By correlating results of the three applied methods, a good estimation of the morphology of the section can be made. Figure 7.16 illustrates an estimated horizontal section in fourth stone course, at a height of approximately 1 meter from the ground.

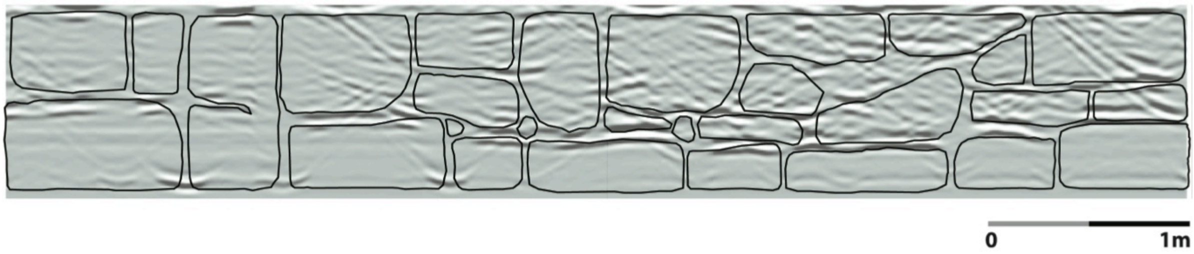
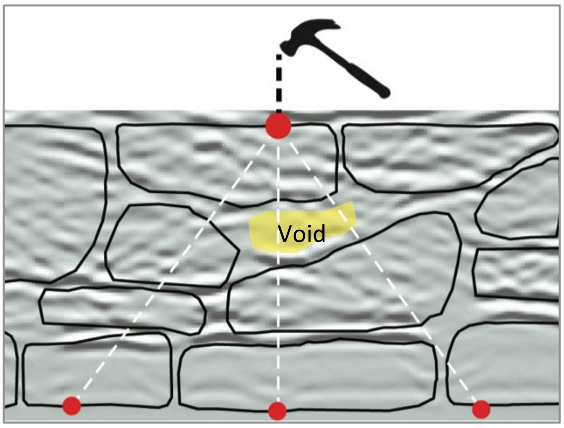


Figure 7. 16- Horizontal plan of 4th course stone morphology estimation on top of radargram.

The appeared morphology is of a massive single leaf wall, consisting of an irregular internal geometry. The estimation process of the morphology of external stones was based on a photographic survey of three sides of the wall allowing positioning of external joints, which was also found to be in perfect accordance with GPR radargrams. The interior stones, voids and interfaces were estimated by the apparent signals in the radargrams, in correlation with sonic and impact echo results. Sonic tests showed a very low velocity in the level of this section, with an average reading of 242 m/sec. This leads to the estimation of a void presence within the transmission route. The estimated void can be seen in yellow in Figure 7.17.



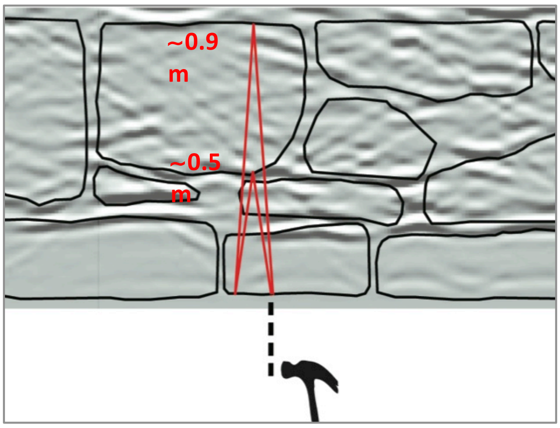


Figure 7. 17- Sonic transmission execution scheme. Figure 7. 18- Impact echo execution scheme

Furthermore, several readings of the Impact Echo tests can also be validated by the morphology. At the level of this plan (4th course of the masonry), interfaces were detected by the impact echo reflection at 0.87m and 0.51m, as seen in Fig.7.18. These are found in the estimated morphology, yet are not the only interfaces in this section.

7.4 Tower Wall Results

7.4.1 Ground Penetration Radar

The external wall of the tower was surveyed with the 800 and the 500 MHz antennas. The result showed that both the antennas were capable of penetrating the wall, which means that the wall was rather homogeneous in composition. However, the unit's arrangement produced a rather poor result, resulting in poor geometrical definition. Both frequencies were used to take advantage of the better resolution of the 800 MHz and the better penetration depth of the 500 MHz. Figure 7.19 shows an example of a horizontal profile executed with the 800 MHz antenna. While it shows a very weak signal from the opposite side, it shows a lot of hyperbolas related with joints inside the wall. No interface between blocks was directly measured, which implies that the units are very close from each other. Figure 7.20 shows a similar profile but with the 500 MHz antenna. Although the signal from the opposite side is stronger, the internal events generate even stronger hyperbolas, making interpretation difficult.

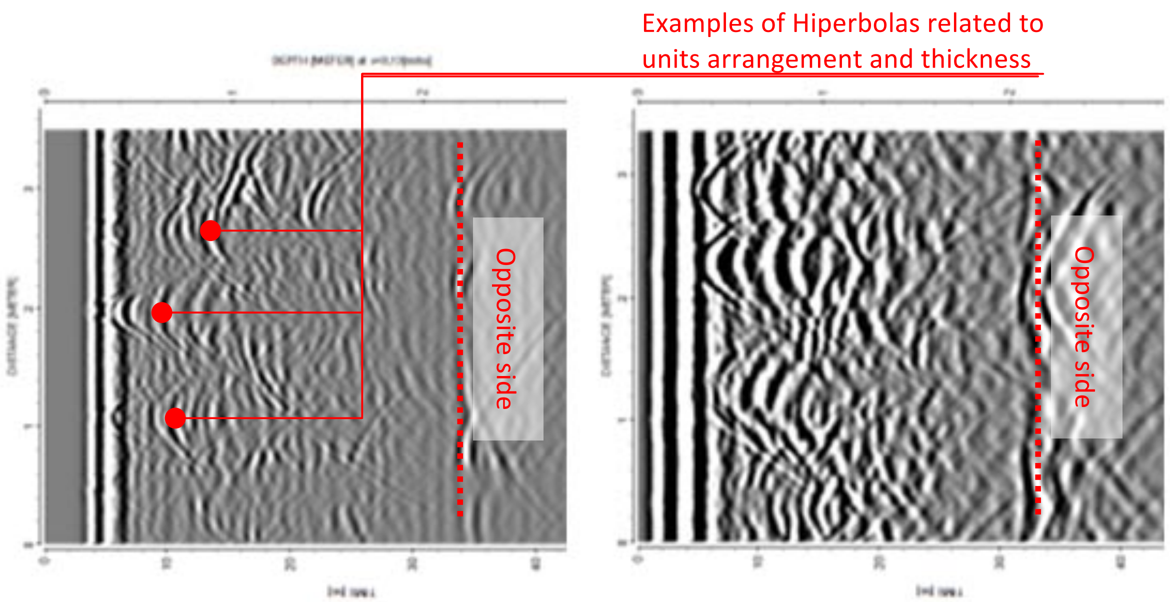
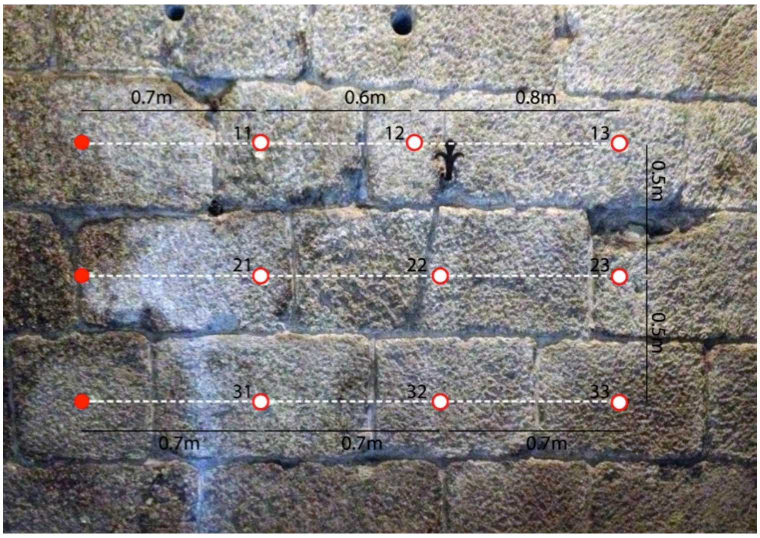


Figure 7. 19- Radargram from tower wall with 800 MHz antenna. Figure 7. 20- Radargram from tower wall with 500 MHz antenna

7.4.2 In-Direct Sonic Transmission

The indirect sonic test was carried out on both horizontal and vertical profiles. The aim of the test was to achieve better information regarding the joints and the near surface geometry of the stones. A prescribed 3 by 3 grid of 0.7m (horizontal) on 0.5m (vertical) spacing was marked on the wall, and tested for each profile separately. Each profile was attained by 10 hammer hits, collecting receiving data from 3 accelerometers. Layout of horizontal and vertical profiles can be seen in Figure 7.21.



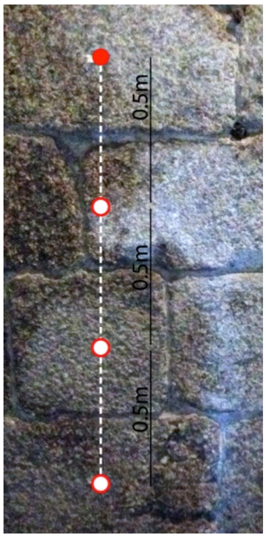


Figure 7. 21- Layout of horizontal and vertical profiles for indirect sonic testing

The results, obtained by LabView ® software, show an average value of 878 m/sec in the vertical profiles and a slightly lower average value of 835 m/sec in the horizontal profiles. Reference results for indirect testing of a single stone show a mean value of 1557 m/sec. The lower results can indicate the presence of some voids in the joints or within the section of the units themselves. This can also be related to stone carving techniques, presenting a regular ashlar façade with inner irregularity, as was presented in Figure 7.12. Full results can be found in Annex 2.

7.5 Discussion of the Results

The short survey conducted allowed gaining some valuable information regarding the morphology of the wall, yet additional testing in other parts of the wall would be advantageous for more decisive conclusions. Nevertheless, local conclusion can be achieved:

(i) The composition of both walls appears to be of a "thick wall" type (as defined by Binda, 2009), meaning a massive wall, consisting of several irregular layers of stone, without a classic structure of 2 external and one internal leaf. This conclusion is in accordance with the assessed morphology of another position in the Castle, which was studied in 2010 (Madeira, 2010);

(ii) The battlement wall seems to be in a more damaged state than the tower wall, showing much lower velocities within its section. This can be related to its empty mortar joints which were noticeable in the visual inspection. The joints of the tower wall, on the contrary, seemed in a better, almost perfect state. This may be related to the difference in thickness of the walls (the tower wall is twice as thick) as well as their location within the premises;

(iii) The battlement wall may have a relatively thin exterior layer, in a depth of 30-60 cm, which was evident in both GPR radargrams and Impact echo reflection results;

(iv) The joints between the granite units have a “well-worked” surface, creating a ashlar façade, but seem to be more irregular on the internal face. This can be concluded from the indirect sonic tests. This is common in historic masonry walls, and has to do with workmanship and efficiency derived stone carving techniques;

(v) In accordance to the methodology suggested in the previous chapter, a boroscopy test would have a meaningful contribution to the validation of the morphologic assumptions;

(vi) It is very advantageous to conduct several non destructive techniques in single locations. This enables creation of based conclusions, allows comprehensive understanding of the section and validations of assumptions that may have been raised from a single executed technique.

7.6 Conclusions

The aims of this testing campaign were to contribute to the level of knowledge available regarding the Guimarães castle and to validate the methodology suggested for the diagnosis of this type of structure in the previous chapters. The main conclusions gained from the campaign were:

(i) It is very advantageous to design a campaign plan before reaching the site. This is essential for both organization of required equipment and conduction of an efficient on site operation.

For that matter, available predesigned methodology suggestions, as developed in this thesis, may be very useful;

(ii) Often non predictable limitations may rise, and sought operations may not be able to be carried out, as in the case of boroscopy in the discussed campaign. Therefore, some flexibility must be engaged in the execution process;

(iii) All of the testing methods are very intricate and must be carried out by experts. Major capacities and limitations of the methods were taken into consideration in the design of the diagnosis methodologies, but not all nuances were studied and addressed. These properties of the techniques are regularly still in the process learning;

(iv) New methodological information can be gained from every executed campaign, and must be documented along with the tangible results of the tests and reported for the wider knowledge.

8. CONCLUSIONS

8.1 Scientific Background

The state of the art of techniques for assessment of masonry walls, covered in chapter two, highlighted the numerous fields possible to explore by current and in-development diagnosis methods. The study disclosed various possibilities for smart selection of these testing methods by having an in-depth acquaintance with their capacities, compatibility concerns and limitations.

In chapter three, a wide look was taken at the historic masonry typologies in Portugal, with an emphasis on rural, urban and military typology structures. This helped to achieve a better comprehension of the diversity of masonry heritage in Portugal and its characteristics, a field that has not yet been sufficiently studied. The study was able to find fundamental differences between the defined typologies: the basic questions of the original designated function, the practice of the execution, durability and masonry quality, building techniques and geometrical properties.

8.2 Diagnostic Methodology Development

The main body of the work focused on diagnostic methodology development in light of the previous findings. A typology-based methodology to the diagnosis process was achieved on the base of the recognized differences between the defined typologies in both their physical and theoretical properties. Eight well-defined typologies (three rural, two urban and three military) were chosen to paradigm the methods. The fundamentals of the methodologies were found to be:

(i) In rural typologies, simple, reachable methods should be applied for both the diagnosis and the intervention procedures. This desired simplicity is in accordance with typology characteristics and with the level of knowledge of local builders, which often execute these processes. Another important aspect of the typology is the additional value of the documenting process in terms of protecting and even regaining lost knowledge, as the structures are frequently vernacular, and not well documented.

(ii) For urban typologies, the repeated nature of the structures should guide the diagnostic practice. Previous studies should be utilized for anticipating damage patterns and for verifying results. Hence, data collected in studies should be published in a database of relatable cases for future works. Another key issue of the typology is its middling size and dense environment. These two characteristics led the study to prefer a step-by-step approach to the diagnosis procedure, exhausting simple methods that are expected to be efficient before turning to others.

(iii) In military typologies the fundamental factor is size, in both structural and sectional scales, and should be the main conductor of the diagnosis procedure. The size fosters many problems, for example, attaining mechanical properties, which is almost impossible in the sectional-composite scale, or surveying and documenting procedures that should be executed in sessions and dictate a necessity in strict management. Another interesting feature is the different wall typologies (standing walls and retaining walls), which should be approached differently, although part of the same structure.

8.3 Validation Process

A testing campaign was carried out in Guimarães castle with the objectives to contribute to comprehension of the castle structure and to validate the suggested methodology. The campaign included direct and indirect sonic transmissions, impact echo reflection tests and GPR scanning. It was found that it is very advantageous to design a campaign plan before reaching the site. This was essential for both organization of required equipment and conduction of an efficient on-site operation. For that matter, available predesigned methodology suggestions, as developed in this thesis, may be very useful. Nonetheless, often non-predictable limitations may rise, and sought operations may not be able to be carried out, as in the case of boroscopy in the discussed campaign. Therefore, some flexibility must be engaged in the execution process.

8.4 Further works

This study found that major advantages could be drawn to the field of historic heritage diagnosis by utilizing typological information. An additional effort should be invested in elevating the level of knowledge and documentation of architectural typologies in Portugal. Further studies are recommended to be carried out in the wide-national scale, documented and be put available to the scientific community and to the public.

This thesis represents a primary attempt to address the subject, and to demonstrate the potential of the coupling of typology and assessment procedures. Methodologies in this study were developed on the basis of eight typologies. This can be expanded and further established on wider foundation. Furthermore, the methodology should be attempted and validated in continuous on site efforts in order to enhance its practicality and precision.

In a broader perspective, a further next step for this type of study would be development of a computed application, which holds information of both typology and testing characteristics, and is able to offer tailor designed diagnosis processes of masonry.

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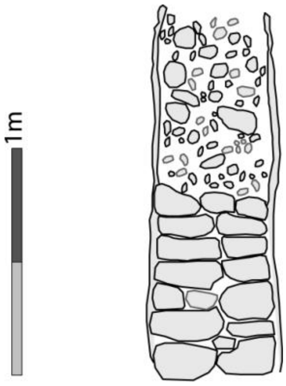
10. ANNEXES

10.1 ANNEX 1- Implementation Tables for Diagnosis of Masonry Typologies

10.1.1 Rural Typology - Double leaf Limestone

RURAL- Single leaf Granite

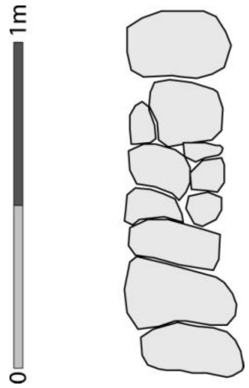


Material	Mortar
Limestone earth	**Air lime**
Thickness	Height
63 cm	**2.5m**
Unit size (h)	Geometry
5-25 cm	**Irregular**
Finish	Found in
Lime	**Algarve**

DAMAGE SURVEY		
Visual Inspection	Compulsory	Visual inspection is the chief test that should be conducted in diagnosis of rural walls. During the inspection typical damages should be checked: ▪ Damage caused by lack of maintenance- biological attack, moisture presence. ▪ Damage due to late alterations that cause additional loading, or change the structural scheme. ▪ Chemical attacks due to animals ▪ Disassembly of external leaf due to lack of cohesion or adequate connectors.
NDT	**Recommendation**	**Appliance**
Infrared	locally recommended	Recommended on plastered surfaces to detect damages, as moisture, voids and inclusions.
Moisture testing	locally recommended	Can be applied in areas of special interest where damaged stones are found, in order to estimate the severity of damage. Test can be applied on adjacent stones in different heights for recognizing the peak level of the damage, by comparing results.
MDT	**Recommendation**	**Appliance**
Micro sampling	Locally recommended	Samples can be taken for the measurement of moisture content and salt presence. Samples can be obtained from adjacent stones in different heights for recognizing the peak level of the damage, by comparing results.

10.1.2 Rural Typology - Single leaf Granite

RURAL- Single leaf Granite

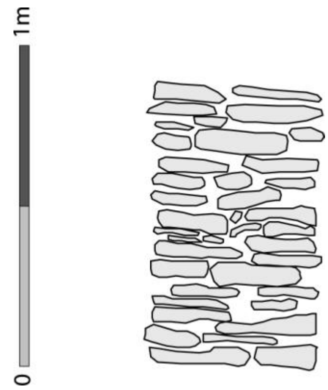


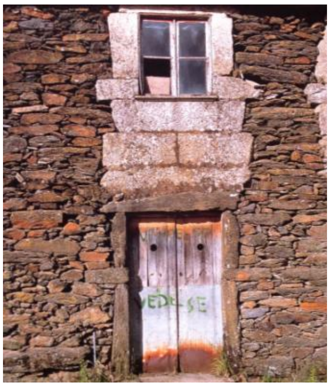
Material **Granite**	Mortar **Dry Stone**
Thickness **36 cm**	Height **2.5m**
Unit size (h) **15-35 cm**	Geometry **Irregular**
Finish **Bare**	Found in **Vila Real**

DAMAGE SURVEY		
Visual Inspection	**Compulsory**	Visual inspection is the chief test that should be conducted in diagnosis of rural walls. During the inspection typical damages should be checked: ▪ Damage caused by lack of maintenance- biological attack, moisture presence. ▪ Damage due to late alterations that cause additional loading, or change the structural scheme. ▪ Chemical attacks due to animals ▪ Disassembly of external leaf due to lack of cohesion or adequate connectors.
NDT	**Recommendation**	**Appliance**
Moisture testing	**locally recommended**	Can be applied in areas of special interest where damaged stones are found, in order to estimate the severity of damage. Test can be applied on adjacent stones in different heights for recognizing the peak level of the damage, by comparing results.
Hardness test	**Locally recommended**	Can be applied in areas of special interest where damaged stones are found, in order to estimate the severity of damage. Test can be applied on adjacent stones in different heights for recognizing the peak level of the damage, by comparing hardness results.
MDT	**Recommendation**	**Appliance**
Boroscopy	**Locally recommended**	As these tests are bound to be conducted and interpreted by experts, and namely are in purpose of finding mechanical characteristics of the masonry, they can be avoided. Not applicable on irregular stone and dry stone
Micro sampling	**Locally recommended**	Samples can be taken for the measurement of moisture content and salt presence. Samples can be obtained from adjacent stones in different heights for recognizing the peak level of the damage, by comparing results.

10.1.3 Rural Typology - Double leaf Schist

RURAL- Double leaf Schist



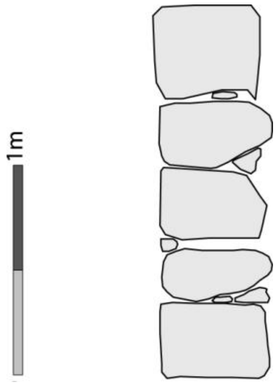


Material	Mortar
Schist	**Air lime**
Thickness	Height
55 cm	**2.5m**
Unit size (h)	Geometry
5-25 cm	**Irregular**
Finish	Found in
Bare	**Alentejo**

DAMAGE SURVEY		
Visual Inspection	Compulsory	Visual inspection is the chief test that should be conducted in diagnosis of rural walls. During the inspection typical damages should be checked: ▪ Damage caused by lack of maintenance- biological attack, moisture presence. ▪ Damage due to late alterations that cause additional loading, or change the structural scheme. ▪ Chemical attacks due to animal residue. ▪ Disassembly of external leaf due to lack of cohesion or adequate connectors.
NDT	**Recommendation**	**Appliance**
Moisture testing	locally recommended	Can be applied in areas of special interest where damaged stones are found, in order to estimate the severity of damage. Test can be applied on adjacent stones in different heights for recognizing the peak level of the damage, by comparing results.
Hardness test	Locally recommended	Can be applied in areas of special interest where damaged stones are found, in order to estimate the severity of damage. Test can be applied on adjacent stones in different heights for recognizing the peak level of the damage, by comparing hardness results.
MDT	**Recommendation**	**Appliance**
Micro sampling	Locally recommended	Samples can be taken for the measurement of moisture content and salt presence. Samples can be obtained from adjacent stones in different heights for recognizing the peak level of the damage, by comparing results.

10.1.4 Urban Typology - Single leaf Granite

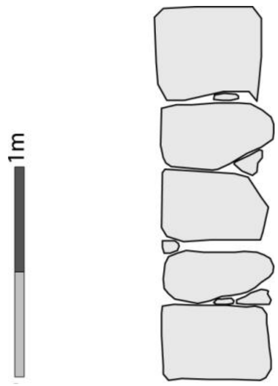
URBAN- Single leaf Granite



Material **Granite**	Mortar **Air lime**
Thickness **55 cm**	Height **25m** ~3.5 m per floor
Unit size (h) **23-37 cm** With small shims	Geometry **Ordinary Stone**
Finish **Bare**	Found in **Porto**

MORPHOLOGY SURVEY		
Single leaf granite wall		
Visual Inspection	Compulsory	▪ Positioning further testing ▪ Local inspection after dismantling ▪ Recognizing different wall types to survey
NDT	**Recommendation**	**Appliance**
Sonic / ultrasonic transmission	**Moderately recommended**	Can provide evidence on wall thickness via direct testing, or joint properties via indirect. Reference measurement should be taken from a single stone. Generally more efficient in the analysis of larger sections.
Impact echo	**Highly recommended**	To detect section thickness if unknown. Reference sonic velocity measurement should be taken from a single stone.
Infrared thermography	**Not recommended**	Not necessary in non-plastered walls.
GPR	**Moderately recommended**	Should be approached implicitly, if other methods are not satisfactory or possible (as boroscopy or coring), Should be applied on undamaged plaster. The use of a steel plate opposite the antenna is recommended in order to find wall thickness.
MDT	**Recommendation**	**Appliance**
Coring	**Moderately recommended**	Not particularly recommended for thin sections, but if all other methods have failed, can be used, preferably in a discrete location.
Boroscopy	**Highly recommended**	Can provide evidence on wall thickness. Boreholes and empty joints should be used if possible, instead of intended drilling.

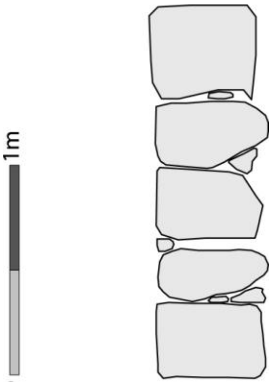
URBAN- Single leaf Granite



Material **Granite**	Mortar **Air lime**
Thickness **55 cm**	Height **25m** ~3.5 m per floor
Unit size (h) **23-37 cm** With small shims	Geometry **Ordinary Stone**
Finish **Bare**	Found in **Porto**

MECHANICAL SURVEY		
Single leaf granite wall		
Visual Inspection	Compulsory	Search for areas of interest: ▪ Representing section ▪ "Special" section- damaged/ overloaded
NDT	**Recommendation**	**Appliance**
Sonic / ultrasonic	Moderately recommended	As a complementary method. Should be applied in same location as quantitative testing. (Flat Jack etc.)
Hardness test	Moderately - locally recommended	A very simple method to achieve validation of homogeneity of mechanical related properties of the near surface.
MDT	**Recommendation**	**Appliance**
Coring	Not recommended	Not recommended in single leaf walls, only for the purpose of cylindrical sample testing.
Micro sampling	Highly recommended	Destructive tests for compression, tension and bending can be conducted and results can be obtained in situ. Allows finding resistance of the stone or mortar units and not the state of stress or modulus of elasticity of the masonry as a composite material.
Flat Jack	Moderately recommended	Local results can be obtained. Location of test to be determined by sonic testing and preferably within a stone unit.
Double flat jack	Moderately recommended	Local results can be obtained. Location of test to be determined by sonic testing and preferably within stone units. Results should be correlated and compared to standardized lab results.
Tube jack	Highly recommended	As the masonry is normally irregular and consists of one leaf, the tube jack can be a good appliance for measurement of local state of stress. General configuration of the tubes can derive from natural joint texture and correlated.

URBAN- Single leaf Granite

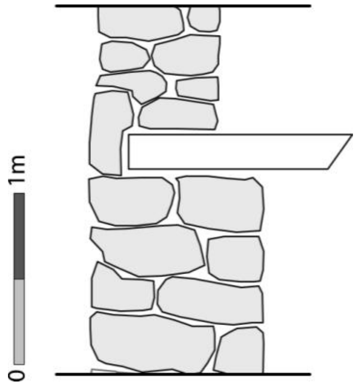


Material	Mortar
Granite	**Air lime**
Thickness **55 cm**	Height **25m** ~3.5 m per floor
Unit size (h) **23-37 cm** With small shims	Geometry **Ordinary Stone**
Finish **Bare**	Found in **Porto**

DAMAGE SURVEY		
Single leaf granite wall		
Visual Inspection	**Compulsory**	Search for typical damages: ▪ Cracking on top floors ▪ Light wells stone deterioration
NDT	**Recommendation**	**Appliance**
Infrared thermography	**Highly recommended**	For hidden crack patterns, inclusions and moisture detection. Should be done in early stages in order to guide further testing efforts as sampling, sonic and others.
Sonic / ultrasonic transmission	**Moderately recommended**	Should be applied in specified locations, preferably in comparative study. Crack pattern mapping is recommended for regular brick and stone masonry. Estimation of crack depth – possible in the case of cracks orthogonal to the surface and applicable only on single blocks.
GPR	**Moderately recommended**	Recommended implicitly if other methods failed. Can fail if cracks not perpendicular to the antenna. Should **not** be applied on sensitive plaster.
Hardness test	**Moderately - locally recommended**	As a complementary method. Should be applied in specified locations and in a comparative method. (samples from both damaged and healthy sources)
MDT	**Recommendation**	**Appliance**
Sampling, Moisture and salt anions content	**Highly recommended**	Sampling for comprehensive data acquisition. Sampling must be made in specified, possibly damaged locations with comparative samples. Must be documented strictly.
Boroscopy	**Moderately - locally recommended**	In the suspicion of void presence can be applied locally. Boreholes and empty joints should be used if possible, instead of intended drilling.

10.1.5 Urban Typology - Single leaf Limestone

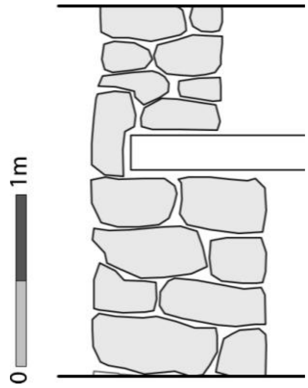
URBAN- Single leaf Limestone



Material **Limestone**	Mortar **Air lime**
Thickness **30-100 cm** Decrease with height	Height **25m** ~3.5 m per floor
Unit size (h) **20-30 cm**	Geometry **Ordinary Stone**
Finish **Lime**	Found in **Lisbon**

DAMAGE SURVEY		
Single leaf plastered limestone wall		
Visual Inspection	Compulsory	Search for typical damages: ▪ Cracking on top floors ▪ Light wells stone deterioration ▪ Change of use
NDT	**Recommendation**	**Appliance**
Infrared thermography	Highly recommended	For hidden crack patterns, inclusions and moisture detection, which can be hidden behind plaster. Should be done in early stages in order to guide further testing efforts as sampling, sonic and others.
Sonic / ultrasonic transmission	Moderately recommended	Direct testing is advantageous as indirect tests may be referring mostly to the plaster layer. Crack pattern may be detectable only if removal of the plaster is possible. Estimation of crack depth – possible in the case of cracks orthogonal to the surface and applicable only on single blocks.
GPR	Not recommended	Recommended implicitly only if other methods failed. Can fail if cracks not perpendicular to the antenna. Should **not** be applied on sensitive plaster.
Hardness test	Not recommended	Not recommended on plastered walls, as rebound results can indicate only of the condition of the plaster and not the masonry.
MDT	**Recommendation**	**Appliance**
Sampling, Moisture and salt anions content	Highly recommended	Sampling for comprehensive data acquisition. Sampling must be made in specified, possibly damaged locations with comparative samples. Must be documented strictly.
Boroscopy	Moderately - locally recommended	In the suspicion of void presence can be applied locally. Boreholes and empty joints should be used if possible, instead of intended drilling.

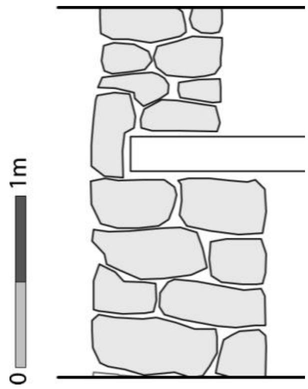
URBAN- Single leaf Limestone



Material	Mortar
Limestone	**Air lime**
Thickness	Height
30-100 cm Decrease with height	**25m** ~3.5 m per floor
Unit size (h)	Geometry
20-30 cm	**Ordinary Stone**
Finish	Found in
Lime	**Lisbon**

MECHANICAL SURVEY		
Single leaf plastered limestone wall		
Visual Inspection	**Compulsory**	Search for areas of interest: ▪ Representing section ▪ "Special" section- damaged/ overloaded
NDT	**Recommendation**	**Appliance**
Sonic / ultrasonic	**Moderately recommended**	As a complementary method. Should be applied in same location as quantitative testing. (Flat Jack etc.) Can also provide data of elastic properties of the masonry, but results are less accurate than other possible methods.
Hardness test	**Not recommended**	Not recommended on plastered walls, as rebound results can indicate only of the condition of the plaster and not the masonry. Can be applied is plaster is removed.
MDT	**Recommendation**	**Appliance**
Coring	**Not recommended**	Not recommended in single leaf walls, only for the purpose of cylindrical sample testing.
Micro sampling	**Highly recommended**	Destructive tests for compression, tension and bending can be conducted and results can be obtained in situ. Allows finding resistance of the stone or mortar units and not the state of stress or modulus of elasticity of the masonry as a composite material.
Flat Jack	**Moderately recommended**	Local results can be obtained. Plaster must be removed. Location of test to be determined by sonic testing and preferably within a stone unit.
Double flat jack	**Moderately recommended**	Local results can be obtained. Plaster must be removed. Location of test to be determined by sonic testing and preferably within stone units. Results should be correlated and compared to standardized lab results.
Tube jack	**Highly recommended**	As the masonry is normally irregular and consists of one leaf, the tube jack can be a good appliance for measurement of local state of stress. General configuration of the tubes can derive from natural joint texture and correlated. Plaster must be removed.

URBAN- Single leaf Limestone

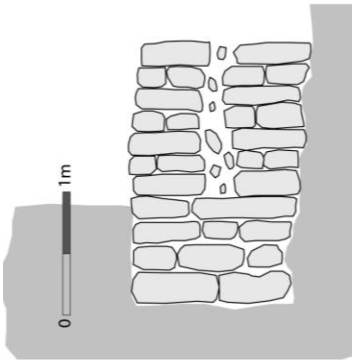


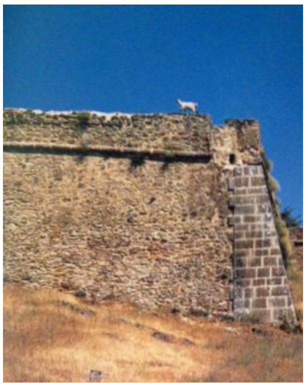
Material	Mortar
Limestone	**Air lime**
Thickness	Height
30-100 cm Decrease with height	**25m** ~3.5 m per floor
Unit size (h)	Geometry
20-30 cm	**Ordinary Stone**
Finish	Found in
Lime	**Lisbon**

MORPHOLOGY SURVEY		
Single leaf mixed masonry wall		
Visual Inspection	**Compulsory**	▪ Positioning further testing ▪ Local inspection after dismantling
NDT	**Recommendation**	**Appliance**
Sonic / ultrasonic transmission	**Moderately recommended**	Can provide evidence on wall thickness. Generally more efficient in multi leaf walls. If practiced, location should be verified in regards to material.
Impact echo	**Highly recommended**	To detect section thickness if unknown. Reference sonic velocity measurement should be taken from a single stone, which may demand plaster removal.
Infrared thermography	**Highly recommended**	Detection of mixed system characteristics and layout Should be applied in an un-windy environment
GPR	**Moderately recommended**	Should be approached implicitly, if other methods are not satisfactory or possible (as boroscopy or coring) Should be applied on undamaged plaster. The use of a steel plate opposite the antenna is recommended in order to find wall thickness.
MDT	**Recommendation**	**Appliance**
Coring	**Moderately recommended**	If no information is available as for the type of masonry and timber, coring can be a sampling method for detection. Location must be chosen after preliminary information is gathered of the location of the different composite materials. Furthermore, it can provide info regarding the assembly of the masonry units, one or 2 leaves.
Boroscopy	**Highly recommended**	Can provide evidence on wall thickness. Generally more efficient in multi leaf walls.

10.1.6 Military Typology - Triple leaf limestone - Retaining wall

MILITARY- Triple leaf Limestone - Retaining wall

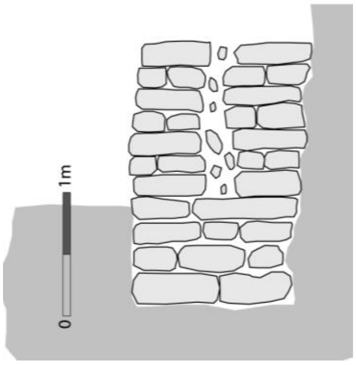


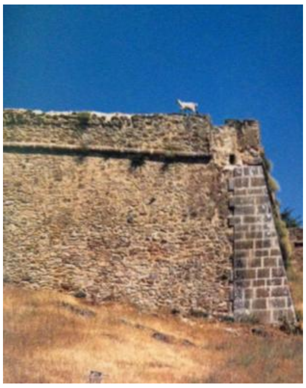


Material	Mortar
Limestone	**Air lime**
Thickness **130 cm**	Height **6m**
Unit size (h) **Ext- 20 cm** **Int- rubble**	Geometry **Cut Stone**
Finish **Bare**	Found in **Setubal**

GEOMETRY/ MORPHOLOGY SURVEY		
Triple leaf limestone retaining wall		
Visual Inspection	**Compulsory**	▪ Positioning further testing ▪ Local inspection after dismantling ▪ Complimentary as reference material for localizing executed tests
NDT	**Recommendation**	**Appliance**
Laser Scanning	**Highly recommended**	Recommended for superficial and not for thickness survey. Can be applied in several sensors to achieve best results.
Sonic / ultrasonic transmission	**Highly recommended**	Direct application- strongly recommended Indirect application- solely for near surface info. Compatible for cut stone geometry for obtaining info of shape of stone.
Impact echo	**Highly recommended**	To detect section thickness if unknown. Very compatible for one side access walls. Reference sonic velocity measurement should be taken from a single stone.
Infrared thermography	**Not Recommended**	Not necessary in non plastered structures.
GPR	**Highly recommended**	Horizontal and vertical profiles should be taken, in sequential order. It is recommended to locate profiles within the courses of the stone for better contact with scanning unit.500 MHZ and 800 MHz antennas should be tried, as thickness is often unknown. Should not be applied on soft or deteriorated surfaces, as friction may cause additional damage.
MDT	**Recommendation**	**Appliance**
Boroscopy	**Moderately recommended**	Preferably applied in existing boreholes or empty mortar joints. Otherwise, can be applied in mortar joints or, as a last resort, by drilling within the stone elements.

MILITARY- Triple leaf Limestone - Retaining wall

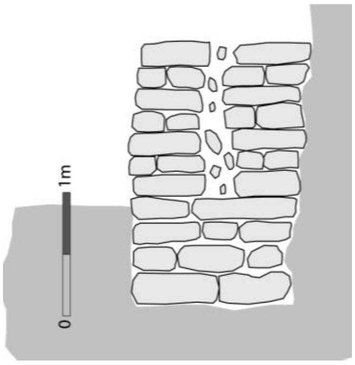


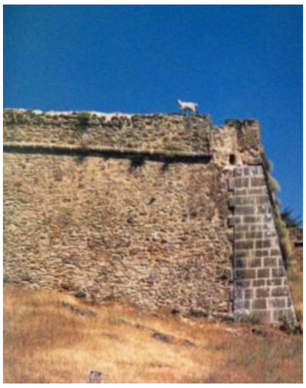


Material **Limestone**	Mortar **Air lime**
Thickness **130 cm**	Height **6m**
Unit size (h) **Ext- 20 cm** **Int- rubble**	Geometry **Cut Stone**
Finish **Bare**	Found in **Setubal**

DAMAGE SURVEY		
Triple leaf limestone retaining wall		
Visual Inspection	**Compulsory**	Search for typical damages: ▪ Moisture and leakage ▪ Local crack patterns due to root loads ▪ Overloading due to change of use or other
NDT	**Recommendation**	**Appliance**
Infrared thermography	**Highly recommended**	For hidden crack patterns, inclusions and moisture detection. Should be done in early stages in order to guide further testing efforts as sampling, sonic and others.
Sonic / ultrasonic transmission	**Moderately recommended**	Indirect tests can supply information regarding near surface condition of the stones as well as state and properties of the joints.
GPR	**Highly recommended**	For detection of voids and inclusions. High or low resolution antennas can be used, for near surface or in-depth analysis accordingly. Should not be applied on soft or deteriorated surfaces, as friction may cause additional damage.
Laser Scanning	**Highly recommended**	For long term monitoring of damage as well as database creation for the case of destruction due to natural disasters.
Hardness test	**Moderately - locally recommended**	A very simple method to achieve immediate mechanical properties relating to superficial surface, which can suggest damage. Should be applied in several locations, including reference locations which seem "healthy".
MDT	**Recommendation**	**Appliance**
Sampling, Moisture and salt anions content	**Highly recommended**	Sampling for comprehensive data acquisition. Sampling must be made in specified, possibly damaged locations with comparative samples. Must be documented strictly.
Boroscopy	**Moderately - locally recommended**	In the suspicion of external leaf detachment or presence of voids, can be applied locally.

MILITARY- Triple leaf Limestone - Retaining wall



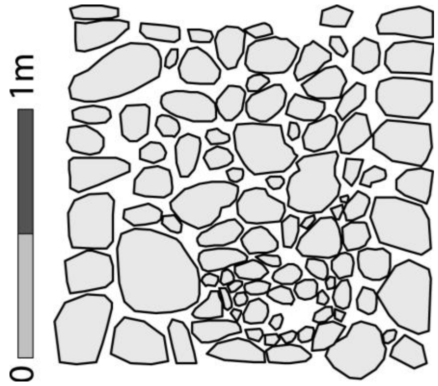


Material **Limestone**	Mortar **Air lime**
Thickness **130 cm**	Height **6m**
Unit size (h) **Ext- 20 cm** **Int- rubble**	Geometry **Cut Stone**
Finish **Bare**	Found in **Setubal**

MECHANICAL SURVEY		
Triple leaf limestone retaining wall		
Visual Inspection	**Compulsory**	Search for areas of interest: ▪ Representing section ▪ "Special" section- damaged/ overloaded
NDT	**Recommendation**	**Appliance**
Sonic / ultrasonic	**Highly recommended**	Results for elastic properties can be achieved with an indirect application. Method is not fully compatible for masonry and inaccuracy of the results should be taken into account.
Hardness test	**Moderately - locally recommended**	A very simple method to achieve validation of homogeneity of mechanical related properties of the near surface.
MDT	**Recommendation**	**Appliance**
Coring	**Moderately recommended**	Sampling should be done in the direction of the loading, and standardized dimensions must be considered.
Micro sampling	**Highly recommended**	Destructive tests for compression, tension and bending can be conducted and results can be obtained in situ. Allows finding resistance of the stone or mortar units and not the state of stress or modulus of elasticity of the masonry as a composite material.
Flat Jack	**Moderately recommended**	Results obtained solely for single leaf. Cannot be applied on whole wall section.
Double flat jack	**Moderately recommended**	Results obtained solely for single leaf. Cannot be applied on whole wall section.
Tube jack	**Moderately recommended**	Results obtained solely for single leaf. Cannot be applied on whole wall section.

10.1.7 Military Typology - Triple leaf Limestone - Standing wall

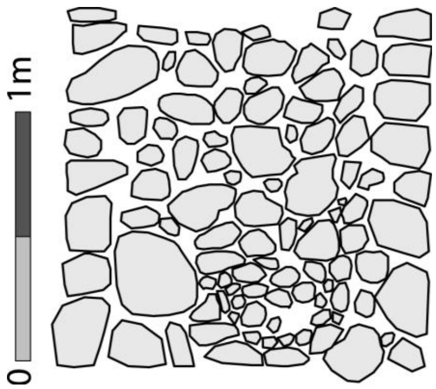
MILITARY- Triple leaf Limestone - Standing wall



Material	Mortar
Limestone	**Air lime**
Thickness	Height
142 cm	**10m**
Unit size (h)	Geometry
20-30 cm	**Ashlar and cut stone**
Finish	Found in
Lime	**Alentejo**

GEOMETRY/MORPHOLOGY SURVEY		
Triple leaf limestone plastered standing wall		
Visual Inspection	**Compulsory**	▪ Positioning further testing ▪ Local inspection after dismantling ▪ Complimentary as reference material for localizing executed tests
NDT	**Recommendation**	**Appliance**
Laser Scanning	**Highly recommended**	Recommended for superficial and not for thickness survey. Can be applied in several sensors to achieve best results.
Sonic / ultrasonic transmission	**Moderately recommended**	Direct application- strongly recommended Indirect application- solely for near surface info, and only if plaster removal is possible.
Impact echo	**Highly recommended**	To detect section thickness if unknown.. Reference sonic velocity measurement should be taken from a single stone and may demand local plaster removal.
Infrared thermography	**Highly recommended**	Recommended for superficial and not for thickness survey. Can suggest information regarding shapes and sizes of the stone units, size of mortar joints, etc.
GPR	**Highly recommended**	Horizontal and vertical profiles should be taken, in sequential order. It is recommended to locate profiles within the courses of the stone for better contact with scanning unit. For very high thicknesses a 500 MHZ antenna can be used. Should not be applied on soft or deteriorated surfaces, or to valuable plaster, as friction may cause additional damage.
MDT	**Recommendation**	**Appliance**
Boroscopy	**Moderately recommended**	Preferably applied in existing boreholes. Otherwise, can be applied in mortar joints exposed by plaster removal, or, as a last resort, by drilling within the stone elements.

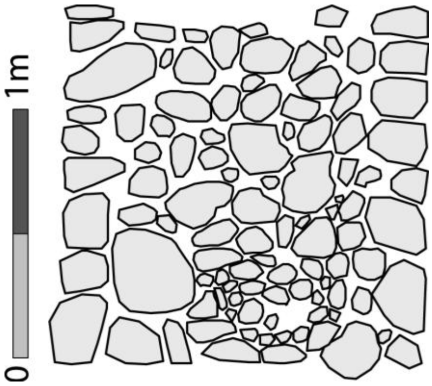
MILITARY- Triple leaf Limestone - Standing wall



Material **Limestone**	Mortar **Air lime**
Thickness **142 cm**	Height **10m**
Unit size (h) **20-30 cm**	Geometry **Cut stone and rubble**
Finish **Lime**	Found in **Alentejo**

DAMAGE SURVEY		
Triple leaf limestone plastered standing wall		
Visual Inspection	**Compulsory**	Search for typical damages: ▪ Moisture and leakage ▪ Leaf separation ▪ Overloading and change of use ▪ Limestone deterioration processes
NDT	**Recommendation**	**Appliance**
Infrared thermography	**Highly recommended**	For hidden crack patterns, inclusions and moisture detection. Should be done in early stages in order to guide further testing efforts as sampling, sonic and others
Sonic / ultrasonic transmission	**Moderately recommended**	Plaster removal is frequently necessary. Direct and indirect transmission can suggest deteriorated state of the stones, presence of voids and lack of mortar, etc. A reference measurement should be taken through a single stone to compare with results.
GPR	**Highly recommended**	For detection of voids and inclusions. High or low resolution antennas can be used, for near surface or in-depth analysis accordingly.
Laser Scanning	**Highly recommended**	For long term monitoring of damage as well as database creation for the case of destruction due to natural disasters.
Hardness test	**Not recommended**	Not recommended for plastered walls, results will only detect condition of the plaster. Can be applied if plaster is locally removed.
MDT	**Recommendation**	**Appliance**
Sampling, Moisture and salt anions content	**Highly recommended**	Sampling for comprehensive data acquisition. Sampling must be made in specified, possibly damaged locations with comparative samples. Must be documented strictly.
Boroscopy	**Moderately - locally recommended**	In the suspicion of external leaf detachment can be applied locally. Existing empty joints or voids should be used for inspection rather than intentional drilling.

MILITARY- Triple leaf Limestone - Standing wall

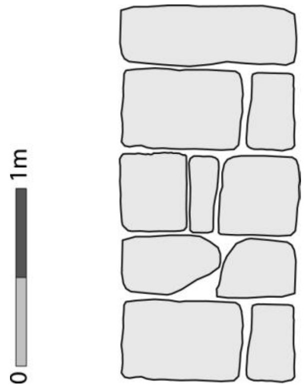


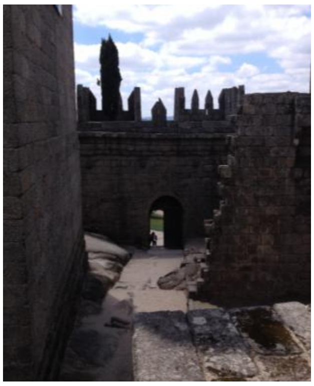
Material	Mortar
Limestone	**Air lime**
Thickness	Height
142 cm	**10m**
Unit size (h)	Geometry
20-30 cm	**Cut stone and rubble**
Finish	Found in
Lime	**Alentejo**

MECHANICAL SURVEY		
Triple leaf limestone plastered standing wall		
Visual Inspection	Compulsory	Search for areas of interest: ▪ Representing section ▪ "Special" section- damaged/ overloaded
NDT	**Recommendation**	**Appliance**
Sonic / ultrasonic	Highly recommended	Plaster removal is frequently necessary. Results for elastic properties can be achieved with direct and indirect applications. Method is not fully compatible for masonry and inaccuracy of the results should be taken into account.
Hardness test	Moderately - locally recommended	A very simple method to achieve immediate mechanical properties relating to superficial surface. Should be applied in several locations, including those inspected as damaged. Cannot be applied on plastered surfaces, as results will relate solely to the plaster layer.
MDT	**Recommendation**	**Appliance**
Coring	Moderately recommended	Sampling should be done in the direction of the loading, and standardized dimensions must be considered.
Micro sampling	Highly recommended	Destructive tests for compression, tension and bending can be conducted and results can be obtained in situ. Allows finding resistance of the stone or mortar units and not the state of stress or modulus of elasticity of the masonry as a composite material.
Flat Jack	Not Recommended	Not recommended for irregular masonry, can be applied to external leaf, to obtain local results.
Double flat jack	Not Recommended	Not recommended for irregular masonry, can be applied to external leaf, to obtain local results.
Tube jack	Moderately recommended	Plaster removal is necessary. Results obtained solely for single leaf. Cannot be applied on whole wall section, yet can achieve individual indications for external leaves.

10.1.8 Military Typology - Single leaf Granite - Standing wall

MILITARY- Single leaf Granite - Standing wall

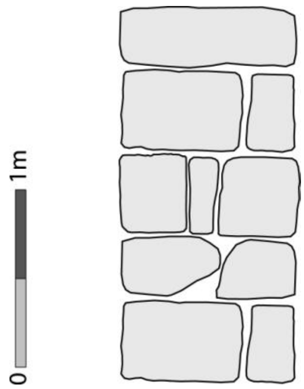


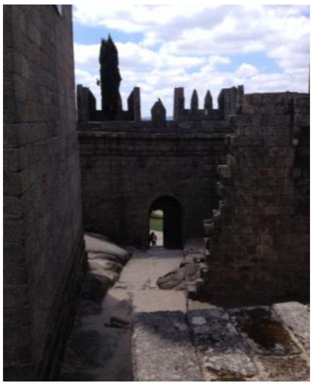


Material **Granite**	Mortar **Dry stone**
Thickness **93 cm**	Height **6m**
Unit size (h) **30-45 cm**	Geometry **Ashlar**
Finish **Bare**	Found in **Guimarães**

GEOMETRY/MORPHOLOGY SURVEY		
Thick-wall granite standing wall		
Visual Inspection	Compulsory	▪ Positioning further testing ▪ Local inspection after dismantling ▪ Complimentary as reference material for localizing executed tests
NDT	**Recommendation**	**Appliance**
Laser Scanning	Highly recommended	Recommended for superficial and not for thickness survey. Can be applied in several sensors to achieve best results.
Sonic / ultrasonic transmission	Highly recommended	Direct application- strongly recommended Indirect application- solely for near surface info. Compatible for cut stone geometry for obtaining info of shape of stone. ("well worked" façade with inner irregularity)
Impact Echo	Highly recommended	To detect section thickness if unknown. Reference sonic velocity measurement should be taken from a single stone and may demand local plaster removal.
Infrared thermography	Not Recommended	Not necessary in non plastered structures.
GPR	Highly recommended	Horizontal and vertical profiles should be taken, in sequential order. It is recommended to locate profiles within the courses of the stone for better contact with scanning unit. For very high thicknesses a 500 MHZ antenna can be used.
MDT	**Recommendation**	**Appliance**
Boroscopy	Moderately recommended	Preferably applied in existing boreholes or empty mortar joints. Otherwise, can be applied in mortar joints or, as a last resort, by drilling within the stone elements.

MILITARY- Single leaf Granite - Standing wall

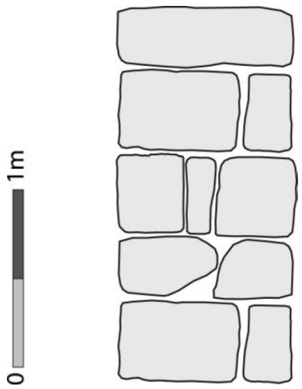


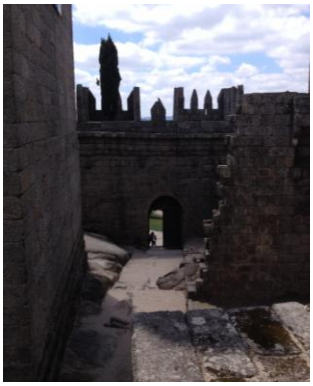


Material **Granite**	Mortar **Dry stone**
Thickness **93 cm**	Height **6m**
Unit size (h) **30-45 cm**	Geometry **Ashlar**
Finish **Bare masonry**	Found in **Guimarães**

DAMAGE SURVEY		
Thick-wall granite standing wall		
Visual Inspection	**Compulsory**	Search for typical damages: ▪ Moisture and leakage ▪ Overloading and change of use ▪ Granite deterioration processes
NDT	**Recommendation**	**Appliance**
Infrared thermography	**Moderately recommended**	Not necessary in the case of non-plastered structures, but can be useful for the detection of moist stones by active radiation execution
Sonic / ultrasonic transmission	**Highly recommended**	Direct and indirect transmission can suggest deteriorated state of the stones, presence of voids and lack of mortar, etc. A reference measurement should be taken through a single stone to compare with results.
GPR	**Highly recommended**	For detection of voids and inclusions. High or low resolution antennas can be used, for near surface or in-depth analysis accordingly.
Laser Scanning	**Highly recommended**	For long term monitoring of damage as well as database creation for the case of destruction due to natural disasters.
Hardness test	**Highly recommended**	A very simple method to achieve immediate mechanical properties relating to superficial surface, which can suggest damage. Should be applied in several locations, including reference locations which seem "healthy".
MDT	**Recommendation**	**Appliance**
Sampling, Moisture and salt anions content	**Highly recommended**	Sampling for comprehensive data acquisition. Sampling must be made in specified, possibly damaged locations with comparative samples. Must be documented strictly.
Boroscopy	**Moderately - locally recommended**	In the suspicion of external leaf detachment can be applied locally. Existing empty joints or voids should be used for inspection rather than intentional drilling.

MILITARY- Single leaf Granite - Standing wall





Material	Mortar
Granite	**Dry stone**
Thickness	Height
93 cm	**6m**
Unit size (h)	Geometry
30-45 cm	**Ashlar**
Finish	Found in
Bare	**Guimarães**

MECHANICAL SURVEY		
Thick-wall granite standing wall		
Visual Inspection	**Compulsory**	Search for areas of interest: ▪ Representing section ▪ "Special" section- damaged/ overloaded
NDT	**Recommendation**	**Appliance**
Sonic / ultrasonic	**Highly recommended**	Results for elastic properties can be achieved with direct and indirect applications. Method is not fully compatible for masonry and accuracy of the results should be taken into account.
Hardness test	**Moderately - locally recommended**	A very simple method to achieve immediate mechanical properties relating to superficial surface. Should be applied in several locations, including those inspected as damaged.
MDT	**Recommendation**	**Appliance**
Coring	**Moderately recommended**	Sampling should be done in the direction of the loading, and standardized dimensions must be considered.
Micro sampling	**Highly recommended**	Destructive tests for compression, tension and bending can be conducted and results can be obtained in situ. Allows finding resistance of the stone or mortar units and not the state of stress or modulus of elasticity of the masonry as a composite material.
Flat Jack	**Moderately recommended**	Results obtained solely for single leaf. Cannot be applied on whole wall section, yet can achieve individual indications for external leaves.
Double flat jack	**Moderately recommended**	Results obtained solely for single leaf. Cannot be applied on whole wall section, yet can achieve individual indications for external leaves.
Tube jack	**Moderately recommended**	Results obtained solely for single leaf. Cannot be applied on whole wall section, yet can achieve individual indications for external leaves.

10.2 ANNEX 2- Test Results of Morphology Survey in Guimarães Castle

10.2.1 Direct Sonic Tests

PointA_Row1			
velocity (m/sec)			
#	**p11**	**p12**	**p13**
1	984	438	529
2	881	611	421
3	1250	498	417
4	898	494	404
5	881	540	376
6	944	450	408
7	873	525	412
8	864	450	418
9			
10			
average	946.9	500.8	423.1
st. dev	129	58	45
Variation Coeff	13.6%	11.6%	10.7%
Test Average			**623.6**
distance [m]	0.93	1.2	1.68

PointA_Row2			
velocity (m/sec)			
#	**p21**	**p22**	**p23**
1	600	451	525
2	672	374	480
3	676	538	476
4	603	366	440
5	607	395	475
6	646	417	464
7	576	398	440
8	442	516	452
9		440	
10		497	
average	602.8	439.2	469.0
st. dev	74	60	28
Variation Coeff	12.3%	13.8%	5.9%
Test Average			**503.7**
distance [m]	1.01	1.23	1.73

PointA_Row3			
velocity (m/sec)			
#	**p31**	**p32**	**p33**
1	571	712	560
2	624	734	429
3	644	719	594
4	577	738	403
5	611	587	428
6	591	610	430
7	585	646	
8	577	511	
9		708	
10			
average	597.5	662.8	474.0
st. dev	26	79	81
Variation Coeff	4.4%	12.0%	17.1%
Test Average			**578.1**
distance [m]	1.22	1.41	1.86

PointC_Row1			
velocity (m/sec)			
#	**p11**	**p12**	**p13**
1	451	397	400
2	468	413	400
3	338	411	263
4	479	475	308
5	309	480	395
6	340	418	396
7	334	366	397
8	449	452	319
9	445	377	315
10	449	383	328
average	406.2	417.2	352.1
st. dev	67	40	51
Variation Coeff	16.4%	9.6%	14.5%
Test Average			**391.8**
distance [m]	1.23	1.01	1.23

PointC_Row3			
velocity (m/sec)			
#	**p31**	**p32**	**p33**
1	417	667	596
2	543	752	348
3	520	485	617
4	571	480	610
5	560	522	560
6	579	479	563
7	550		610
8	443		607
9	463		536
10	479		536
average	512.5	564.2	558.3
st. dev	58	117	80
Variation Coeff	11.3%	20.7%	14.4%
Test Average			**545.0**
distance [m]	1.23	1.01	1.23

Wall Average	
#	**TA**
A1	623.6
A2	503.7
A3	578.1
C1	391.8
C3	545.0

Average	**528.4**
st. dev	88
Variation Coeff	16.7%

10.2.2 Indirect Sonic Tests

Vertical- Point A			
velocity (m/sec)			
#	**B**	**C**	**D**
1	581	806	1042
2	588	893	909
3	694	1000	1261
4	595	943	1103
5	595	847	938
6	556	962	893
7	735	847	1071
8	694	1136	1014
9	820	1124	1110
10			980

average	650.9	950.9	1032.1
st. dev	89	119	111
Variation Coeff	13.7%	12.5%	10.8%

Distance	0.5m	1.0m	1.5m
Average velocity		**878.0**	**[m/sec]**

Horizontal- Point A			
velocity (m/sec)			
#	**11**	**12**	**13**
1	864	1032	719
2	1092	985	no signal
3	1094	707	847
4	972	897	no signal
5	1077	778	830
6	854	739	857
7	787	956	875
8			775
9			808
10			827

average	962.9	870.6	817.25
st. dev	129	129	50
Variation Coeff	13.4%	14.8%	6.1%

Distance	0.7m	1.4m	2.1m
Average velocity		**883.6**	**[m/sec]**

Horizontal- Point B			
velocity (m/sec)			
#	**21**	**22**	**23**
1	972	693	847
2	886	583	691
3	959	838	729
4	897	915	775
5	636	828	no signal
6	824	892	no signal
7	722	805	729
8	864	782	538
9		729	
10		875	

average	845	794	718.2
st. dev	115	102	103
Variation Coeff	13.6%	12.8%	14.4%

Distance	0.7m	1.4m	2.1m
Average velocity		**785.7**	**[m/sec]**

10.2.3 Reference Stone- Direct & Indirect Sonic Tests

Reference-Direct	
velocity (m/sec)	
#	**ac1**
1	2773
2	2773
3	2905
4	2652
5	2542
6	2905
7	2542
8	3050
9	2905
10	2440

Reference-Indirect	
velocity (m/sec)	
#	**ac1**
1	1667
2	1346
3	1892
4	1750
5	1273
6	1628
7	1750
8	1250
9	1458
10	1556

average	**2748.7**
st. dev	199
Variation Coeff	7.2%

average	**1557.0**
st. dev	219
Variation Coeff	14.1%

distance [m]	0.61

distance [m]	0.34

10.2.4 Impact Echo Tests

Point_23			
Frequency [HZ]			
#	**peak1**	**peak2**	**peak3**
1	451	1586	2819
2	451	1574	2758
3	452	1587	2783
4	451	1575	2685
5	452	1587	3003
6	452	1575	2564
7	445	1575	2588
8	452	1588	2215
9	452	1575	
10	452	1575	2819
average	451.0	1579.7	2692.7
st. dev	2	6	223
Variation Coeff	0.5%	0.4%	8.3%
Distance [m]	**3.05**	**0.87**	**0.51**

Point_4			
Frequency [HZ]			
#	**peak1**	**peak2**	**peak3**
1	952.1	1562.5	2600.1
2	964.4	1562	2557
3	952	1562	2294
4	964	1562	2319
5	964	1562.5	2197
6	964.4	1562.5	2294
7	964.4	1562.5	2246
8	799		2185
9			1940
10			
average	940.5	1562.3	2292.5
st. dev	57	0	198
Variation Coeff	6.1%	0.0%	8.6%
Distance [m]	**1.46**	**0.88**	**0.60**