Typology based Method for Choosing Old Masonry Walls Inspection Procedures

L.F. Ramos[1], F.M. Fernandes[2] & D. Chesler[3]
[1]*ISISE - University of Minho, Guimarães, Portugal*
[2]*ISISE - University Lusíada – Norte, Vila Nova de Famalicão, Portugal*
[3]*Former MSc student, University of Minho, Guimarães, Portugal*

ABSTRACT: The diagnosis of historic masonry walls is an intricate and complex field and has been an object of research for many years. This paper aims to propose practical methodologies for the diagnosis of historic masonry walls, specifically based on their typological characteristics. In order to develop such procedures, information relating to historic masonry typologies in Portugal, classified as rural, urban and military was gathered and techniques for the assessment of historic masonry were studied. All information was integrated to develop a pattern typology oriented methodology. Developed methodology was tested and validated in a small diagnosis campaign carried out in the Guimarães Castle. Methodology was proven to be advantageous and although the study is limited and focused on the Portuguese architectural specificities, it still holds global classifications, and therefore can be useful for any diagnosis procedure of a historic masonry wall.

1 INTRODUCTION

Historic masonry walls and their diagnosis processes present a great challenge to preservation researchers and designers/annalists. When planning an intervention for a historical monument the designer/annalist must consider numerous factors. Many destructive to non-destructive tests are available for his dispense, but many other factors must be taken into consideration during the decision making process. Each wall can be different from his formers, and hold surprising findings. This leads to a difficulty in gaining correct assessment of the walls, especially related to the decision of what tools to use, and raises the question of the possibility of creating a global useful methodology to choose the right tools for a better diagnosis.

Significant factors may be the type of the structure, its size, the available local materials, used construction techniques, physical characteristics, and even the level of significance to the cultural heritage. This must be considered as the available tests often have elevated costs, and complicated execution processes. Previous studies (Binda & Saisi, 2002) have shown that a relation can be found between masonry morphology and geometry to its mechanical properties and structural behaviour. Thus, surveying these typologies has a great prospective in achieving better assessments and higher accuracy in masonry testing.

2 MASONRY TYPOLOGIES IN PROTOCOL

For the protocol of the research, Portugal was chosen as a case study and its masonry structures were classified by typology. Three main categories were chosen, dividing the constructions into rural, urban and military type. These classifications embody fundamental differences between them, which lie in the basic questions of the original designated function and practice of its execution. Rural and urban housing typologies were designed for dwelling purposes, and oriented for their inhabitants' needs and economic abilities, on the other hand, monuments and military typologies, were generally intended for much more durable functions. 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. Furthermore, typology can indicate structural characteristics as morphology, geometry, regularity, etc. These properties are fundamental inputs when designing a diagnosis procedure.

The three masonry typologies in the country were surveyed, their differentiating characteristics obtained, and pronounced repeating properties within each typology were assessed. A summary of the surveyed typologies and their mechanical properties is given in Table 1. Nonetheless, other variables have shown to be significant leading to the definition of common sub typologies. These sub typologies vary in morphology, building materials and geometry. They serve as the base for the study.

Table 1 - Summary of surveyed masonry structures related 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	Self weight, weight of the floors and roof	Self weight, weight of the floors and roof	Self weight, 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.

Figure 1 exhibits the typologies obtained from previous studies in Portugal that were chosen as the base for this study: (a) Rural single leaf granite wall, found in Vila Real; (b) Rural double leaf limestone and earth construction, found in Algarve (Casella, 2003); (c) Rural double leaf schist wall, found in Alentejo; (d) Urban single leaf granite wall, found in Porto (Mota, 2009); and (e) Urban single leaf Limestone wall, found in Lisbon (Pinho, 2000); (f) Military triple leaf limestone retaining wall, found in Setubal (Casella, 2003); (g) Military triple leaf limestone standing wall, found in Alentejo (Casella, 2003); (h) Military single leaf granite standing wall (thick wall), found in Guimarães.

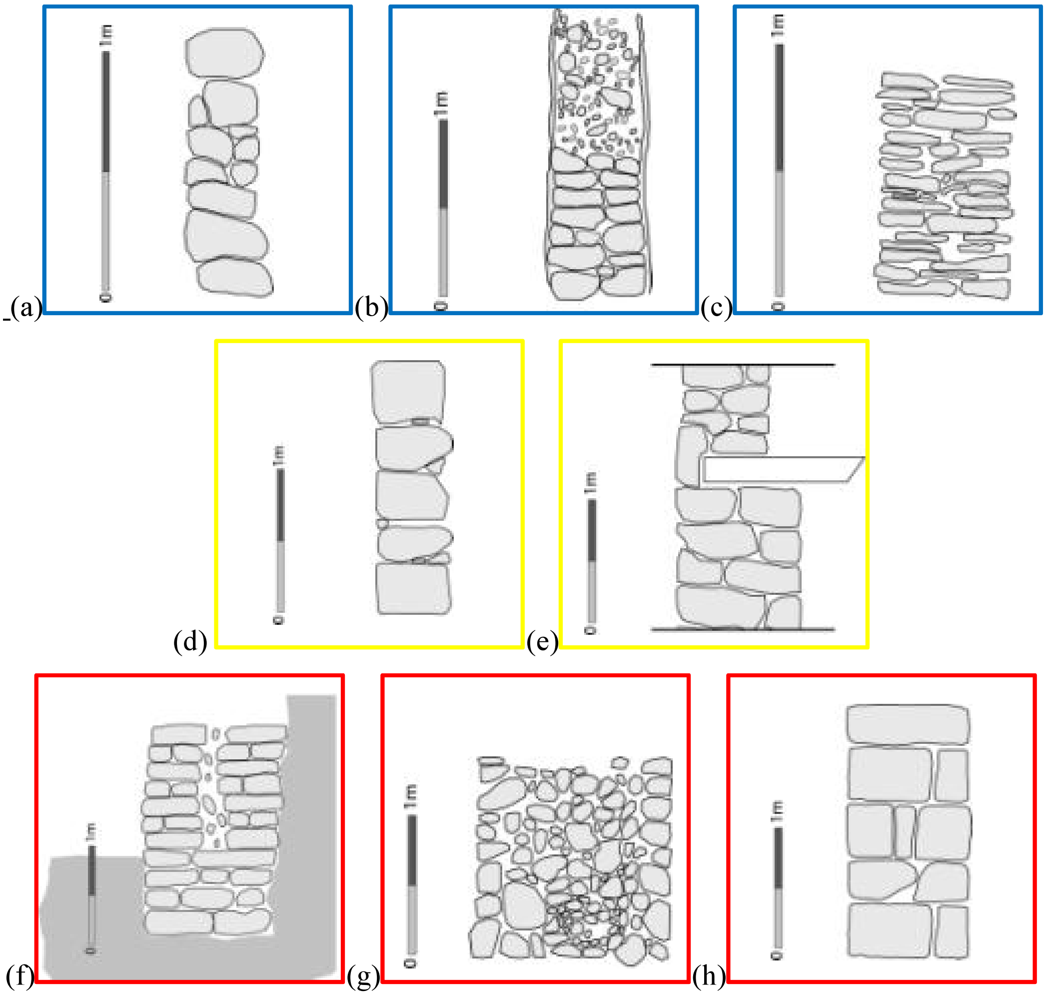


Figure 1 - Common masonry typologies in Portugal.

3 PROPOSED METHODOLOGY

The proposed methodology is a pattern guidance tool, starting from a general theoretical guideline for each typology, followed by the definition of the diagnosis question and branching out to classifications within the typologies themselves.

As a first step, general guidelines for each typology were defined independently. Rural structures, which are small scale in both section and elevation, and are generally simply built, dictated simple, reachable methods for both the diagnosis and the intervention. This desired simplicity is an outcome of the typology itself and its basic characteristics. Simple constructions call for simple preservation measures. Urban typology structures, which can generally be considered as medium size wall sections, the main guideline is its repetitive nature. Previous studies of these typologies are available and can be an important tool for anticipating damages, expecting and verifying results and for choosing the correct inspection methods, based on in situ experience. Military wall typologies, challenge the researcher with the aspect of size. Massive sections and wide-spreading of the structure impose limitations, and different types and quality of masonry can be expected within a single monument. Consequently, the general approach to choosing inspection procedures for each typology is essentially different.

The second step was defining the specific question of the inspection, referring to the fact that damage surveying will necessarily dictate other procedures than morphologic or geometric survey. As a third and last step, the physical variables within each typology were taken into consideration. The sub classifications that were chosen are geometry, material, morphology and finish technique.

This methodology enables smart selection of inspection procedures. Primarily, a reserve of available procedures was defined for each typology taking into consideration its general guideline and properties (as size and building technique). Secondly, selection of available tests was further narrowed in accordance with subcategories. In this manner, different combinations of techniques are found useful for a combination of different elements. To complete the pattern guidance tool, a corresponding implementation tool was adapted for each end typology. The possible procedures are classified on a scale of recommendation, starting from compulsory tests to not-recommended tests and primer guidelines for execution of the process.

Tables 2 and 3 show the funnel pattern methodology and implementation tool for the damage survey of type (b) wall (see Figure 1): Ordinary limestone double leaf plastered rural wall.

Table 2 - Funnel pattern methodology for damage survey of a double leaf limestone rural wall.

Table 3 - Implementation tool for damage survey of a double leaf limestone rural wall.

Plastered Double Leaf Limestone		
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 and salt 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.

4 APPLICATION

The recommended methodology was tested and validated in a small diagnosis campaign carried out in the Guimarães castle. A non-destructive testing campaign was held to complement the study of methodology for inspection and diagnosis of military constructions.

4.1 Methodology Planning

The site conditions were classified according to the methodology pattern and were recognized as indicated in Figure 2.

Figure 2 – Methodology for pattern recognition.

The question of the inspection was defined as morphological survey. The testing compound deriving from the two given inputs, prescribes through the funnel pattern methodology a compound of: 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.

4.2 *Morphologic Survey*

4.2.1 *Visual Inspection*

As a first and compulsory step, a visual inspection was conducted, consisting of primer visual survey, photographic survey, and positioning of further testing. The Castle of Guimarães, as is visible in Figure 3a, consists of a central watchtower which is surrounded by eight lateral towers connected by a battlement. The location chosen for the testing process was an interior battlement wall which allowed conducting direct sonic testing, as well as GPR scanning and Impact Echo reflection.

The chosen interior battlement wall has an apparent thickness of 0.93 m (as in Figure 3b). 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 3c presents the testing areas in the wall.

(a) (b) (c)

Figure 3 - Views from Guimarães Castle: (a) plan of the castle with location of conducted campaign pointed out (Adapted from: Moreira, 2010), (b) apparent cross-section of the wall, and (c) general layout of the tested wall (GPR profiles in dashed white lines and sonic tested area in red).

4.2.2 *Ground Penetration Radar*

Three horizontal profiles were carried out along the main axis of the stone units, and one vertical radargram. These radargrams are illustrated in the following figures. Figure 4 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 0.3-0.4m 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.

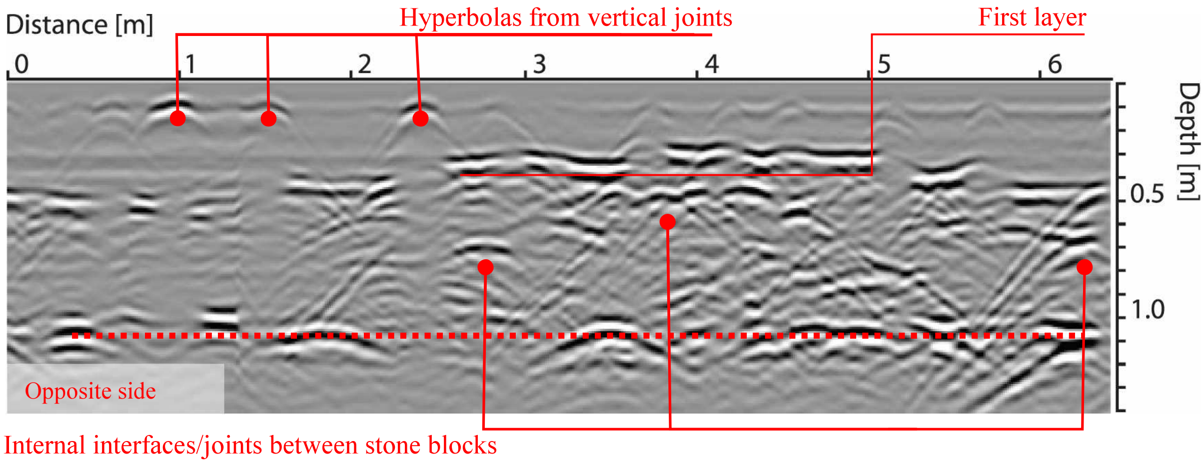


Figure 4 - Horizontal radargram from the 4th row of battlement wall.

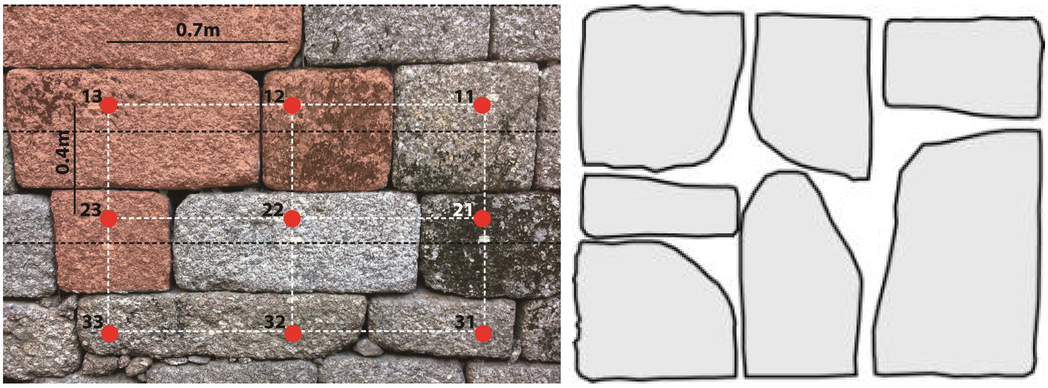
The additional horizontal profiles that were obtained from the 5th and 6th rows of the wall showed similar results. In the vertical profile collected, the inner structure can further be observed. A first layer is evident, with a rather irregular thickness, an inner layer, which apparently is larger than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

4.2.3 *Direct Sonic Transmission*

As part of the preliminary study, direct sonic tests were performed on a single granite stone from the masonry wall. Ten measurements were acquired to obtain an average value. The average value obtained was 2748.7 m/sec, with standard deviation of 199 m/s and a coefficient of variation equal to 7.2%. The measured velocity is within the range of expected velocity in historic stone (Moreira, 2010). Indirect transmission was also obtained on the reachable surface. The average value obtained was 1557 m/s, with standard deviation of 219 m/s and a variation coefficient of 14%.This data was used as reference value in further testing operations.

The corresponding direct sonic test was carried out on a prescribed 3 by 3 grid of 0.7m (horizontal) and 0.4m (vertical) spacing. Two hitting points were set on the opposite side of the wall; each pulsed in sets of 10 hits, collecting data from two accelerometers placed successively in the nine receiving points. Layout of the receiving grid can be seen in Figure 5a.

The average velocity through the wall obtained from the tests was: 533.7 m/sec, with a coefficient of variation equal to 15%. This velocity is substantially lower than the reference velocity through a single stone (2775 m/s), 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 state, 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 Figure 5b, was widely used in historic times.



(a) (b)

Figure 5 - Aspect of the (a) layout of the testing grid for direct sonic testing, and (b) horizontal plan of the masonry section illustrating exterior regular joints with irregular interior shape.

4.2.4 *Impact Echo*

Impact echo reflection test was carried out in four stones, two of which were suspected to be transversal stones, and two that were obviously part of a layered section. 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 6a. 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.

$$d = \frac{C_p}{2f}$$

Results of two measured points showed results representative of wall morphology. One of the points 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 the other points. All measurements showed a very low coefficient of variation (less than 1%). Figure 6b illustrates this diagnose.

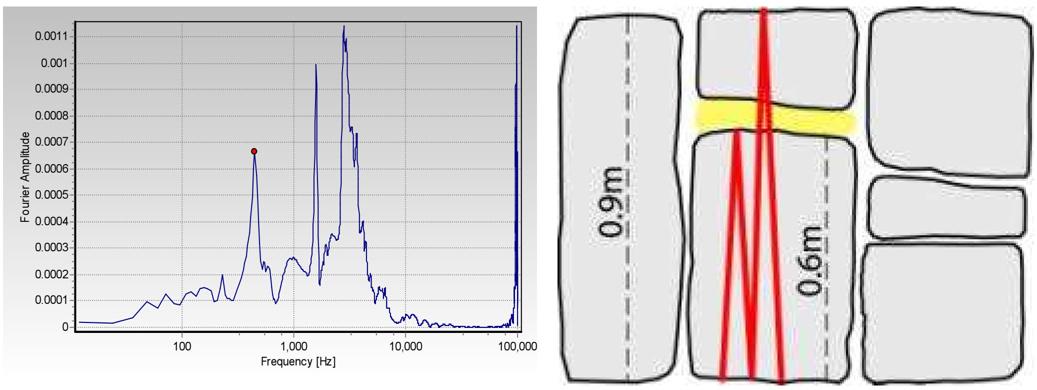


Figure 6 - Plot of (a) frequency signal showing multiple peaks, and (b) horizontal plan of masonry section illustrating interior interfaces with large, detectable joints.

4.3 *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 illustrates an estimated horizontal section in 4th stone course, at a height of approximately one meter from the ground.

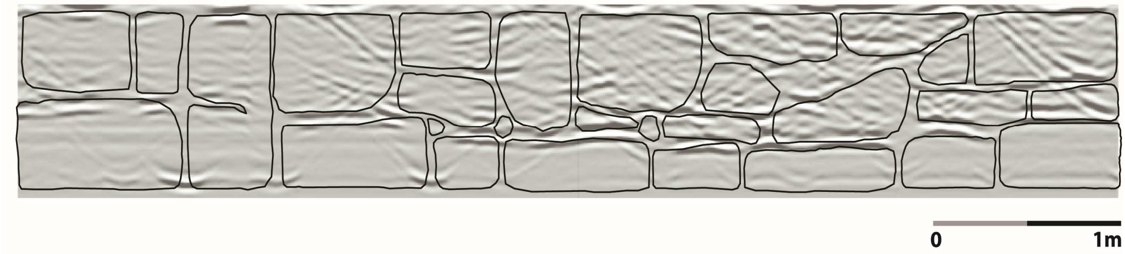


Figure 7 - Horizontal plan of 4th course stone morphology estimation on top of radargram.

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 8a.

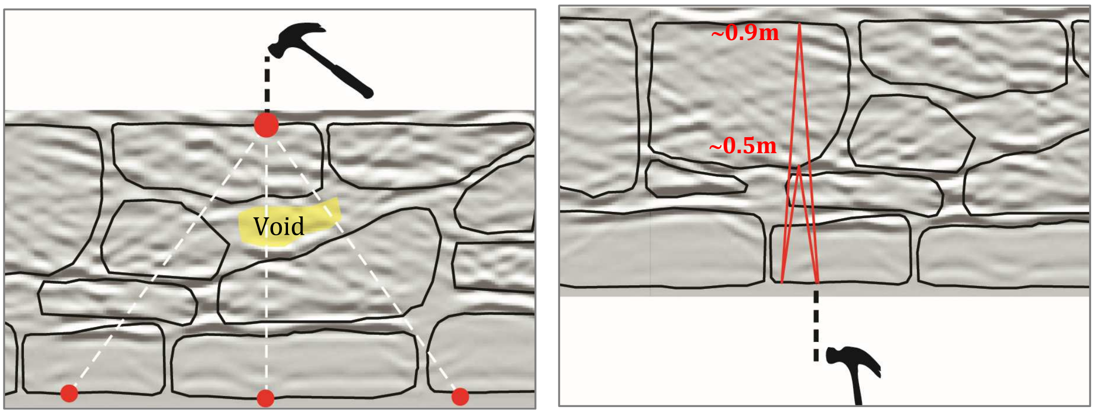


Figure 8 - Execution schemes and interpretation of (a) sonic transmission and (b) impact-echo.

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 Figure 8b. These are found in the estimated morphology, yet are not the only interfaces in this section.

5 CONCLUSIONS

The study showed that advantages could be drawn to the field of historic heritage diagnosis by utilizing typological information. Using typology based methods can make the diagnosis process efficient in terms of time and methods of assessment chosen, usefulness of results and minimal damage to the heritage.

The preliminary guidelines for the inspection of the prescribed typologies are inherently different due to the properties of the typologies themselves. Inspection of rural typologies must initially take into consideration simplicity and feasibility. Urban typology diagnosis is guided by repetition and previous studies, and should prioritize a step-by-step approach preferable due to its size and density characteristics. In military typologies, the fundamental factor is size, and designing a broad campaign while attaining complimentary results. Secondary guidelines for the inspection correspond to varying physical properties within the typologies themselves, creating a funnel pattern methodology, eliminating non useful test methods.

The validation process must be an inherent part of the methodology development. The studied campaign illuminated the importance of preplanning for a successful application, yet simultaneously showed the advantage of flexibility in situ to complete the campaign. Complimentary tests must be conducted in a recurring location in order to validate results which otherwise cannot be fully trusted. For completing the task of this pattern methodology much wider applications should be held to validate all proposed scenarios.

Furthermore, this study lies on the basis of eight typologies, found in Portugal. It has a potential to be further established on a wider foundation, including a comprehensive database which holds global classifications that can be useful for any diagnosis procedure of a historic masonry wall.

REFERENCES

Binda, L. & Saisi, A. 2002. State of the Art of Research on Historic Structures in Italy, Proceedings of 11th Advanced Research Initiation Assisting and Developing Networks in Europe (ARIADNE) workshop.

Casella, G. 2003. Grammars of Stone - Survey of typologies of wall constructions, Regional centre of traditional arts, Porto (in Portuguese).

Moreira, S. 2010. Report on Non Destructive Testing in the Castle of Guimaraes, Minho University, Guimarães (in Portuguese).

Mota, E.M.V. 2009. Characterization and In-Situ Investigation of Stone Masonry Walls, Dissertation submitted for partial fulfilment of the requirements of the degree of Master in Civil Engineering - Expertise in Structures, University of Porto, Porto (in Portuguese).

Pinho, F.F.S. 2000. Walls of Ancient Buildings in Portugal, Lisbon, LNEC, ISBN 9789724918648 (in Portuguese), pp.412.