

ADVANCED MASTERS IN STRUCTURAL ANALYSIS OF MONUMENTS AND HISTORICAL CONSTRUCTION

Master's Thesis

Amruta Shrikant Uplekar

Structural characterization and analysis of the Castle of Arbeteta, Spain



University of Minho

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of Arbeteta, Spain**

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Year: 2018 - 2019

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.

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ABSTRACT

The Castle of Arbeteta, Guadalajara (Spain) is strategically located on top of the cliff rocks with a drawbridge as its only entrance. The castle has undergone various changes in over the time of centuries. It was once a two storey structure, of which only the ruins of the external walls exist. The castle is in a continuous state of degradation due to abandonment.

Currently, there is an ongoing intervention project where a new use is going to be given to the castle. This will inevitably alter the current state of the existing structure. Preliminary inspection works and a detailed archaeological survey was carried out which specified the phases of construction of different sections of the castle. However, there is still need of a better characterization of the stone masonry walls and their structural behaviour. The main research question of the present thesis deals with the possible influence of the construction evolution of the castle on its structural behaviour. The thesis thus try to link two commonly separated and hermetic fields from the conservation projects: archaeological survey and structural analysis. For that matter, a non-destructive campaign consisting of indirect sonic tests and dynamic identification, which aimed at a thorough characterization of all the structural elements was planned. The campaign was carefully planned according to an archaeological research previously carried out. Secondly, a numerical model was made to analyse the structural behaviour of the castle, based upon photogrammetry model and the same archaeological survey. The experimental data collected through indirect sonic tests and dynamic identification was used to calibrate the model.. The results of the thesis show that indeed taking into account the archaeological findings improved our knowledge on the structural behaviour of the castle and has to be taken into account before carrying out a rigorous structural analysis

Keywords: FEM; Structural Analysis; Stone masonry; Non-linear analysis; NDT; Dynamic identification; archaeological survey; construction evolution

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RESUMO

O castelo de Arbeteta, em Guadalajara (Espanha) está estrategicamente situado no topo de um penhasco rocoso que tem uma ponte levadiça como unico acesso. O castelo tem sido submetido a muitos cambios e alterações estruturais durante estes séculos. Num momento da sua história, o castelo era uma estrutura de dois andares, dos que agora só as ruínas das paredes de alvenaria de pedra exteriores ainda existem. O castelo está agora num processo de degradação continuo devido ao seu abandono.

No momento, existe um projeto de intervenção no castelo e um novo uso vai ser proposto no castelo. Isto vai alterar inevitavelmente o estado atual da estrutura existente. Inspeções preliminares do castelo e um levantamento arqueologico detalhado foram realizados e ajudaram a identificar as diferentes fases de construção nas diferentes partes do castelo. Contudo, uma melhor caracterização das paredes de alvenaria de pedras é necessária, para ajudar a compreender melhor o seu comportamento estrutural. Esta investigação estuda principalmente a possível influência da evolução estrutural do castelo no seu comportamento estrutural. A tese portanto trata de ligar dois campos necessários nos projetos de conservação que estão normalmente separados e muito compartimentados: o levantamento arqueologico e a análise estrutural. Com este objetivo, uma campaha de ensaios experimentais não destrutivos que incluiu ensaios sónicos indireitos e ensaios de identificação dinâmica foi planejada e destinada a caracterizar em detalhe todos os elementos estruturais do castelo. A campanha foi planejada cuidadosamente de acordo à investigação arqueologica previamente realizada. Numa segunda parte do trabalho, um modelo numerico foi preparado para analisar o comportamento estrutural do castelo, baseado no modelo fotogrametrico e no levantamento arqueologico. Os resultados experimentais recoletados dos ensaios sonicos e dinamicos foram usados para calibrar o modelo numérico. A tese mostra que, de fato, a consideração das descobertas arqueologicas melhoraram o entendimento do comportamento estrutural do castelo e tem de ser tidos em conta antes de realizar um análise estrutural rigoroso.

Palavras chave: elementos finitos; análise estrutural; alvenaria de pedra; análise não linear; ensaios não destrutivos; identificação dinâmica; levantamento arqueológico; evolução construtiva

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1. INTRODUCTION

There are several historical constructions which have become symbols of culture and architectural aesthetics but also engineering marvels. These structures have huge scale and magnificent spans. Their existence is both inspiration and connection with our past. It is necessary to preserve them so that they can be passed on to the next generation.

Among these structures are forts and castles, which were once built as defensive architectural feature, but many of them are now in a state of ruin due to abandonment and loss of function. They are showing the signs of degradation, lack of use and material deteriorations due to withstanding past raids, plundering, climatic conditions and facing changing environmental aspects. Given this ruined condition with partial collapses and missing parts, they might require some structural analysis and repair/strengthening able to prolong their life.

One such structure is the castle of Arbeteta in Spain, which is in a state of ruin and needs conservation. This work proposes to study in detail the structural condition of the building with a particular focus on understanding its historical chronology and material properties.

1.1 Objectives

As previously stated, the present thesis put a particular focus on the historical chronology of the castle. More specifically, the main research question of the thesis is whether or not the historical evolution of the castle has a significant influence on the structural behavior of the castle. In order to address the aforementioned research question, the work embraces the following three specific objectives:

- a) Structural characterization of the stone masonry walls of the castle by means of non-destructive testing in terms of: (a) external and internal morphology; and (b) mechanical properties;
- b) Extract correlations between the construction phases of the building identified by the archaeological survey and the morphological, material and mechanical properties of the masonry.
- c) Preparation of a numerical model based on the existing photogrammetric model and calibrated with the experimental data and dynamic identification tests and incorporating the findings from the archaeological investigation.

1.2 Outline and organization of the thesis

Besides this introductory chapter, this thesis is composed of six additional chapters, and their description is given below.

Chapter 2 addresses the history of the Castle of Arbeteta and its surrounding. It also includes the castle's history and the various phases of construction throughout its history.

Chapter 3 addresses the 3D modelling of the Castle and its simplification.

Chapter 4 Identification of the Material characteristic by NDT and Masonry qualitative Index analysis

Chapter 5 discusses the process of Operational Modal Analysis of the structure

Chapter 6 addresses the calibration of the experimental model with numerical model. It also discusses the updating of the model for calibration while Chapter 7 compiles the major conclusions and recommendations.

2. HISTORIC SURVEY

This chapter reviews the site surroundings, location and historical background of Castle of Arbeteta. It also includes the chronological construction of the castle since its conception, which is summarized based upon the archaeological findings (En, G., & Castillo, E. L. (2019)). Then, the morphology of the structure and the construction of the 3D model, which will be further used for modal analysis and Finite element modelling (FEM), are described. The stratigraphic information about the castle which is discussed in this section will further provide a conjectural base for constructing the 3D model.



Figure 1:View of the castle

2.1 Site location of the Castle of Arbeteta

Castle of Arbeteta is a the Spanish castles located in the town of Arbeteta, in the province of Guadalajara. It is located as in Figure 2, in the ravine that forms the stream of the Rambla, in

the foothills of the Alto Tajo of the Alcarreña plateau. It is a strategically located castle of the province, which has a cliff on its northwest and south side being defended by a dry moat that precedes it by overhanging.

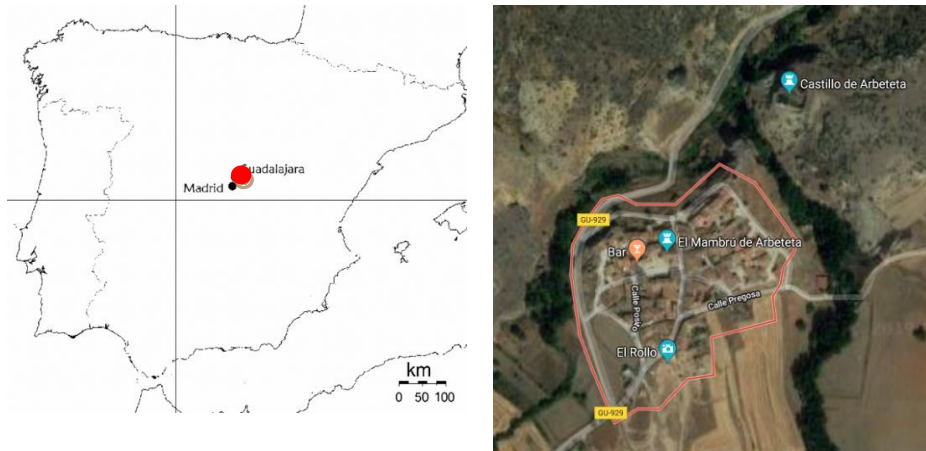


Figure 2:Location of province of Guadalajara and the castle of Arbeteta

2.2 Description of the structure

The castle has an irregular polygonal shape of approximate area of 1,440 square meter. It was once a two storey structure, of which only the ruins of the external wall exist. The thickness of the external walls vary in between 0.75 m to 2.6 m, as it will be further discussed in Chapter 3. The general external dimensions of the castle can be seen in Figure 3.

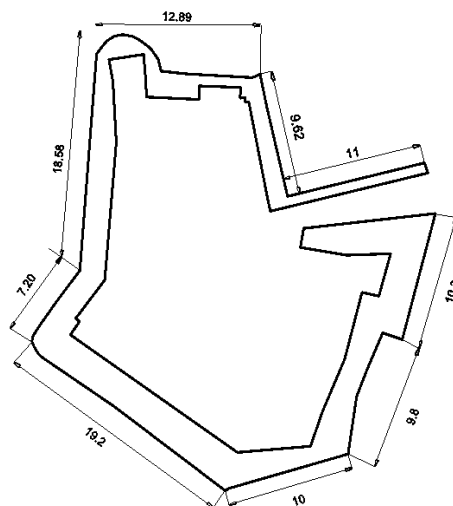


Figure 3:Plan of the Castle (measurements in meter)

It has a central courtyard with a cistern carved in rock, which is still preserved. The narrow pass through which the castle is now accessed, was once cut to surround the castle of a moat and make it only accessible through drawbridge. To the East, at the entrance of the castle one can see the remains of its tower. Figure 4 shows an old plan of the castle that was before abandonment.

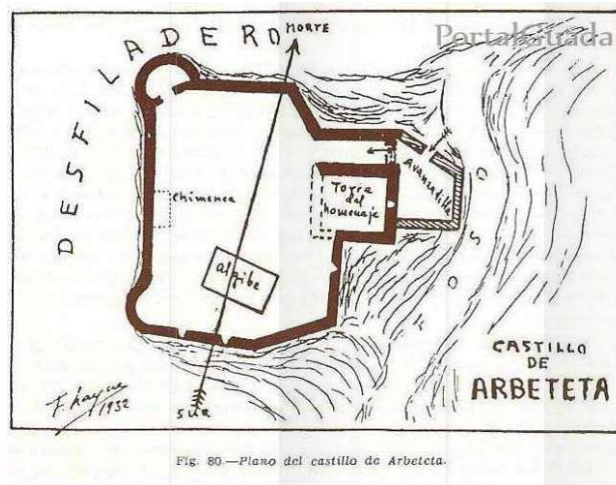


Figure 4: Plan of the Castle Dated 1932 A.D. (En, G., & Castillo, E. L. (2019))

2.3 History of the Castle

The castle most probably has an Islamic base. It was strategically located to obtain control over the Tagus river, which once flowed on the eastern side of the castle. As said before, it had a tower, which was built during the same time as the fortification of the city of Medinaceli, that is during the reign of Abd al-Rehman III (889/91 – 961 A.D.).

It can be said that the castle came into existence in 10th-11th century A.D. The oldest documentation which confirms the existence can be found after these territories were conquered by Alfonso VII and later allocated to the city of Cuenca in January 1190. This reference states its name as 'Arbetetam'. Since this time onward, the town and its castle were under the jurisdiction of the city council of Cuenca. From thereon, they controlled the colonization and defense of this border strip between the kingdom of Aragón and the Islamic territory, in the vicinity of the city of Molina de Aragón.

Arbeteta from this time onward and during the 12th and 13th centuries was an important point of passage for pastures and cattle and also for the communication between the cities of Soria and Cuenca. At the end of the 13th century, due to its strategic location, many small kingdoms tried to gain control over the castle. The continuous fights between these small kingdoms, created an area of constant conflict.

The conflicts continued within the Cuenca council in diverse attempts to recover their patrimony until an agreement reached and was signed in 1501. After that moment, the population, under the jurisdiction of Cuenca, remained in the land of a royal estate with its castle under the guardianship appointed by the crown.

2.4 Structural evolution of the castle

To know the historical potential of the castle, stratigraphic survey was carried out by a team of archaeologists. This section is intended to understand the phases of construction of the castle based on the archaeological research performed by this team (En, G., & Castillo, E. L. (2019).

The archaeological team concluded that there are a total of six phases of evolution of the castle of Arbeteta from its construction. A part of construction from each phase can still be seen in the castle. The main hypothesis of the thesis is that these construction evolution has an influence on the current structural behavior of the castle in terms of material properties, geometrical configuration and other constructive features, such as the level of connection between adjacent walls. Hence, this study is necessary as it forms the basis for NDT's and 3D modelling of the castle.

Each wall of the castle is annotated for better understanding. The following Figure 7 shows the nomenclature that is used to represent the constructive elements of the fortress. The same nomenclature is used to refer to exterior and interiors sides of the wall. This will further prove to be useful while understanding the character of the walls.

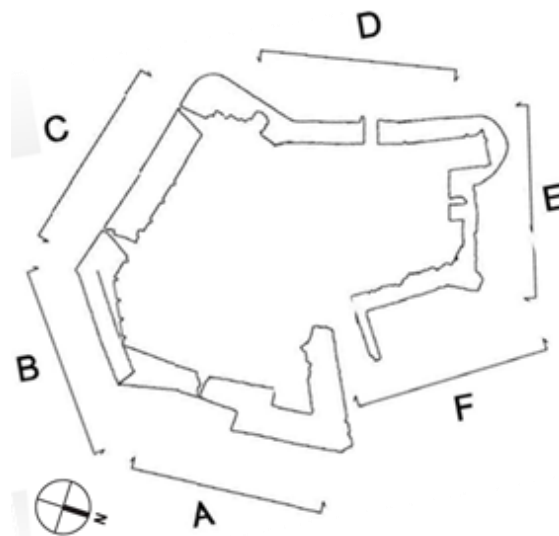


Figure 5: Nomenclature used for the facades of the castle

In summary, the evolution of the castle in different phases is as follows. The archaeological plans from the report with all the identified construction phases upon which the present work is based are presented in Annex A

Phase I : Border enclave 9th-11th century

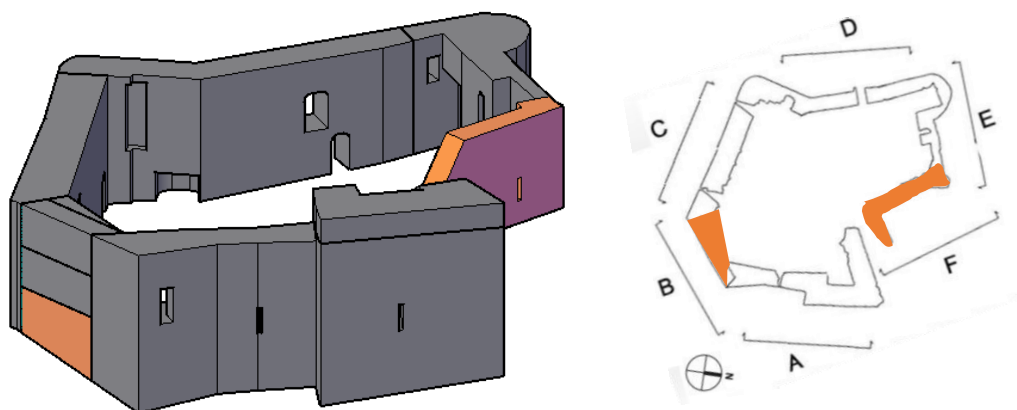
Phase II : Repopulation of the fortress.

Phase II B : Remainings of battlements 10th -11th century

Phase III : Manor Castle. The late 15th century early 16th century

Phase IV : Land tenure from Castilla 17th – 18th Century

Phase V : Abandoned and in a state of ruins 19th – 20th century

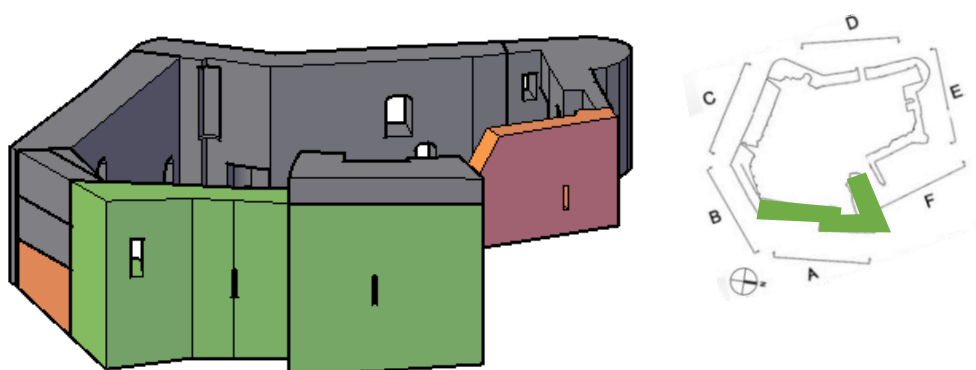
Phase I:**Figure 6:Phase I in wall F and base of wall B**

The above Figure 6 shows that the Wall F and base of wall B belongs to this phase. In case of wall B, it has three successive construction layers on top of it. The interior fabric of this wall was constructed in medieval period (Phase III). The construction comes from north to south making the new exterior corner from top to bottom.

In wall F, at this stage the extension of the wall that forms the south facade and the south-eastern is maintained. The masonry is more regularity in the outside courses than inside. It has very angular masonry, which has two faces with mortar filling.

Phase II:

Phase II focuses on the entire south east and the eastern side, Zones A and a middle area of zone B. as seen in Figure 7 Facade A shows construction of the modulus of the frontal tower, called the tower. Only the base of the tower remains now. No evidence of a previous phase can be seen here.

**Figure 7:View and key plan of wall A constructed in Phase II**

The structure is composed of four layers that support the ground in the latitudinal on the side, areas where they settle on the rock of the cliff. This portion at the base, not being in line with the rock, may be due to its advanced position on the previous fortification line (Phase I).

In zone B, the base of the wall is placed directly on the rock, without any foundation, giving a flat surface for it. The portion of the Zone A, which is said to be the tower keep of the castle, shows relatively regular ashlar masonry. The interior shows a mortar heavily laden with gravel river mixed with ceramic, which seems to come from the archaeological sites surrounding the castle.

It has high-rise walls which were designed to defend against attacks with torsion weapons, except for the small paw, they do not show a difference of thickness in the base or wall. They were designed to take on artillery impacts. For this reason they were high is the line of battlements and had merlons for defense that will be filled up by masonry in Phase III.

Phase II B:

Much information of this phase is unavailable. Only remains from this phase are observed on the wall B, the masonry from this phase rests between Phase I which is the base of wall B and Phase III, which is the top of the wall B. It can be seen in Figure 8.

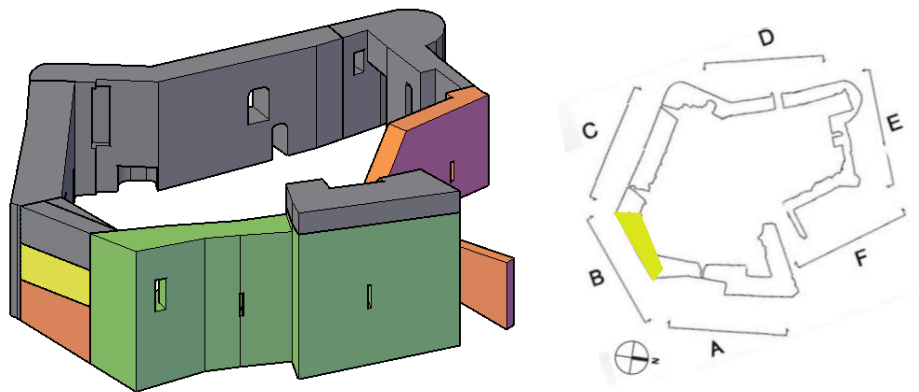


Figure 8:View and key plan of wall B constructed in Phase II

Phase III :

This phase can be said to be a great constructive phase, as it gives the castle its current form. It was probably turned into a manorial castle at the end of the 15th century and as it was within the territorial expansion of the lords of Medinaceli.

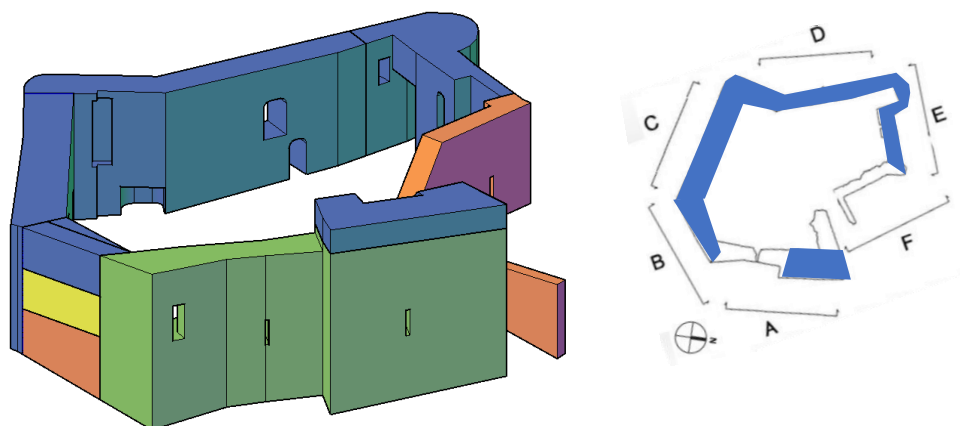


Figure 9: View and key plan of wall B, C, D and E constructed in Phase III

In this Phase, the entire west front, wall C, the north, zone D and the east, zone E, are built. This Phase of construction is supported by the remains of walls constructed in previous phases, walls A, B and F. In the area of exit, confluence of this Phase III on Phase I, with the conversion of a wall in a gate can be seen, while on the west and the new work surpasses part of the walls of Phase I, II, and IIB.

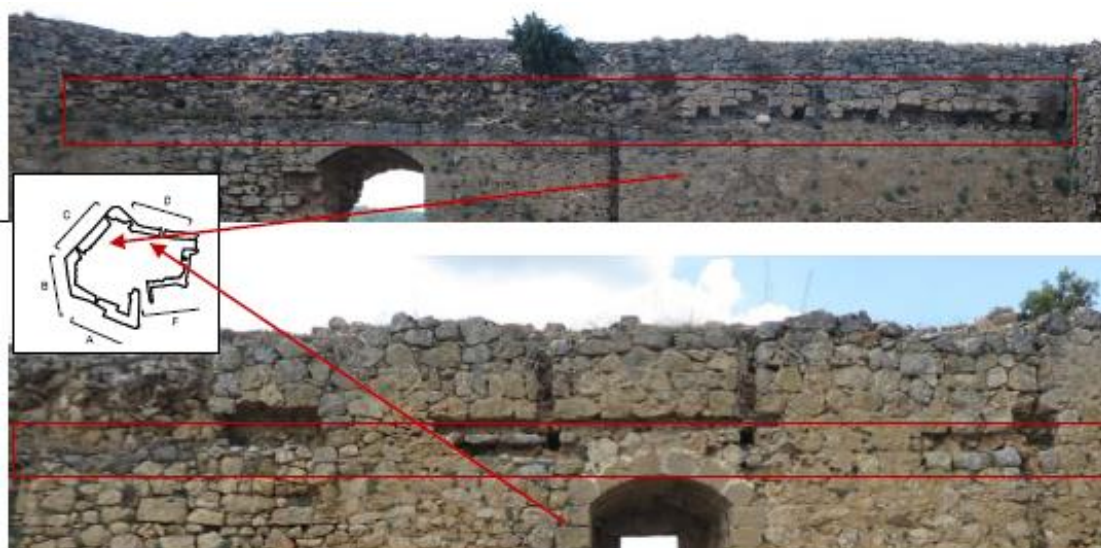


Figure 10: Niches in walls where wooden joist rested

It is possible that there were other vertical structural elements of wood as seen in Figure 10. Niches in the walls can be seen which suggest that a second floor existed. There was a possible existence of chimney in wall D as seen in Figure 11

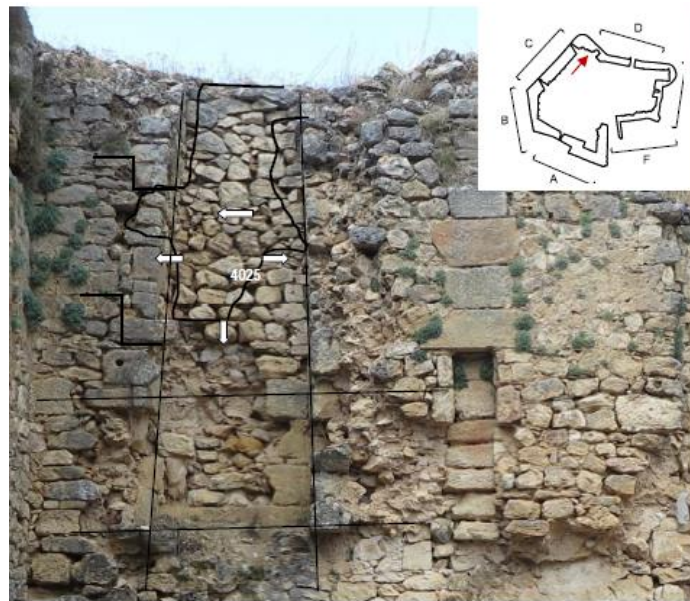


Figure 11: Position of a chimney in wall D

The construction shows strong walls of a width only similar to the side of the entrance tower. If the walls of Phase I had a thickness of about 1.70 m, in Phase II they approach 2 m. and in this Phase III there is an average of 2.5 m. varying in curve points and areas with double, overlapping masonry.

These walls rise entirely in a vertical plane without any thickening at its base. The height of the walls in this phase denotes defensive measures taken before the end of the 15th century. The wall thickness absorbs the impacts due to its volume. In the event of possible landslides, the height is lowered for better protection.

Phase IV:

The castle of Arbeteta is presented with three great constructive phases, after the completion of the third, in second half of the 16th century, the building enters a state of lethargy. Any signs of repair cannot be seen and the structure is in the phase of abandonment and spoliation of its construction material.

During this phase, a section of a wall on the northern ridge from the west was repaired. In this area, even today at the same point, the buckling of the walls towards the interior of the castle can possibly be observed as is not visible in photographs is marginal. On the other hand, from within it seems that there is a part of the masonry of less thickness, possibly one of the chimney shots and, as it is on its left side, it has been reconstructed, see Figure 12



Figure 12:Castle in the state of degradation due to abandonment

Phase V :

As in the case of any other large castles out of use and without custody, its becomes an effective quarry for the buildings of neighboring towns. In the castle of Arbeteta we can clearly follow the pillage that suffers, especially in regard to stone material. The window sills and doors, together with all the woodwork of the slabs, seem to have been stolen from the site.

In some cases, as is the loss of the corner supports and entrance arch, this looting involves the imbalance of the facades causing cracks and volume losses in the walls.

3. CONSTRUCTION OF 3D MODEL

With modern technology, several new techniques are available to record 3D information and generate high-resolution digital images. As most of the historical structures have a complex geometry, this technology is of a great advantage. For this 3D mapping two main methods can be used: the range-based methods, which are passive sensors that use a laser beam to record spatial information of the scene, and the image-based methods which involve the photogrammetry and use the structure from motion approach to reconstruct a digital 3D model from bidimensional photos.

For modelling of the castle of Arbeteta, Point cloud model was used. The Autodesk based software ReCap was used as it is easy to work with. Figure 13 shows the point cloud model of the castle of Arbeteta which was used to get accurate dimensions for the drawing of the solid model in Autocad 3D. The ReCap point cloud model was provided by Madrid based architectural firm: PROSKENE Conservation and Cultural Heritage.

AutoCAD and Recap, because of being Autodesk products, they allowed to easily cut the required level of section in ReCap and import it in Autocas and use it as a base map.



Figure 13: Point cloud Model of the castle in ReCap

3.1 Modelling decisions

As the castle is situated on a cliff and has a countour site, it wasn't easy to model it. Moreover, due to it currently being in a state of ruin, the model was simplified to accommodate the ruin part, namely the simplification of the material losses and the wall edges. Following decisions were taken during carefully modeling the castle ruins.

As the castle is situated on a countour site, first model was created using exact dimentions of the site. But as a side effect, extra small surfaces were created at the base of the model in AutoCAD due to too much detailing , complicating the model. Hence, a little liberty was taken with respect to the dimentions of the base while slicing the model. Final model as seen in Figure 14

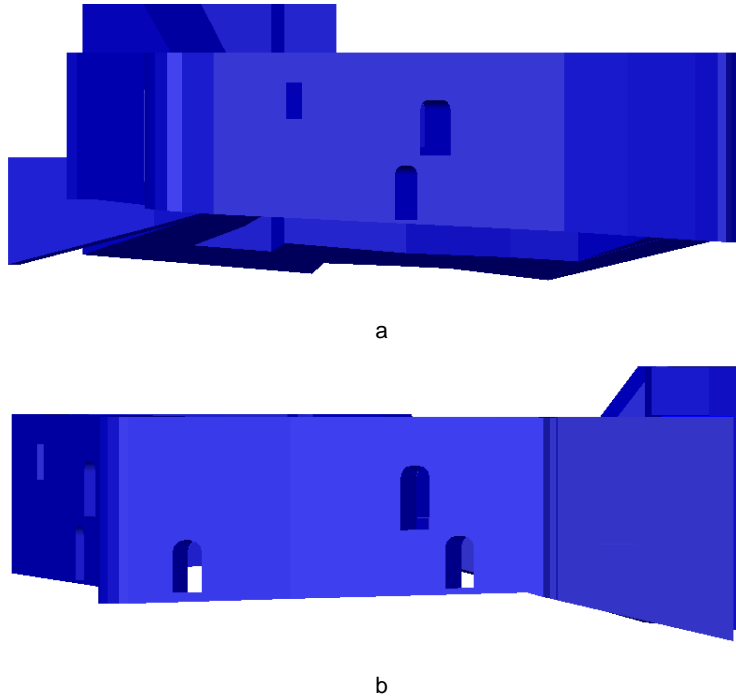


Figure 14:Final model with different level of base from a. front side b. back side

As the model shows quiet high degree of deterioration at the top and loss of stone units at a lot of places, As in Figure 15 below, it was simplified using measurements as close as possible to the pointcloud model. Care was taken that it match the minimum dimention of the mesh to be used further for FEM.

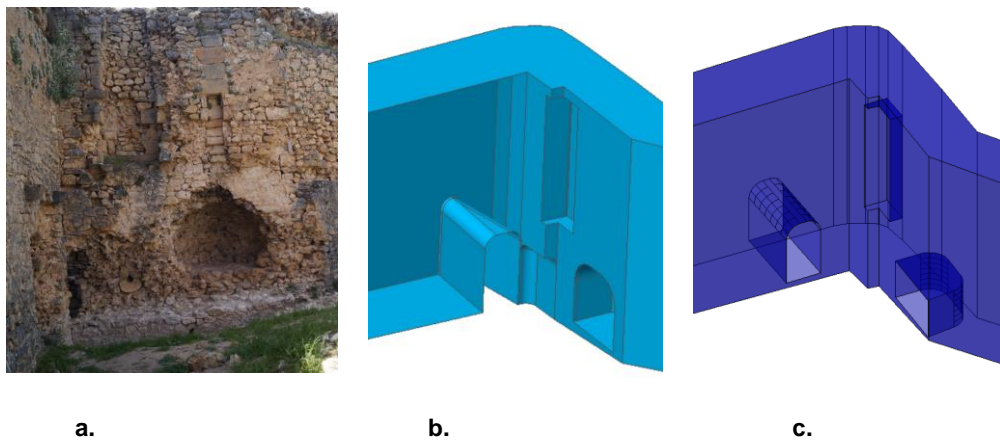


Figure 15:showing the simplification of detailing damage with respect to the ruins of castle a. Image of the damage b. model in DIANA c. After Meshing of the model

As seen in Figure 15. b, the window openings are in a funicular shape and narrow down on its way to external façade. In the first model Figure 15. b, the exact same window was modeled, but as it caused complications in meshing, it was simplified to a regular opening . The degraded walls were modelled as in Figure 16.

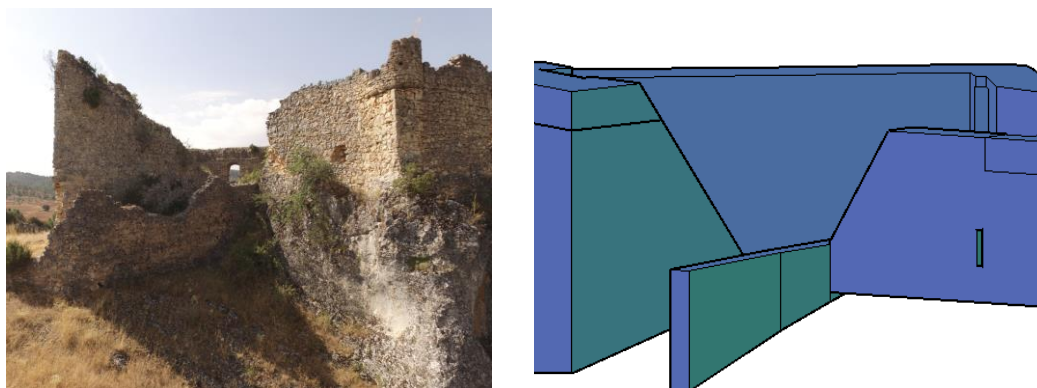


Figure 16:Modelling of deterioration of the walls at the entrance

3.2 Division of model

As said before, the model was based on the chronology of construction of the castle and hence it was further divided into parts according to the archaeological drawings. This was done as the archaeological drawings suggests difference in construction technique in each phase and the structural and dynamic behaviour of the castle is hoped to be affected by it. Also the model was further simplified to make the meshing and application of material properties easier.

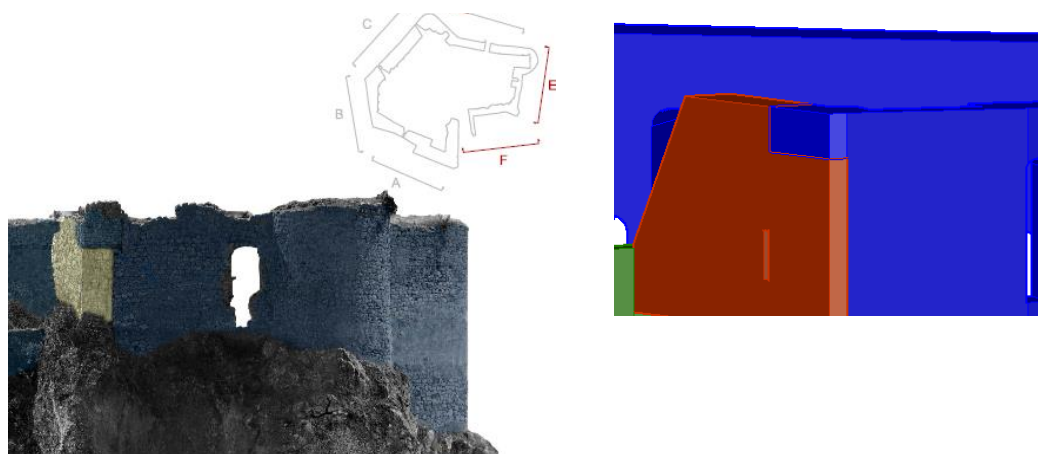


Figure 17:Division between wall E and F

As seen in the Figure 17, the connection in between wall F and E was divides such that they formed two separate solids. This was done as it was anticipated that the connection between the two walls shall be weak or even completely disconnected.

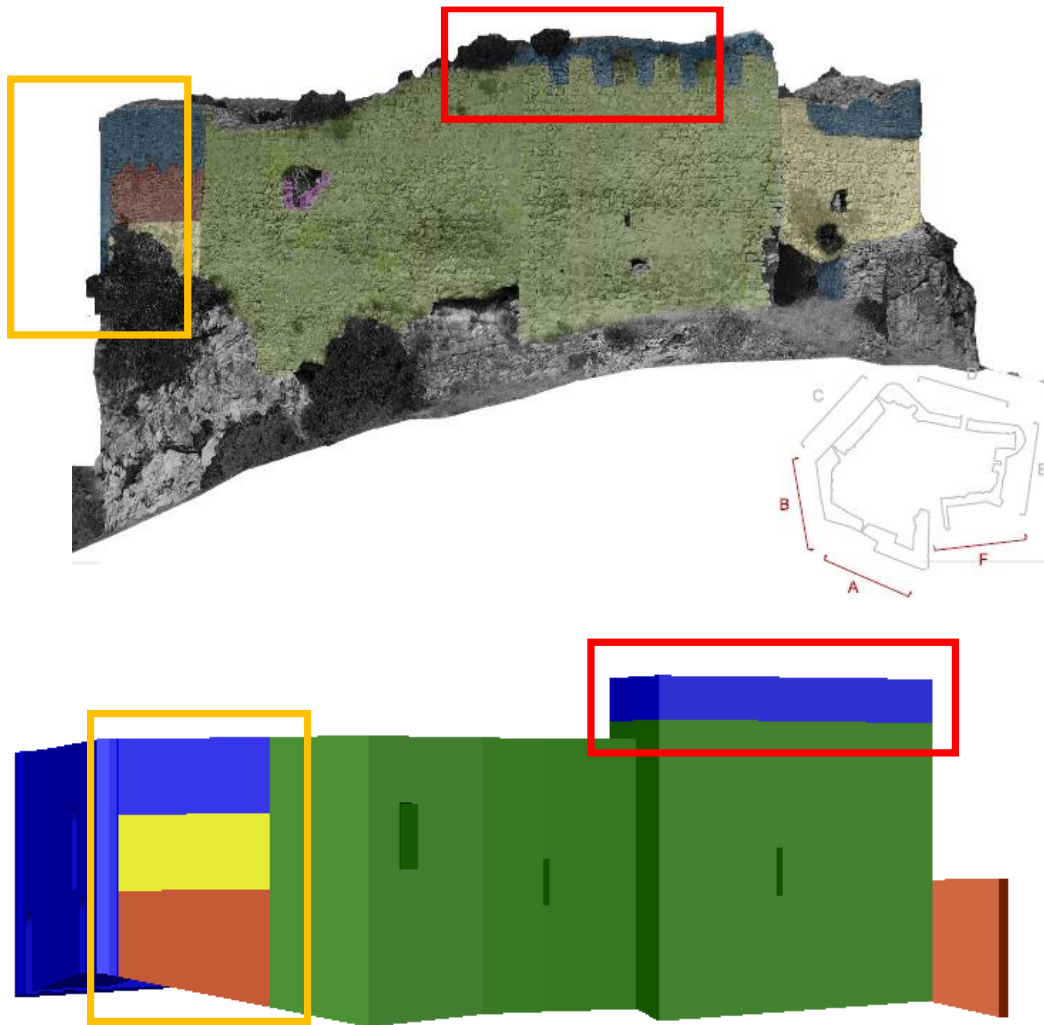


Figure 18: Division between wall B (left) and A according to construction phases

For wall B, the layers of connection were only visible from outside. But since the castle is located on a cliff. Access was not possible. Hence the wall was modelled into three different layers horizontally, see Figure 18

4. MATERIAL CHARACTERIZATION AND NDT TESTING

Non-destructive tests provide means to evaluate masonry without causing damage which can be visual. They do not provide a direct measure of material properties and sometimes need to be correlated between a few NDT results. It is possible to gain a general understanding of a materials properties but at times a combination of NDT's is required to understand the same.

In order to understand the material properties of the stone masonry and current state of the structure, an on-site investigation was carried out on the Arbeteta Castle. To obtain the values of mechanical properties of each wall of the castle, indirect sonic tests were performed and the results were compared with the masonry quality index .

This chapter describes the process, analysis and results of the sonic tests carried out on each façade, which is analysed and compared to the archaeological information, for better understand of the behaviour of the structure. These mechanical properties will be further used to calibrate FEM.

4.1 Masonry Quality Index (MQI)

In order to understand the morphology of the castle it is necessary to calculate the Masonry Quality Index (MQI) of each façade, as every wall was build in a different time period. Evaluating the masonry structure according to the MQI can be one approach to have a preliminary evaluation that assists later in proposing solutions. MQI is a method suggested by (Borri, A., Corradi, M., Castori, G., & De Maria, A. (2015)) which involves the use of several parameters to assess the masonry. To calculate the MQI, these parameters should be considered and correlated according to the following equation:

$$MQI = SM \times (SD + SS + WC + HJ + VJ + MM) \quad (1)$$

Where:

SM: Conservation state and mechanical properties of the units

SD: Unit dimensions

SS: Unit shape

WC: Walls leaf connections

HJ: Horizontal bedding characterisation

VJ: Vertical joints characterisation

MM: Mortar mechanical properties

Using the above parameters and equation no 1 , a characterization of the each of masonry walls of the castle has been performed. As seen above, the MQI considers evaluation parameters

such as dimension and shape of stone units of the wall, wall leaf connections, horizontal and vertical joints character and mechanical properties of the mortar. The masonry quality index shall refer to its quality of masonry and therefore its capability to withstand loads. As the cross section of each of the wall wasn't visible, it was assumed to be a three-leaf stone masonry wall. The inner leaf probably consisted of small stones from ravine with mortar. This was considered as it is mentioned above in Chapter 2 that the stones from ravine were used for construction. The same can be concluded from the inner leaf of the masonry visible in Figure 19. Upon visual inspection, the stone units do not appear to be bigger than 0.4m x 0.6m in dimensions. Also the dimensions of the stones units is smaller as in comparison to its thickness which is 1.4 m, as seen in the Figure 19. No through stone can be seen in the broken section of the masonry, which means that the inner and outer leaf may lack a good connection, which is usually achieved by the presence of a through stone.



Figure 19: Broken wall exposing inner leaf and Inner leaf of the masonry wall

The following figure 20 shows 1m x 1m of the masonry of each wall of the castle which represents the condition of the entire façade. It was difficult to come to a conclusion about MQI of each wall as different areas of the same wall exhibit dissimilar deterioration. For example, wall D is the longest wall in the structure and in some places it shows loss of mortar of different depth, ranging from surface erosion to exposure of the stone units in the masonry up to 0.15 m in depth. Therefore, taking this in consideration, MQI was calculated for the entire façade of the wall.

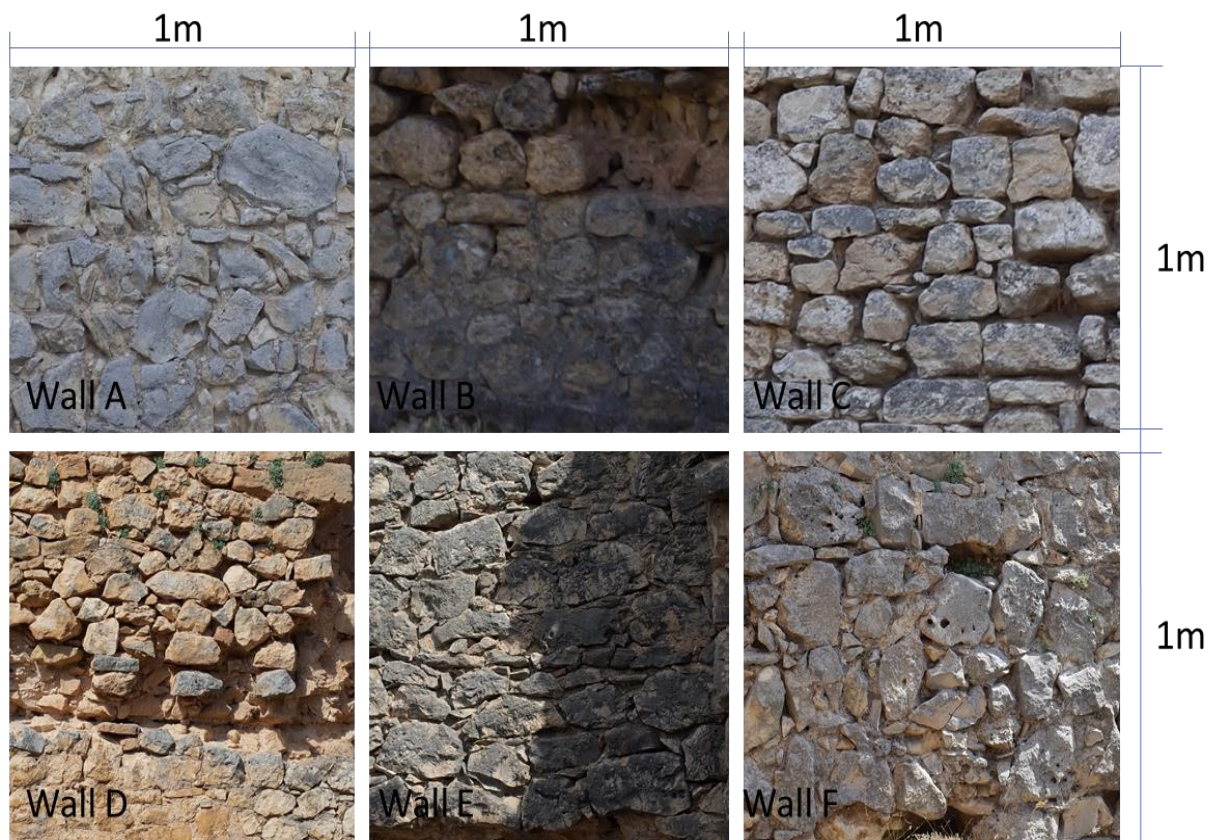


Figure 20: Difference seen in the morphology of each wall

Three values for each wall are calculated, namely to judge its masonry quality for vertical loading, horizontal in plane and out of plane loading.

For vertical action, As per Table 2, a value between 5 to 10 indicates a good quality of masonry, Category A whereas a value between 2.5 to 5 indicates average quality of masonry, Category B. As the value for all the walls computed is between 3.5 to 1.8. This indicates that the behaviour of masonry to endure vertical loading is inadequate for all the walls except for wall C, as it has a value of 3.5

For horizontal in plane loading, As per Table 2 a wall has to score a value between 10 to 7 to be considered good to endure a horizontal in plane load. A value of 7 to 4 will indicate that the quality of wall is sufficient to withstand the said loading condition. As the values obtained for each of the castle walls are between 3 to 1.75, which is a category for inadequate masonry quality, the walls may not have adequate strength to withstand the horizontal in plane load.

As in the case of horizontal out of plane loading, As per Table 2 the values indicating good behaviour of masonry are similar under vertical loading are between 10 to 5 for category A, 5 to 3 for category B and below 3 for category C. Similar to results obtained for vertical and horizontal in plane loading, wall C has a higher value of 4.5, indicating an adequate behaviour of masonry under horizontal out of plane loading.

Table1: Values computed for all the walls.

	Wall A	Wall B	Wall C	Wall D	Wall E	Wall F
Vertical loading	2.5	3.2	3.5	2.5	2.1	1.8
Horizontal in-plane loading	2.45	2.45	3	2.45	2.1	1.75
Horizontal out-of-plane loading	2.45	2.8	4.5	2.8	2.45	1.4

Table2: Masonry categories as a function of MQI ,changing the external actions (Borri, A., Corradi, M., Castori, G., & De Maria, A. (2015)(8)

Masonry category	Masonry category		
	C	B	A
Vertical actions (V)	$0 \leq MQI \leq 2.5$	$2.5 \leq MQI \leq 5$	$5 \leq MQI \leq 10$
Out-of plane actions (O)	$0 \leq MQI \leq 4$	$4 \leq MQI \leq 7$	$7 \leq MQI \leq 10$
In-plane actions (I)	$0 \leq MQI \leq 3$	$3 \leq MQI \leq 5$	$5 \leq MQI \leq 10$

A, good behavior of masonry; B, behavior of average quality of the masonry; C, inadequate behavior of masonry

Hence, it can be concluded that the walls A,B,D,E and F belong to category C of masonry quality index which refers to inadequate quality of masonry, whereas, wall C exhibits better quality with respect to vertical loading and horizontal out of plane and in-plane actions and can be considered to be an average category of masonry. Details of the MQI calculation can be seen in Annex B

These results will further be correlated with the results obtained from the indirect sonic tests.

Eventhough this method of calculation is purely based visual inspection of the analyser, it can give a good review of the state of the masonry when accessibility to perform NDT's can be an issue. For better results, a few NDT's should be combined to give a better understanding of the behaviour of masonry.

4.2 Sonic pulse velocity tests

The sonic pulse velocity (SPV) test was performed in order to evaluate the material properties the masonry walls of the castle. It was carried out by hitting the wall gently with a hammer and recording the time until the receiver, detects a wave. This test measures the velocity of the sound wave moving through the masonry. Indirect tests are performed with a receiver on the same wall face as that of the impact.

In order to obtain more reliable results through sonic tests, the application of this method to masonry structures and the processing of the measured data should account various factors such as: the characteristics of the wall, namely their constituents and internal structure, the used setup (position of sensors) that must be chosen considering the specific parameters being

studied; and the specific conditions under which the test is performed such as the load and stress distribution on the wall. (Miranda, L. F., Rio, J., Miranda Guedes, J., & Costa, A. (2012).) Indirect sonic impact tests were conducted on all the internal walls of the castle, for which the P and R wave propagation velocities were determined. The equipment used included one instrumented impact hammer (PCB Model 086D05) with a measurement range of ± 22240 Npk, one accelerometer (PCB model 352B) with a measurement range of ± 5 g and 1000 mV/g sensitivity, a personal computer, cables and a data acquisition system from National Instruments.

For better understanding of the morphology of the structure, two to three locations were chosen on each wall. An average of the obtained values was considered to calculate the material properties. Each test set consisted of three hammering points and three receiving points. The impact was applied always on the uppermost point and the accelerometer was placed sequentially on each of the corresponding reception point, approximately 1m below it. A series of ten to fifteen readings were performed at each point. The location for the tests can be seen in Figure 21. The outcome and morphology of each wall is analysed further.

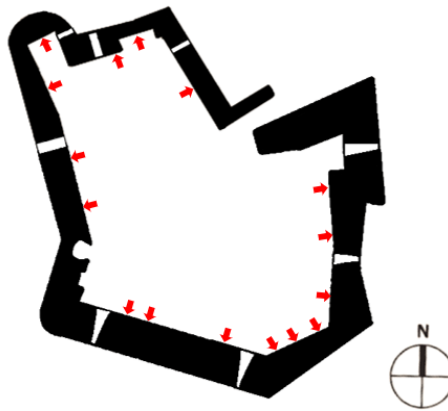


Figure 21: showing the locations of indirect sonic tests.

Sonic tests can be useful to estimate the global Young's modulus of stone masonry walls by measuring the velocity of propagation of the elastic compression, P , and surface waves (Rayleigh), R , through indirect tests. The relationship between P -wave (V_p) and the R -wave (V_r) velocities with Young's modulus (E) and Poisson's ratio (ν) for a homogeneous material are given by Eq. 2 and 3. Table 2 shows the values of mechanical properties of each wall obtained upon analysis of the indirect sonic tests. For initial calculations, the mass density was assumed to be of 20 kN/m³ for each façade.

$$\frac{V_p}{V_r} = \sqrt{\frac{2(1-\nu).(1+\nu)^2}{(1-2\nu).(0.87+1.12\nu)^2}} \quad (2)$$

$$V_p = \sqrt{\frac{E}{\rho} \frac{(1-\nu)}{(1+\nu).(1-2\nu)}} \quad (3)$$

Wall A:

As mentioned in second chapter, Wall A was constructed in Phase II of construction of the castle. The thickness of the wall varies between 2 m to 3 m. Upon visual inspection, it appears to be coursed stone masonry with stones of varying dimensions ranging from 0.4 x 0.2m to small stone wedges measuring about 0.05m to 0.2m . In comparison to other walls, which will be analysed further, wall A exhibits similar construction pattern throughout the façade of the wall. The masonry is compact and there seems to be little to no loss of mortar between the stone units. This can be observed in the results of the sonic tests. The average V_p for wall A was 1444 m/s with coefficient of variation between 4% to 10% for each point. Upon calculations, the Young's modulus is computed to be 3.1 GPa. The selected test locations for Wall A as seen in the Figure 22

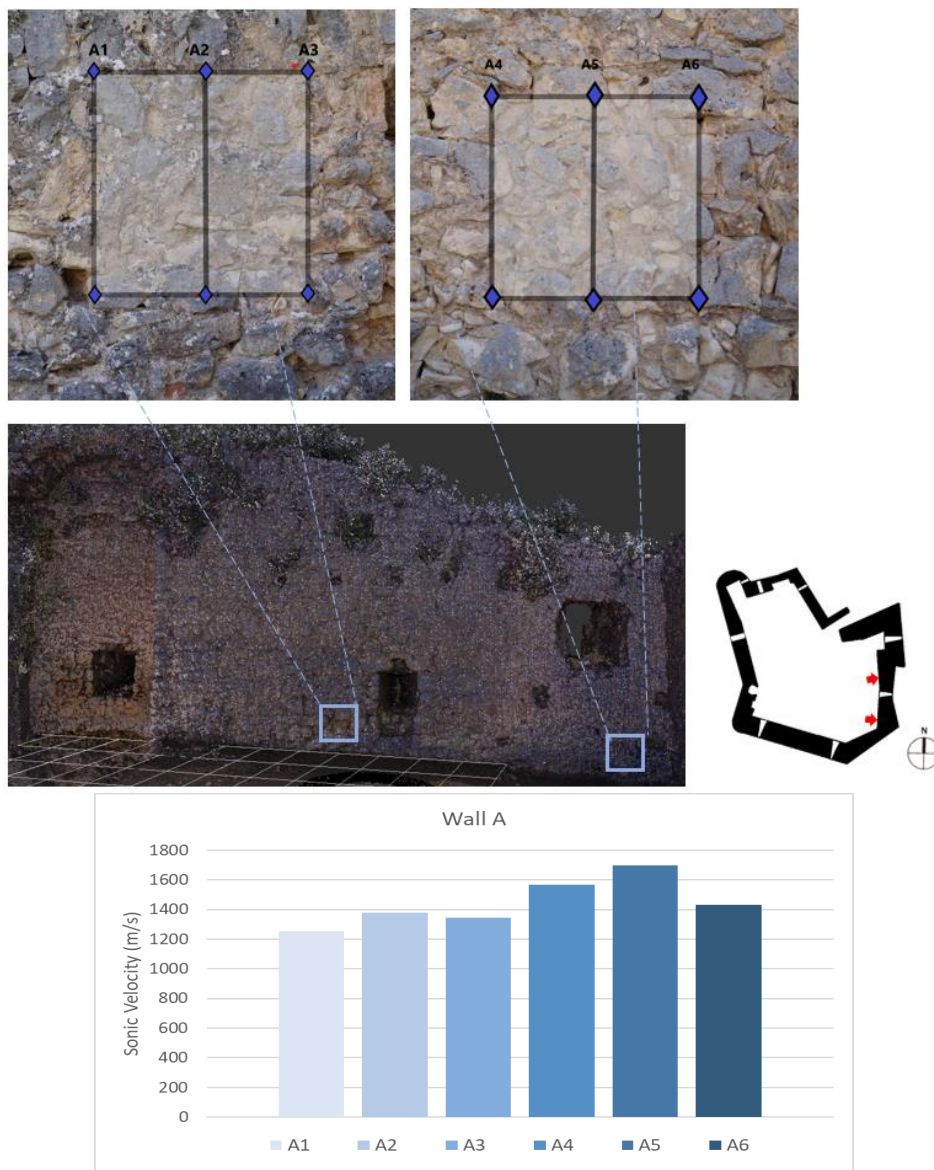


Figure 22: Location of testing points on Wall A and the sonic velocities obtained at each point : A1, A2, A3, A4, A5 and A6.

Wall B:

Wall B can be said to be the wall with smallest width and maximum number of construction phases. The wall is made up of coursed stone masonry. The wall appears to have undergone degradation of the surface of the stone units and loss of mortar. This can be seen in Figure 23 showing the testing points selected for indirect sonic test. Three locations were selected, the first one comprising of points B1, B2 and B3. On visual analysis, this location had less variation in dimensions of the stone units ranging from 0.3 m to 0.2m and the degree of loss of mortar is less. As seen in Figure 23 a and b, this location has a higher frequency of closer to 2000 m/s with respect to other test points.

The second location which consists of points B4, B5 and B6 appears to have smaller units of stone with dimension of 0.1m to 0.3m with thicker layer of mortar. And the final location consisting of points B7, B8 and B9 had same dimensions of stone units 0.3m to 0.4m as the first but has suffered greater loss of mortar. The average V_p for wall B was 1213 m/s with coefficient of variation between 2% to 12% for each point. Upon calculations, the Young's modulus is computed to be 2.51 GPa. The selected test locations for Wall B as seen in the Figure 23.

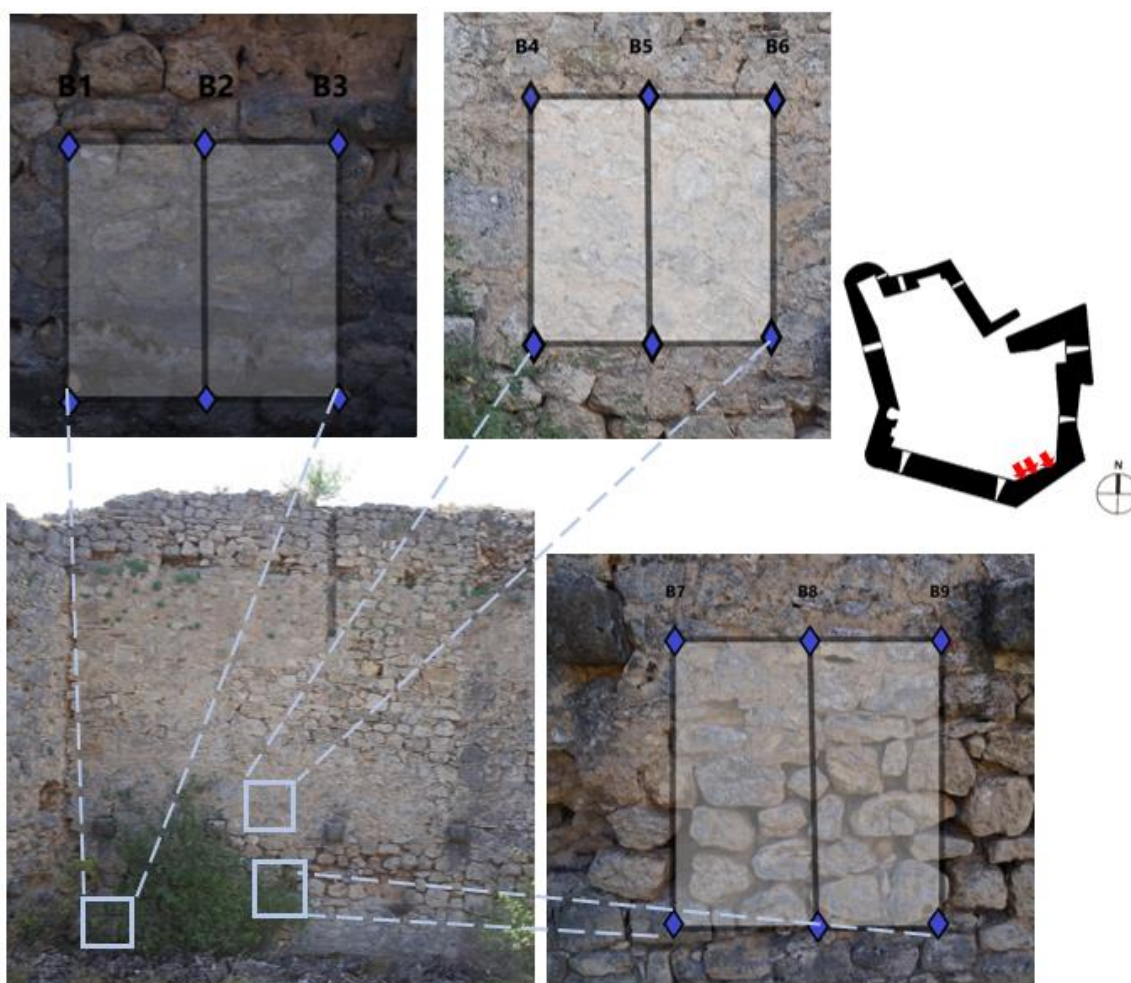


Figure 23(a): Location of testing points on Wall B

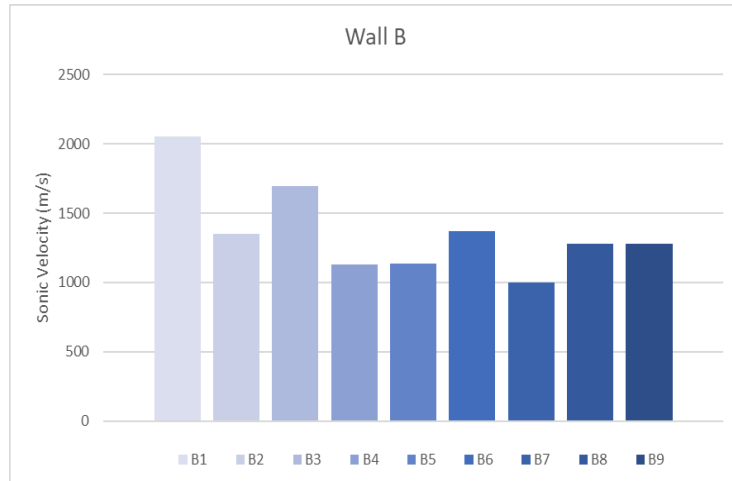


Figure 23(b): Sonic velocities obtained at each point : B1, B2, B3, B4, B5, B6, B7, B8 and B9.

Wall C:

Upon visual inspection, it can be said that the Wall C and D were a target of plundering for the stone units as they appear to be removed from the masonry. Also loss of mortar is quite evident in this façade. The wall is made up of coursed stone masonry but with undressed stones. This can be seen in Figure 24 a and b, showing the testing points selected for indirect sonic test. Two locations were selected, the first one comprising of points C1, C2 and C3 and the second one which consists of points C4, C5 and C6. The dimension of stone units 0.1 m to 0.4 m approximately. The average V_p for wall B was 1624 m/s with coefficient of variation of 7% for each point. Upon calculations, the Young's modulus is computed to be 2.1 GPa. The selected test locations for Wall C as seen in the Figure 24 a and b

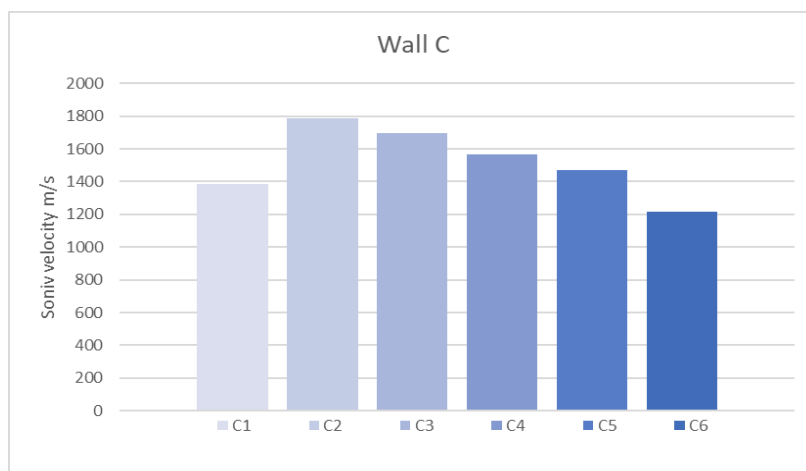


Figure 24(a): Sonic velocities obtained at each point : C1, C2, C3, C4, C5 and C6

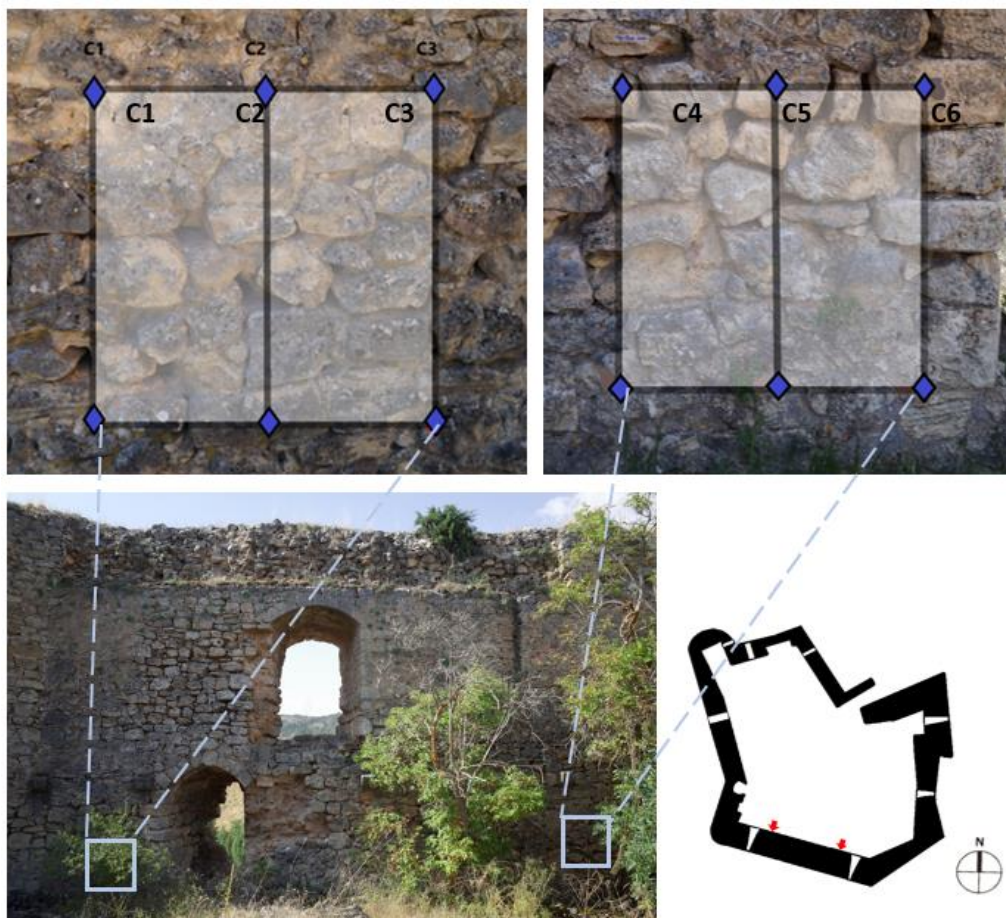


Figure 24(b): Location of testing points on Wall C

Wall D:

Wall D can be said to be the longest wall with length of about 19 m and thickness of 2.5 m . The wall is made up of coursed stone masonry. It appears to have undergone heavy degradation of surface of the stone units and loss of mortar. This can be seen in Figure 25 showing the testing points selected for indirect sonic test. Two locations were selected, the first one comprising of points D1, D2 and D3. On visual analysis, this location had less variation in dimensions of the stone units ranging between 0.3m to 0.1m or even less. The degree of loss of mortar is less.

The second location which consists of points D4, D5 and D6 appears to have smaller units of stone with thicker layer of mortar.

The average V_p for wall D was 1168 m/s with coefficient of variation around 7% for each point. Upon calculations, the Young's modulus is computed to be 2.02 GPa. The selected test locations for Wall D as seen in the Figure 25.

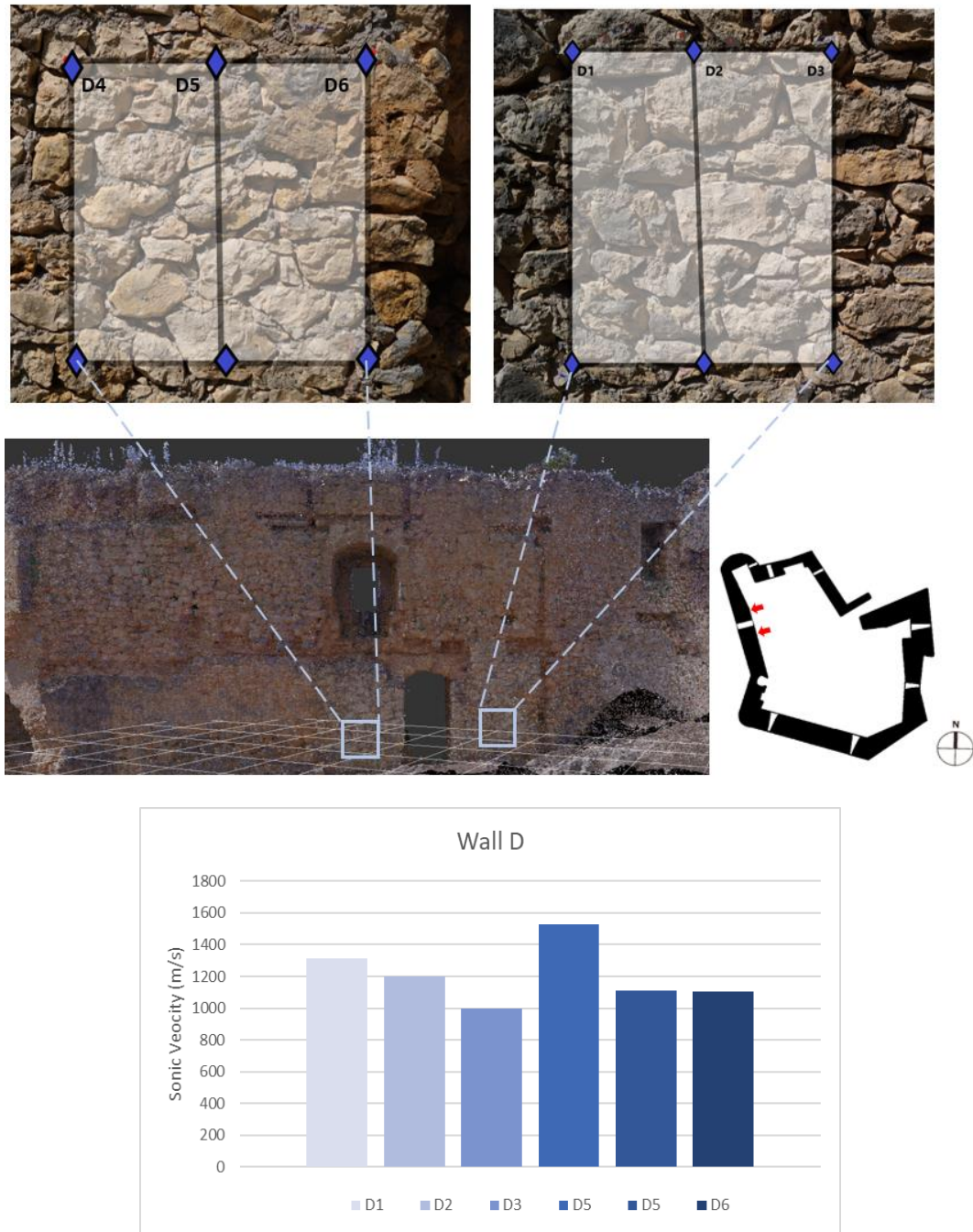


Figure 25: Location of testing points on Wall A and the sonic velocities obtained at each point : D1, D2, D3, D4, D5 and D6.

Wall E:

Wall E shows a lot of variation even though it seems to be constructed simultaneously. The wall is made up of coursed stone masonry. The wall appears to have undergone heavy degradation of surface of the stone units and loss of mortar. This can be seen in Figure 26 showing the

testing points selected for indirect sonic test. Of the three locations, the first one comprising of points E1, E2 and E3 is of coursed masonry whereas the other two locations are uncoursed and show varying size of the stone units ranging from 0.4m x 0.2 m to 0.15m x 0.1m. As seen in Figure 26.

This location has a higher sonic velocity closer to 2400 m/s with respect to other test points.

The second location which consists of points E4, E5 and E6 show some recent attempt to repoint the joints with cement mortar. But the traces of a new mortar are still quite low.

The average V_p for wall E was 1801.58 m/s with coefficient of variation between 8% for each point. Upon calculations, the Young's modulus is computed to be 3.9. The selected test locations for Wall E as seen in the Figure 26.

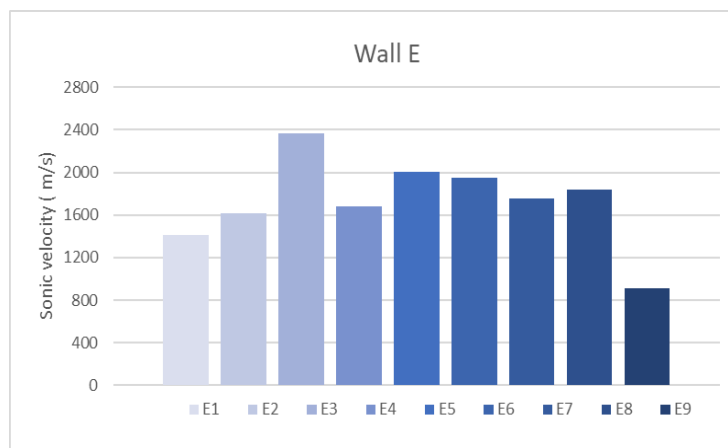
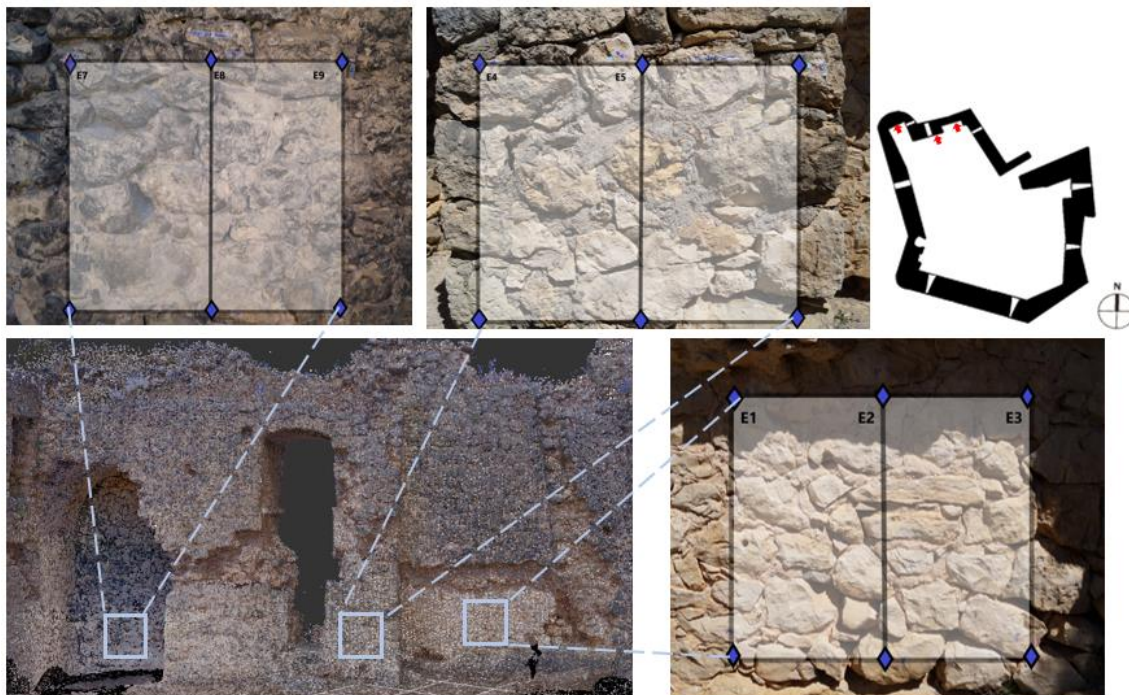


Figure 26: Location of testing points on Wall E and the sonic velocities obtained at E1, E2, E3, E4, E5, E6, E7, E8, E9

Wall F:

The wall is made up of uncoursed stone masonry. It can be said to be the wall with a lot of damaged parts and loss of material. The locations were selected, the first one comprising of points F1, F2 and F3. On visual analysis, this location had quite a variation in dimensions of the stone units and but the stone units and mortar binding seems to be compact. In the testing point F2, there is presence of a void between impact and receiver point. But it doesn't seem to affect the velocity of sonic waves as there doesn't seem to be much variation in the velocity of the three points.

The average V_p for wall F 1166 m/s with coefficient of variation between 3% for each point. Upon calculations, the Young's modulus is computed to be 2.01 GPa. The selected test locations for Wall B as seen in the Figure 27.

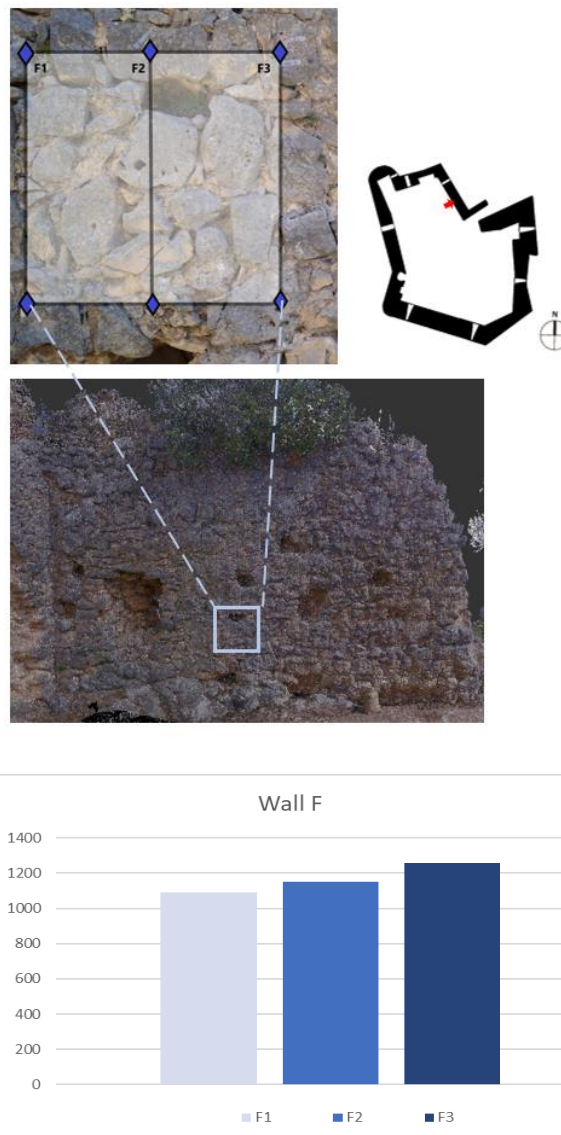


Figure 27: Location of testing points on Wall A and the sonic velocities obtained at each point : F1, F2 and F3.

Table 3 shows the values of mechanical properties of each wall obtained upon analysis of the indirect sonic tests. Equations 2 and 3 were used for calculations. These values will be further used to calibrate the numerical model with the experimental one.

Table 3: Results obtained by sonic tests:

	Average Vp/Vr	Average Vp	Poissons ratio(ν)	E (GPa)
Wall A	1.71	1444	0.3	3.11
Wall B	1.82	1213	0.22	2.5
Wall C	2.29	1624	0.4	2.1
Wall D	2.1	1168	0.32	2
Wall E	2.06	1801	0.31	3.9
Wall F	1.61	1166	0.3	2

Results

The value of Young's modulus obtained for walls B,C and D are quite close and it can be related to archaeological data, discussed in Chapter 2, which says that the three walls were built in the same phase of construction. The MQI value for wall F is less than 2, for all three kind of loading calculations. These results indicate a rather high value of the Poisson's ratio for wall C. But masonry can be very inhomogeneous; thus, only global variations of the Poisson's ratio and the modulus of elasticity can be indicative.

Furthermore, the MQI values are dependable and can be used to verify the outcome of other NDT. They more or less give an idea about quality, workmanship and the behaviour of masonry under different load conditions. The information about material properties obtained from the indirect tests will further be used to evaluate the finite element model.

In conclusion, it can be said that the results from MQI and Sonic tests can mostly be co-related to understand the morphology of masonry walls. which can be explained by following example: As few sampling points are usually chosen for sonic tests. The velocity of waves depend on the morphology of the area between the impact point and receiving point. If the analysis of the sonic tests tend to be inconclusive, which can happen due to may reasons, MQI can help choose between the correct values of sonic tests. But this may vary from case to case.

5. DYNAMIC IDENTIFICATION

Dynamic identification is the characterization of the main dynamic properties of structural systems based on the analysis of their vibration responses to an input force. Such properties, referred to as modal parameters (i.e., frequencies, mode shapes, and damping ratios), define the inherent characteristics of the system and provide useful information about its state. Modal parameters are related to the physical and mechanical properties of the analysed structure, like mass, stiffness, and energy dissipation, thereby allowing for their characterization even in the absence of viable experimental testing procedures, through the solution of an inverse problem. (Martini, R., Carvalho, J., Barraca, N., Arêde, A., & Varum, H. (2017))

A building is continuously exposed to the risk of damage, whether due to exogenous or endogenous causes. If not detected in due time, such an adverse condition can compromise the structural integrity and ultimately risk users' safety. Structural changes in a building happening over time will be reflected by changes in its modal properties, hence it is important to track the dynamic response of structures.

The main objective of this study in this thesis is to compare the modal data obtained through the campaign of OMA with the FEM. This data can be used further for calibrating the finite element model that will be later constructed and to update the selected material properties. However, it can also be used to evaluate constructive aspects of the building, such as the level of connection between perpendicular walls or between walls constructed in different phases. For that reason, the dynamic campaign was carefully planned taking into account the results from the archaeological report discussed in Chapter 2, which will be further explained.

5.1 Plan of the OMA campaign

To completely understand the behaviour of the castle, three setups were planned. One reference accelerometer was placed in wall F as seen in Figure 28. Setup 1 comprised of 8 accelerometers which were placed in Walls E and F. Setup 2 was arranged to cover walls A and B and consisted of 7 accelerometers and finally Setup 3 was positioned at Walls C and D and consisted of 5 accelerometers. The accelerometers were oriented to measure the out of plane accelerations of the structural. Additionally, other accelerometers were placed for the in-plane measurements for one point of each setup. Figure 28 shows the position of the accelerometers. Reference accelerometers was placed on Wall F, as in Figure 28

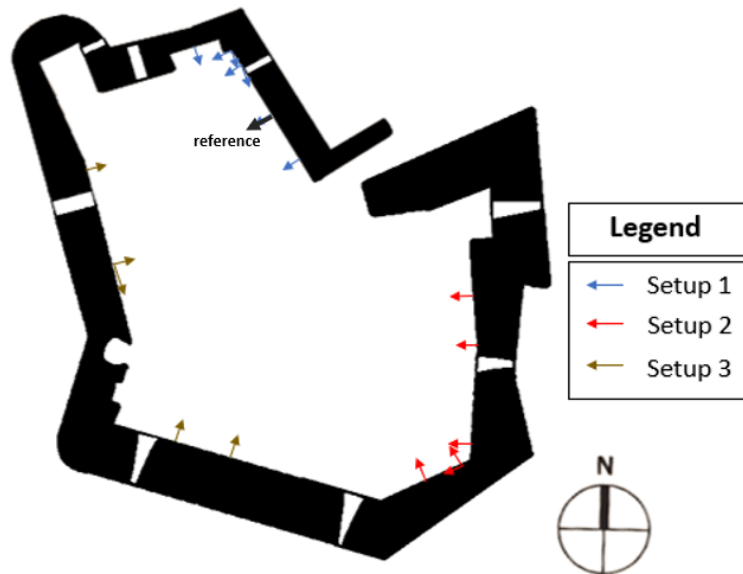


Figure 28: showing the location of accelerometers

As in Figure 29, the accelerometer were placed to check the connection between the walls A-B and E-F. This was done as the archaeological data suggests that the above mentioned wall connections shall be weak as they were constructed in different phases. Presence of a crack can also be observed in these two areas.

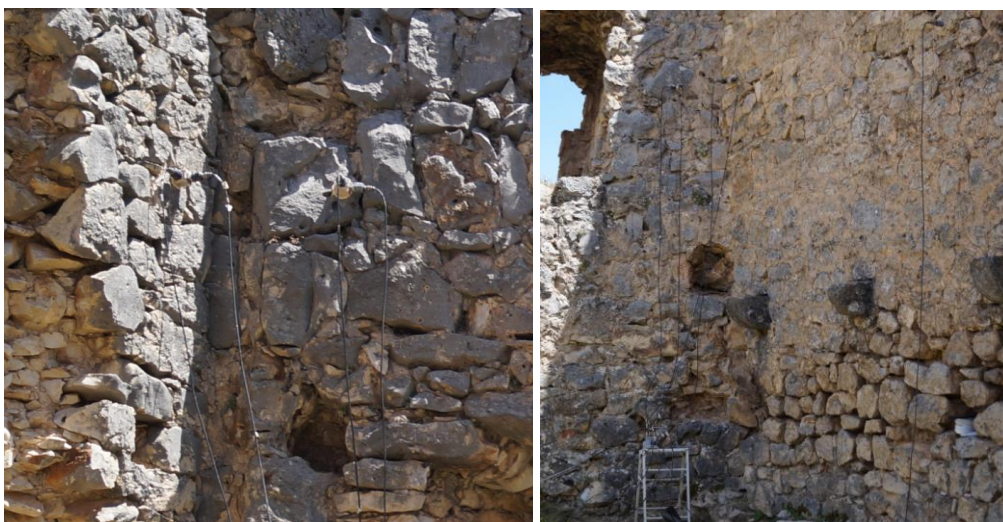


Figure29 :The in-plane and out of plane placement of accelerometer on wall connections E-F and A-B

5.2 Data collection

The ambient vibration techniques are based on dynamic response measurements of a virtual system under natural (ambient or operational) conditions, and the assumption that the excitations are random in time and in the physical space of the structure (Ramos, L. F., 2007). In other words, structures are excited by natural vibrations, such as wind load, traffic or human induced vibrations, and the response of the structural system is measured with high sensitive sensors or accelerometers during its service condition.

The equipment used is composed of piezoelectric uniaxial accelerometers with sensitivity of 10 V/g and frequency range from 0.15 to 1000Hz (measurement range +/- 0.5g), data acquisition board, cables and computer. The total recording duration for each measurement was 30 minutes. Due to the difficulties to access the castle and carry the necessary equipment needed to reach the top most part of the walls, it was not possible to put the accelerometer in the highest position in the walls. The manageable height was 3.5 m was used to locate all the accelerometers. In each setup, an accelerometer was also placed at a height of 1.5 m.

5.3 Results

A software named ARTeMIS modal was used for the analysis of the dynamic behaviour of the structure. This program does a pre-processing of the signal, which automatically eliminates the linear trend, makes the Fourier Transform, and filters the signal in order to eliminate the noise

The geometry of the structure was first constructed in AutoCAD 3D and then was defined in the configuration file, where the different points, lines and surfaces as well as the boundary conditions for the nodes at ground level were defined. The geometry which was imported in the software can be seen along with the location of accelerometers in Figure 30. The orientation of the arrows gives the direction of the measured accelerations.

Two methods have been used for the identification of the modes, namely FDD (Frequency Domain Decomposition) and SSI (Stochastic Subspace Identification). The FDD method is a non-parametric method developed in the frequency domain (FD). It is based on the estimation of the modal parameters from the power spectral densities of all the measurement points after the application of the Fast Fourier Transform (FFT) process to the signals. With this method, it is possible to choose manually the possible principal modes of the structure, selecting the top of the peaks of the spectral density graph accelerometers were located in the corresponding point.

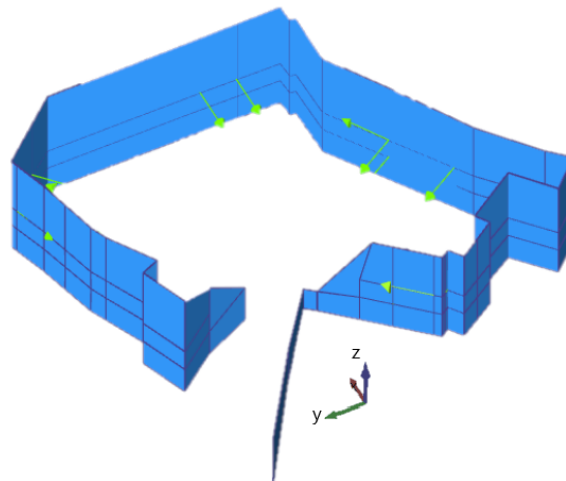


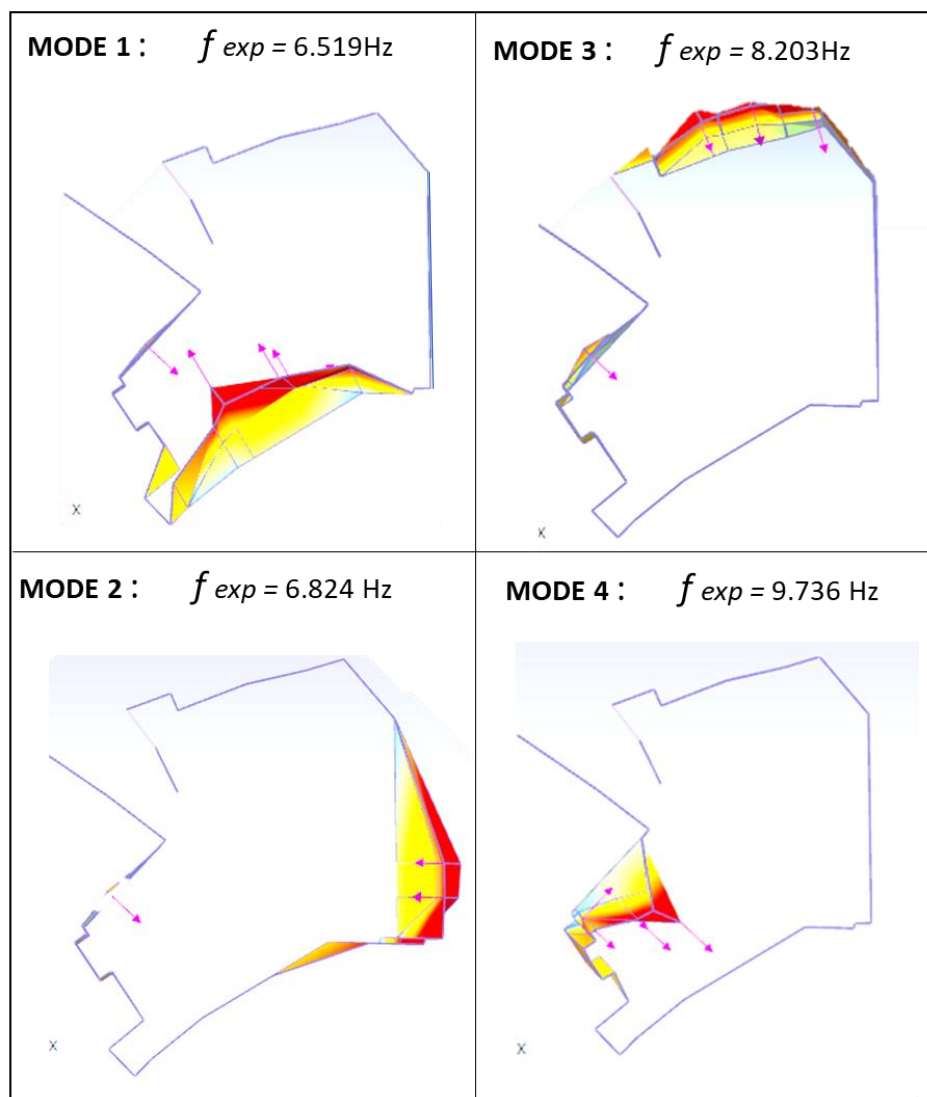
Figure 30: ARTeMIS model with accelerometers in positions

After all the analysis of validation, four modes were selected for updating the finite element model using the FDD and UPC methods. To characterize the dynamic behaviour of civil engineering structures, it is not necessary to estimate a high number of modes as this could lead otherwise to subsequent difficulties in the calibration of the numerical model. Moreover, the first few modes usually provide sufficient accurate information to characterize the structural behaviour. (Lourenço *et al.* (2002))

Table 4 Frequencies and determined with FDD and SSI-UPC method.

	FFD(Hz)	SSI-UPC (Hz)	MAC Value
Mode 1	6.51	6.54	0.92
Mode 2	6.87	6.84	1
Mode 3	8.2	8.18	0.97
Mode 4	9.73	9.72	0.9

Table 4 presents the identified frequencies and regarding the FDD and SSI-UPC methods, respectively. Additionally, it shows the comparison of the results of the two methods in terms of the Modal Assurance Criterion (MAC). The MAC is the most well-known statistic indicator of the degree of consistency between mode shapes. This mathematical measure is often used to pair modes shapes derived from analytical models with those obtained experimentally; however, it can also be used to compare the results derived from two different dynamic identification techniques. The value obtained for MAC is between 0 and 1, with 1 indicating completely reliable mode shapes. From this it is possible to conclude that that there is a high correlation between the correspondent mode shapes calculated from the two methods.

Table 5. Final Modal shapes and frequencies of the different modes obtained with ARTeMIS

These selected modes can be seen in Table 5. Which presents the estimated mode shape configurations of the structure. The natural frequencies of these modes range from 6.5 to 9.7 Hz. Rather close frequency values were found for the first (6.5 Hz) and second (6.8 Hz) modes, but in general the frequencies are well spaced.

The first mode is the one with a frequency of 6.5 Hz which presents the out of plane movement of the wall D. The second one corresponds to the frequency of 6.8 Hz, and is observe in wall C. The third mode has a frequency of 8.2 Hz and was detected in wall A. Finally, the fourth mode has a frequency of 9.7Hz and was detected in wall F. All of the above modes exhibit an out of plane behaviour.

To conclude with dynamic identification, the following points summarize it.

First, a modal analysis of the numerical model is suggested to get a preliminary idea about the expected frequency values and mode shape configurations of the structure. Next, the number of points to be measured were defined in accordance with the need of the dynamic identification test and the preliminary data from the Chapter 2. Based on the available number of sensors, a setup plan was established with one fixed measuring point or reference sensor, while the other sensors are moved around the structure also called free sensors. The reference point should not coincide with a node of the structural mode shapes (i.e. a point with zero modal displacement) in order to avoid inaccurate results. These modes will now be used to calibrate the FEM model.

6. FINITE ELEMENT MODEL

Finite element modelling is a tool for analysing the behaviour of complex structures. The finite element method is a numerical solution method that simplifies a problem into many subdomains called finite elements, and solves the associated kinematic, constitutive and equilibrium equations to obtain the solution of the boundary value problem.

This chapter state the calibration of the experimental model with the numerical one. For the model to be calibrated, further updating of the basic geometry was necessary.

6.1 Meshing

As mentioned before, the photogrammetry model was used as a base to draw solid 3D model in AutoCAD 3D. as the castle is in a state of ruins, is was hard to model it exactly as it is and had to be simplified as shown in Chapter 3

Once the model was complete, it was divided into eleven parts based upon its phases of construction from the archaeological data and material properties (Table 6) derived from the NDT's as seen in Figure 31

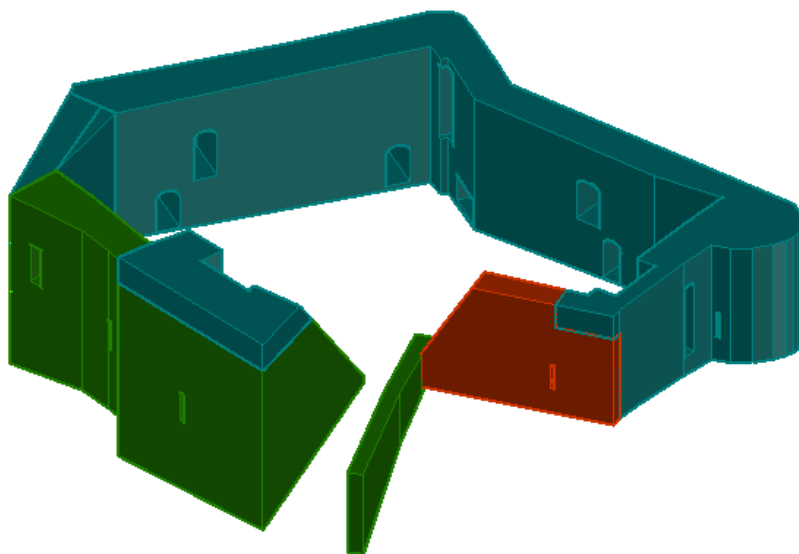


Figure 31:Final AutoCAD model divided into phases

The AutoCAD model was exported to FX+ Midas software, which pre-processes the model, so that it can be further exported into DIANA for analysis. This software was chosen as it was user friendly and is easier to check solid surface, mesh the model, merging the nodes and apply supports in it. Respective material properties were applied to each solid in it as well, Table 6. The walls C,D and E which were constructed in the same phase, were further divided into single solid blocks so as to apply their respective material properties which were achieved as a result

of indirect sonic test, see Figure 31. This decision was taken because even though the walls were built simultaneously, over the period of time and depending upon the degree of degradation, mechanical properties may change. Once the model was imported in FX+ Midas, a mesh of dimension 0.5 m was applied and rectified. Nodes under the range of 0.1m were merged together to avoid complications during calibration. The TE12L element was used for meshing the model ,see Figure 32.

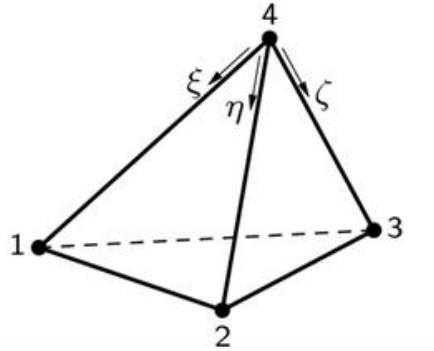


Figure 32: three node iso-parametric solid tetrahedron element – TE12L (TNO DIANA BV, 2009).

The TE12L element is a four-node, three-side iso-parametric solid tetrahedron element. It is based on linear interpolation and numerical integration. The polynomials for the translations u, v, w . During the process of meshing, mechanical properties of Young's modulus, Poisson's ratio and mass density were applied according to Table 6. Regarding the boundary conditions of the model, all degrees of freedom of nodes at ground level were restricted.

Table 6: Mechanical properties

	Mass Density (N/m ³ /g)	Poissons ratio(ν)	E(GPa)
Wall A	2000	0.3	3.11
Wall B	2000	0.22	2.5
Wall C	2000	0.4	2.1
Wall D	2000	0.32	2
Wall E	2000	0.31	3.9
Wall F	2000	0.3	2

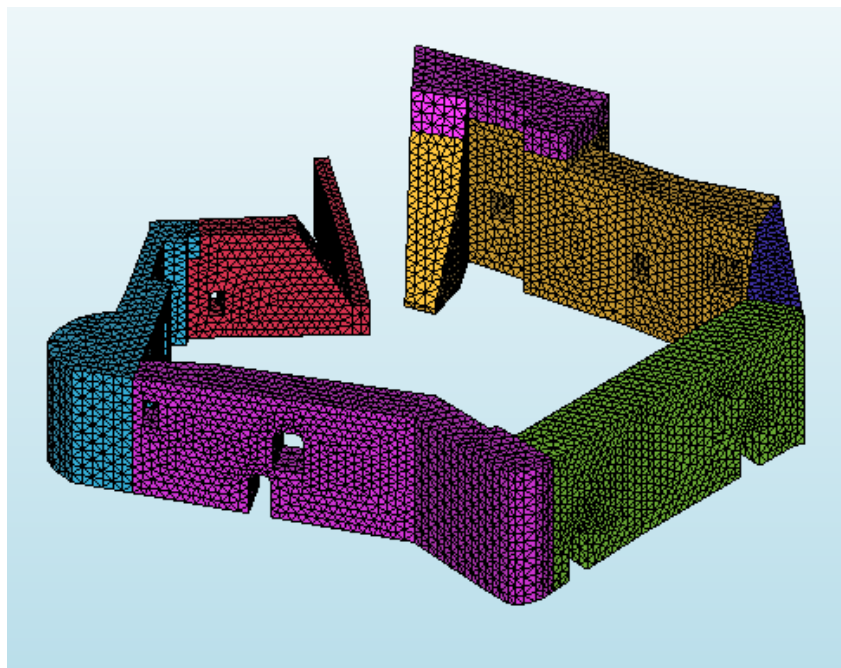


Figure 33: Final DIANA meshed model- with Walls C,D,E further sliced to behave as individual solids

6.2 Calibration of the model

Once the pre-processing was done and the model was exported into DIANA, a few Structural Eigenvalue analysis were run to calibrate the model as per the frequencies obtained in the modal analysis, as seen in Table 7

Table 7: Frequencies from Modal analysis

	f_{exp} (Hz)
Mode 1	6.51
Mode 2	6.82
Mode 3	8.2
Mode 4	9.73

First analysis was run in DIANA where all the walls were connected. This was done to get an idea for further analysis. As it was known that wall connections A-B and E-F lacked good connections, next analysis was run while disconnecting these two sets of walls. The first frequency obtained from OMA was at 6.5 Hz in wall D, whereas the first frequency obtained from FEM was 9.4 Hz and it corresponded with the wall A. Results of this analysis showed an out of plane behaviour of wall A and wall F and complete detachment between wall A-B.

Hence for further calibration, interface elements were chosen to be introduced in between the wall connection as the values of normal and shear stiffness can be determined. As the values were unknown, a trial and error method was adopted. Hence the value of normal stiffness modulus was taken as $10e+9$ N/m³ and shear stiffness modulus $4e+8$ N/m³. The location of interface elements can be seen in Figure 35 .

As seen in Figure 34 , the T18IF element was chosen for to be placed in between two solids to further calibrate the models. It is an interface element between two planes in a three-dimensional configuration The local xyz axes for the displacements are evaluated in the first node with x from node 1 to node 2 and z perpendicular to the plane. Variables are oriented in the local xyz axes. The element is based on linear interpolation. By default DIANA applies a 3-point integration scheme. [nlc = 3] .(TNO DIANA BV, 2009).

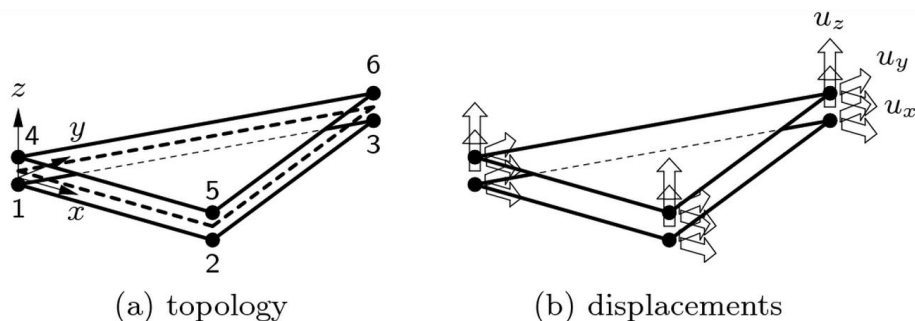


Figure 24:Interface element placed at located indicated with red box

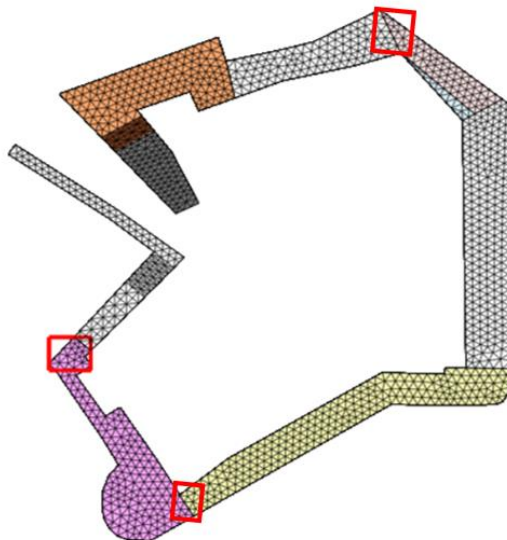


Figure 35 Location of interface elements.

Based upon the analysis which were run, it was quiet clear that the geometry of the model needed updating. Going back to the onsite photographs of the castle which were taken for

photogrammetry model were closely examined. Hence the following issues with the archaeological drawings were found:

The separation between the wall A-B was shown at a different location. Hence it was remodelled. Secondly, a crack/separation was found in external façade of wall D. This change was incorporated in the model as it may prove necessary for the calibration. Finally the connection between the walls E-F was found to be weak too. But the crack seen in picture was different than seen in the archaeological drawings. See Figure 36. Also, as said in chapter 2, liberty was taken while modeling the geometry of castle with respect to the countour slopes. For better results, the countours seen in wall C were added too. The changes made in the model can be seen in Figure 37

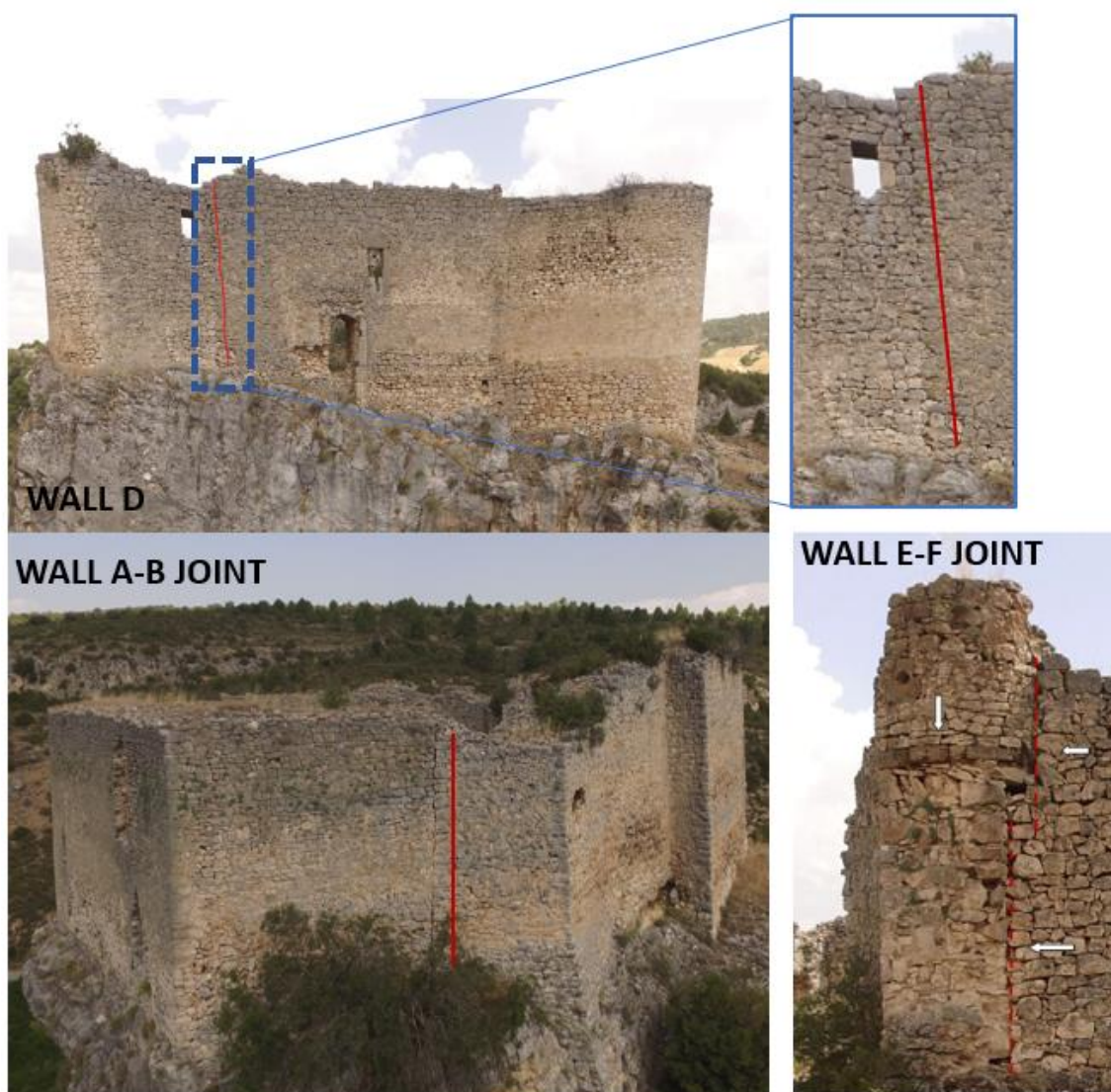


Figure 36: Separation seen between the wall joint of wall A-B , E-F AND wall D

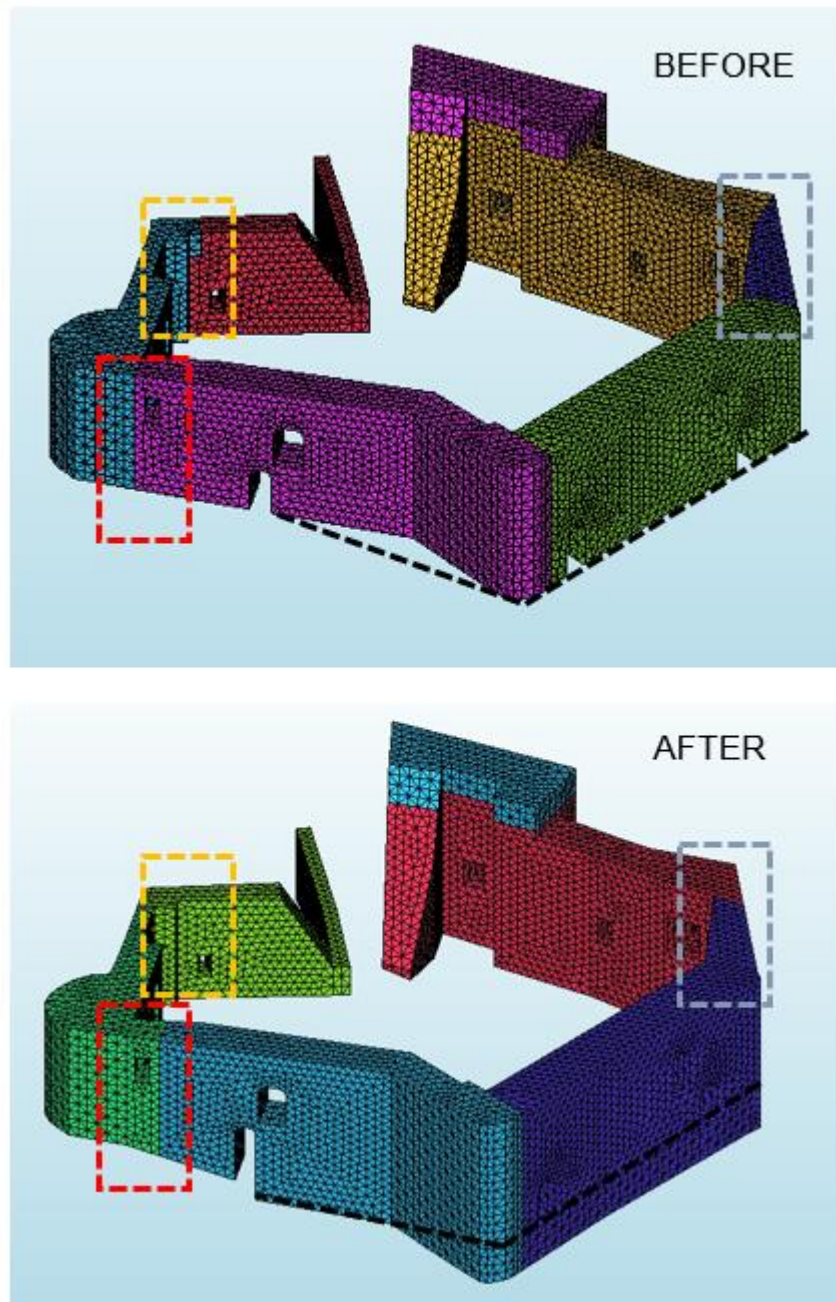


Figure 37: Changes made in model for calibration

Once all the necessary elements were included in the model, the material properties were updated as well. The Young's modulus and mass density of the masonry was modified in order to match the values of the frequencies and the modal shapes.

Upon making these changes, further to define the degree of separation between above mentioned wall connections, interface elements were added again as per Figure 35

After making a few changes in properties of the interfaces and Young's modulus, see Table 8 a and b ;the model was calibrated as seen in Table 9

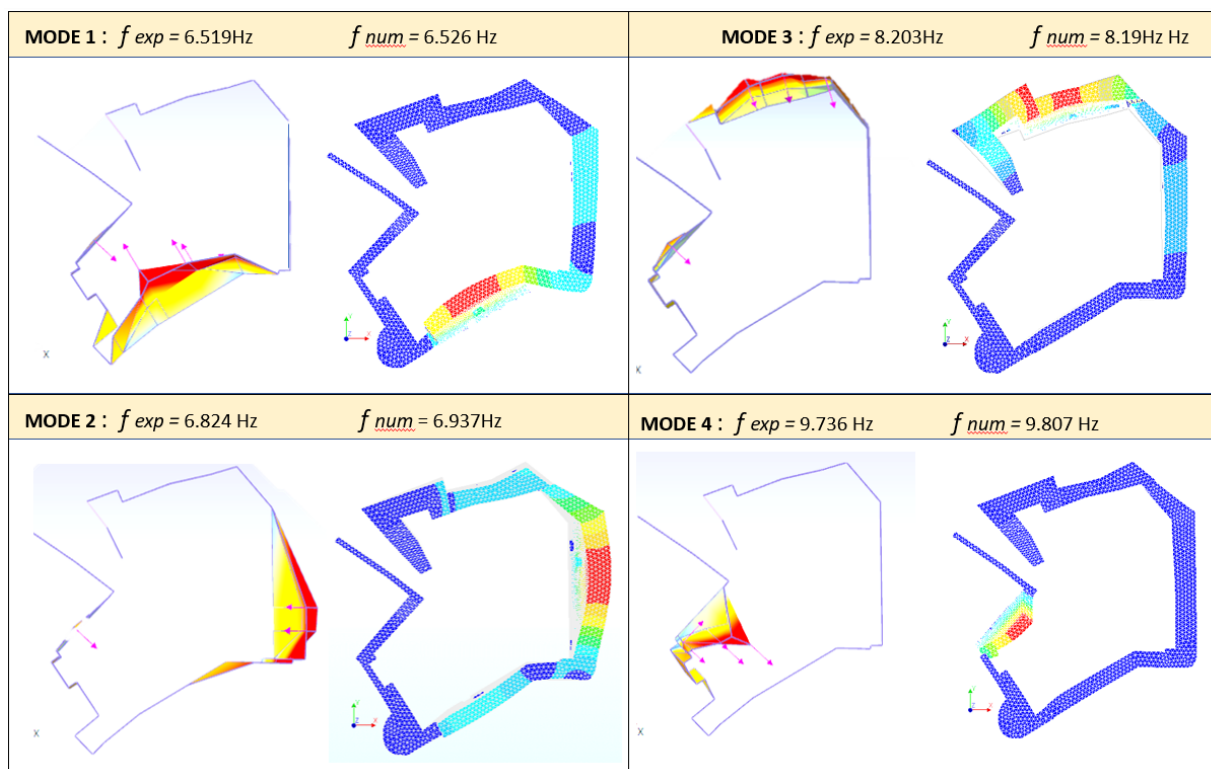
Table 8(a): Update mechanical properties of calibrated model

	Original values			Update values		
	Mass Density (N/m3/g)	Poissons ratio(v)	E(GPa)	Mass Density (N/m3/g)	Poissons ratio(v)	E(GPa)
Wall A	2000	0.3	3.11	2100	0.3	2.8
Wall B	2000	0.22	2.5	2000	0.22	2.5
Wall C	2000	0.4	2.1	2150	0.4	1.7
Wall D	2000	0.32	2	2200	0.32	2.1
Wall E	2000	0.31	3.9	2000	0.31	3.9
Wall F	2000	0.3	2	2100	0.3	2

Table 8(b): Update mechanical properties of calibrated model

	Before calibration		After calibration	
	Normal stiffness (N/m3)	Shear stiffness (N/m3)	Normal stiffness (N/m3)	Shear stiffness (N/m3)
Interface A-B	1.00E+09	4.00E+08	1.00E+08	4.00E+07
Interface D-E	1.00E+09	4.00E+08	5.00E+08	2.00E+07
Interface E-F	1.00E+09	4.00E+08	1.00E+08	1.00E+08

Table 9: Modal shapes and frequencies of the updated FEM and OMA



After the model was calibrated, MAC calculation was also performed to confirm the calibration of the two models. For this, nodes which represented the position of accelerometers were manually selected from FEM. Then the values for the modal shapes of those points were compared with the data obtained from ARTeMIS. This process was done with the implementation of the formula shown in Equation 4 in a spread sheet.

$$MAC_{u,d} = \frac{\left| \sum_{j=1}^m \phi_j^u \phi_j^d \right|^2}{\sum_{j=1}^m (\phi_j^u)^2 \sum_{j=1}^m (\phi_j^d)^2} \quad (4)$$

The MAC values and the frequencies are shown in Table 10. After examining the above numbers, it could be said that the finite element model presents a very similar behaviour to the actual structure. Thus, the results obtained from a structural analysis of this model should represent the reality of the real structure, and provide dependable data to interpret the stability of the castle.

Table 10: Modal shapes and frequencies of the updated OMA and FEM

	f_{exp} (Hz)	f_{num} (Hz)	MAC Value
Mode 1	6.51	6.52	0.82
Mode 2	6.82	6.93	0.97
Mode 3	8.2	8.19	0.95
Mode 4	9.73	9.8	0.81

Once the calibration of the two models is achieved, the FEM model can be used to perform structural analysis with applying load sets such as dead load (self weight) and / or wind load. These further analysis will give an idea about the buildings structural behaviour under these load sets and will help plan for future interventions.

7. CONCLUSION AND RECOMMENDATIONS

Within this thesis, a detailed study of the ancient castle ruins was done. In general, three main research steps were performed.

One of the first task of this thesis was to study and understand the history and chronology of various phases of construction works of the castle. The phases of historical evolution were carefully studied and applied to understand it's structural behaviour. This also included the characterization of the current condition of the structure based on an in-situ visual inspection and application of NDTs. The next step was the application of non-destructive tests to the Castle of Arbeteta, namely dynamic identification analysis and sonic tests. The results of these investigation techniques allowed identifying important mechanical and dynamic properties of the structure, such as frequencies and modes of vibration, and the modulus of elasticity of the masonry.

The indirect sonic test, applied in the walls of the building, allowed estimating the Poisson's ratio and the modulus of elasticity of the each of the wall. The results indicated were used for the calibration of the numerical model with very less changes needed. Hence it can be said that the results from indirect tests were very useful in calculating the mechanical properties of the masonry.

The third research step of this thesis regarded the construction and calibration of a 3D finite element model of the castle. The dynamic identification was successfully applied to the structure. The first four modes of vibration were clearly identified with natural frequencies ranging between 6.5 to 9.7 Hz. The signal processing was performed with two different SSI methods, obtaining consistent results based on the calculated MAC values with results obtained between 0.8 and 1.

It is also important to notice that the information obtained with these tests is not always easy to interpret and they have to be confirmed with other methods and means of calculations, if applicable.

Hence, it can be said that historical chronology of a building is an important factor in understanding its structural behaviour. The study carried out shows that with the help of NDTs it possible to replicate the real mechanical properties of the structure in the model for various analysis which could help in understanding the strengthen of the structure, as it can lead to accurate calibration of the OMA and FEM models.

FUTURE WORK

As there are future plans of proposing intervention in the structure, he calibrated model can be used to conduct structural analysis of the castle. This will help in identifying any possible structural deficiencies of the building that need to be addressed before any kind of intervention

works. A set of analysis dealing with dead load, wind load and a combination of both should be performed to understand the strength and stability of the structure.

Upon results from the above said analysis, required interventions shall be proposed. The essential structural and material consolidation of ruins should be carried out carefully and the interventions should be planned taking into consideration the heritage value of the castle ruins. Upon planning the interventions, another set of analysis should be conducted to check the structural performance of the building.

Repair work of the castle should be considered. This will include dealing with loss of mortar and loss of material (stone units). It should be overcome using traditional techniques and material. For this, lab test to determine the components of mortar need to be conducted and analyse to re-create the similar composition to be compatible with the current building material.

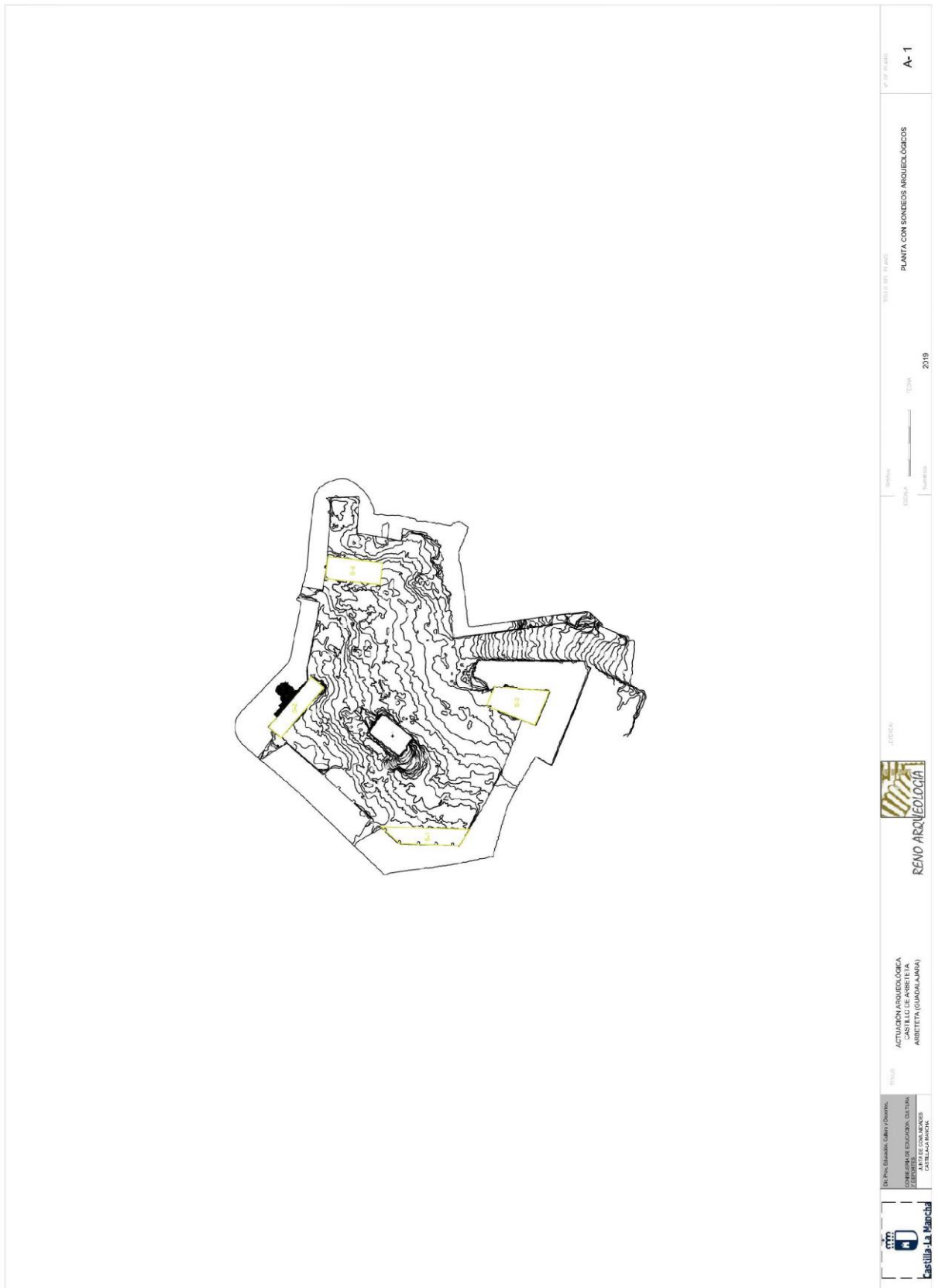
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Appendix A

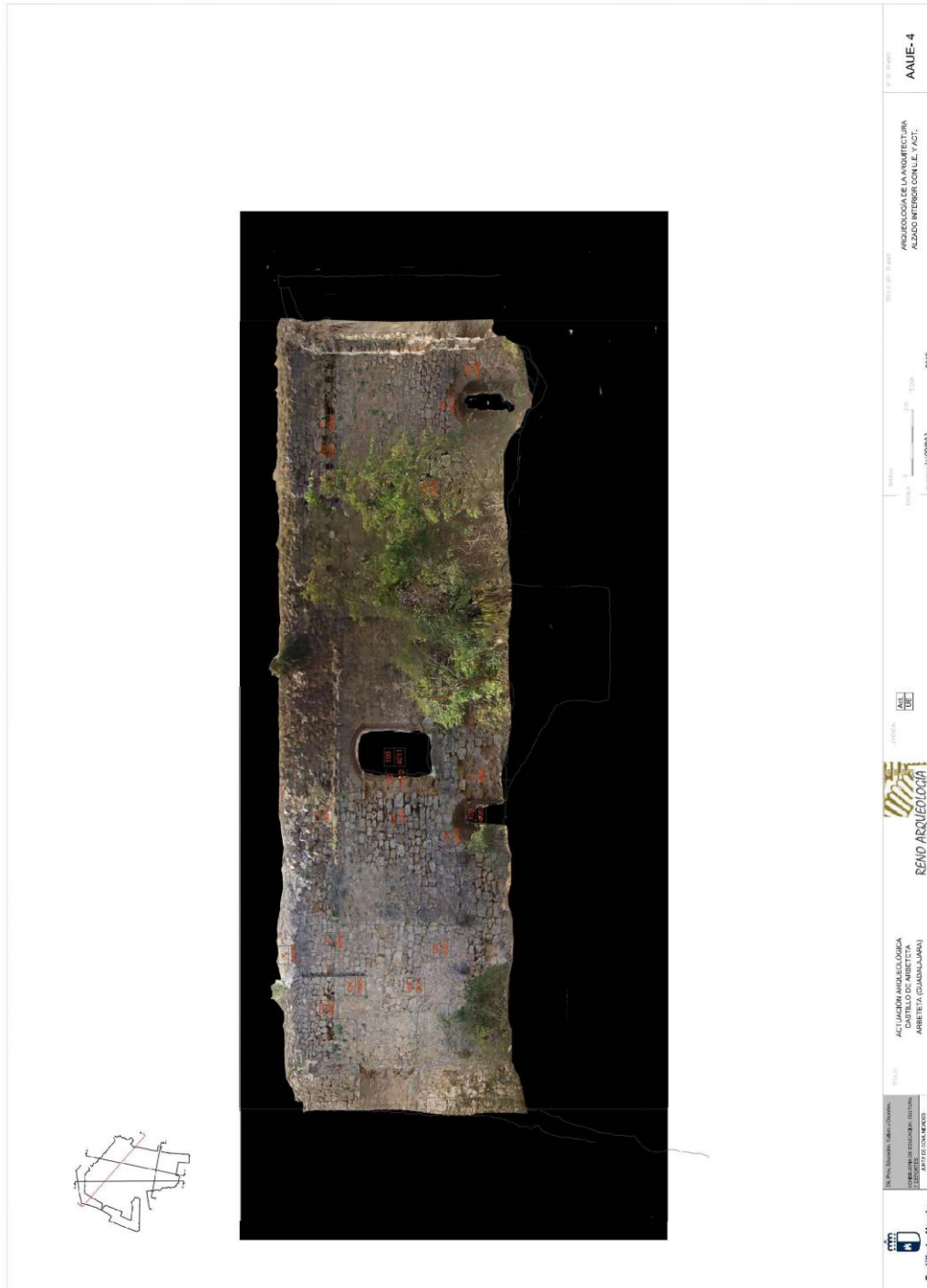
Archaeological drawings and chronological mapping of Arbeteta castle (En, G., & Castillo, E. L. (2019).



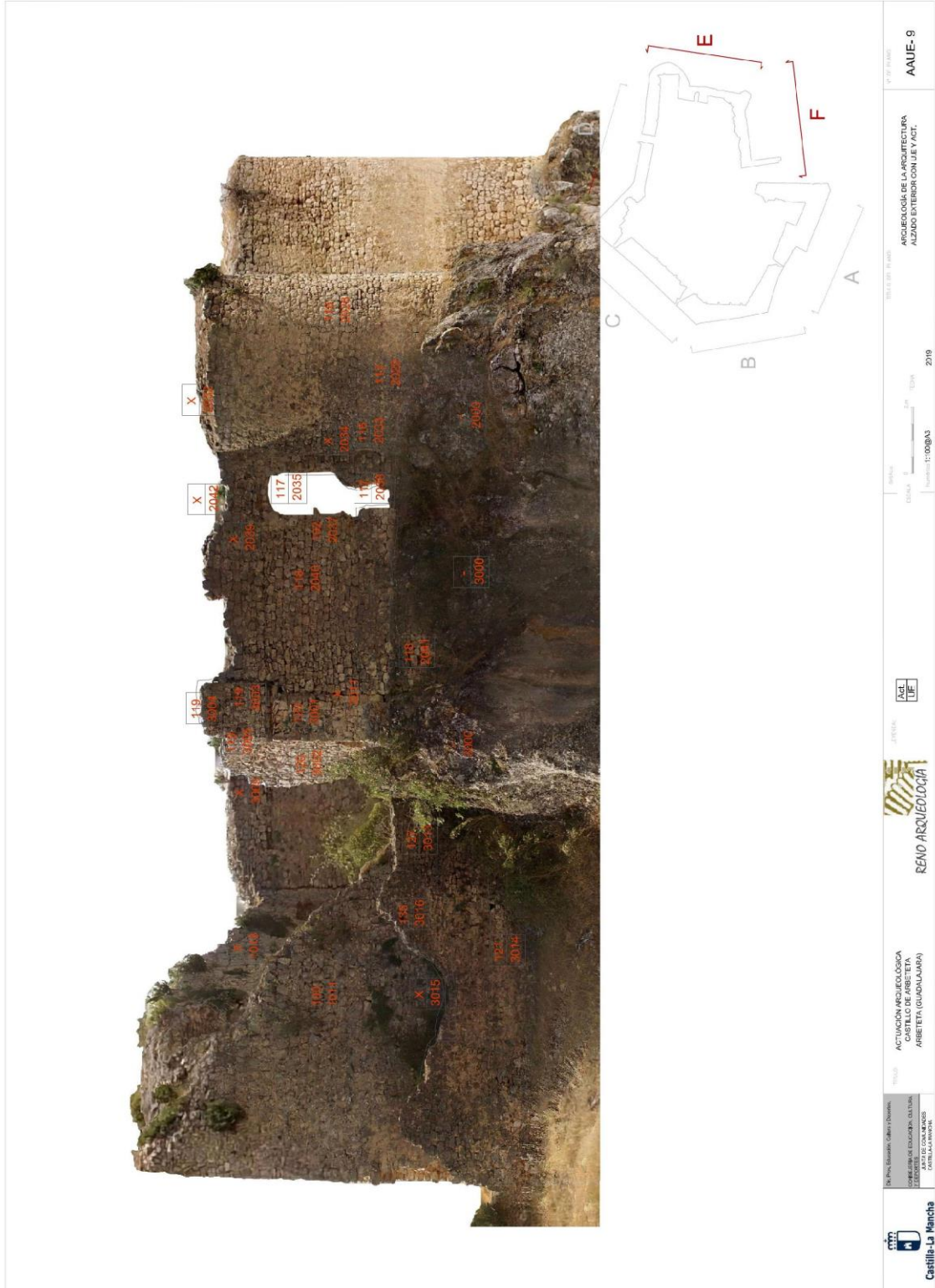


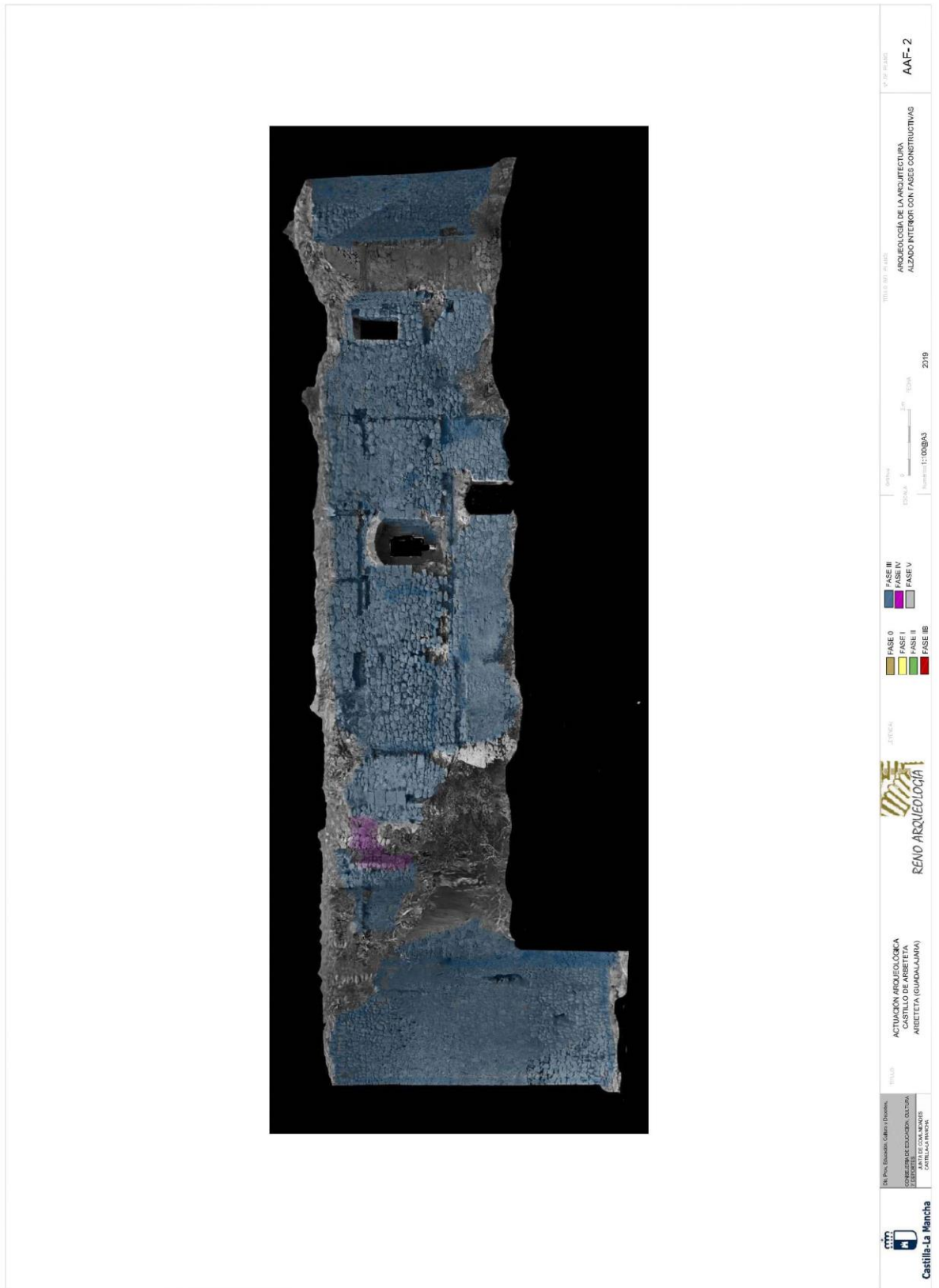










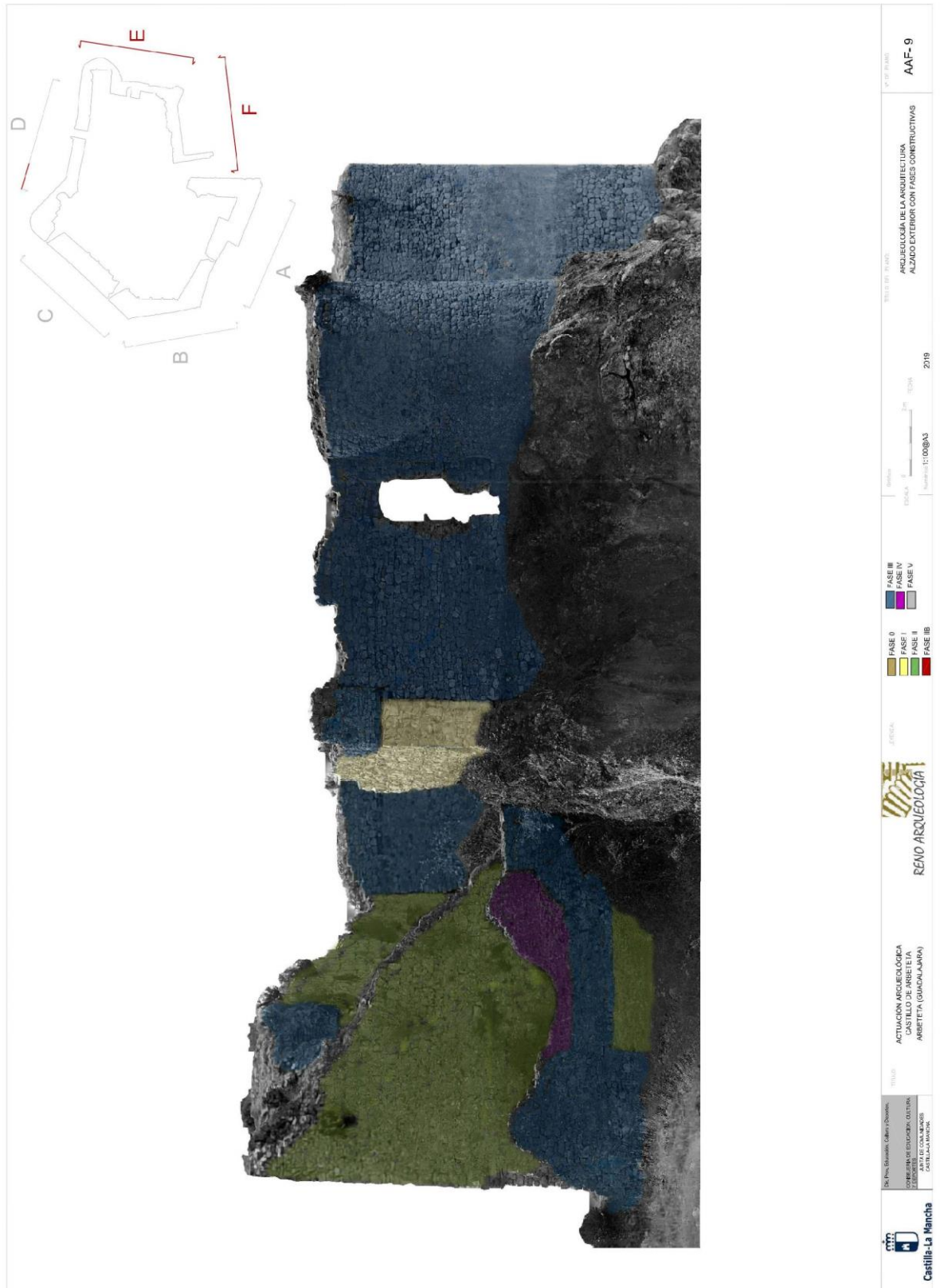




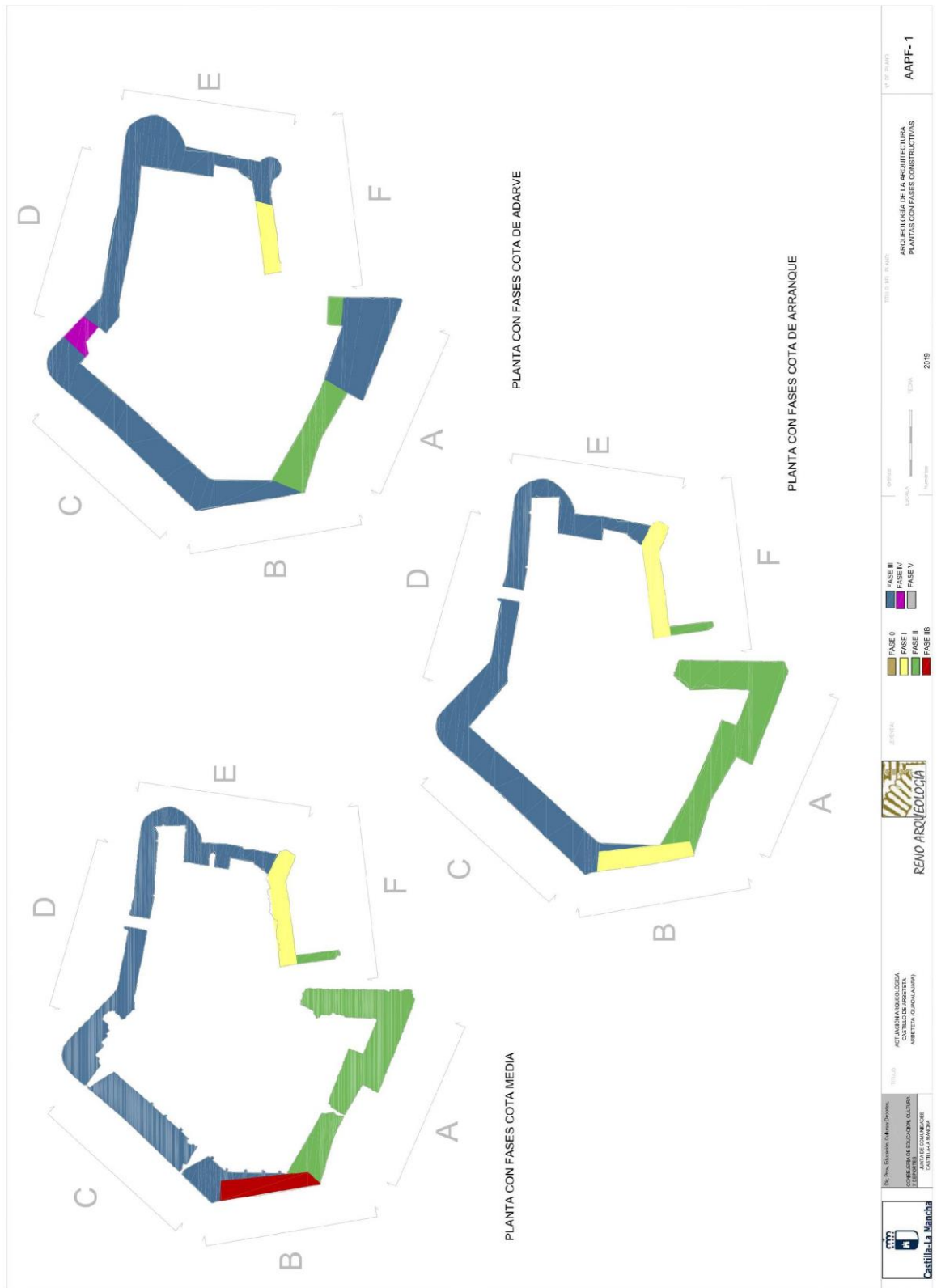












ANNEX B

MASONRY QUALITY INDEX CALCULATIONS

Numerical values for analysis

	A	B	C	D	E	F
HJ	NF	PF	PF	NF	NF	NF
WC	PF	NF	NF	PF	NF	NF
SS	PF	PF	PF	PF	PF	PF
VJ	NF	PF	NF	NF	NF	NF
SD	PF	F	PF	PF	F	PF
MM	PF	PF	PF	PF	PF	PF
SM	PF	PF	F	PF	PF	PF

Vertical loading									
NF	PF	F	A	B	C	D	E	F	
0	1	2	0	1	1	0	0	0	
0	1	1	1	0	0	1	0	0	
0	1.5	3	1.5	1.5	1.5	1.5	1.5	1.5	
0	0.5	1	0	0.5	0	0	0	0	
0	0.5	1	0.5	1	0.5	0.5	1	0.5	
0	0.5	2	0.5	0.5	0.5	0.5	0.5	0.5	
0.3	0.7	1	0.7	0.7	1	0.7	0.7	0.7	
MQI			2.5	3.2	3.5	2.5	2.1	1.8	
Estimated f_c (MPa) HIGH			2.7	3.2	3.4	2.7	2.6	2.4	
Estimated f_c (MPa) LOW			1.6	1.9	2.0	1.6	1.5	1.4	
Estimated shear strength (MPa) HIGH			0.0	0.1	0.1	0.0	0.0	0.0	
Estimated shear strength (MPa) LOW			0.0	0.0	0.0	0.0	0.0	0.0	
Estimated E (MPa) HIGH			1225.6	1374.1	1454.9	1225.6	1157.4	1093.1	
Estimated E (MPa) LOW			839.4	948.0	1007.4	839.4	789.8	743.2	
Horizontal in-plane loading									
NF	PF	F	A	B	C	D	E	F	
0	0.5	1	0	0.5	0.5	0	0	0	
0	1	2	1	0	0	1	0	0	
0	1	2	1	1	1	1	1	1	
0	1	2	0	1	0	0	0	0	
0	0.5	1	0.5	0	0.5	0.5	1	0.5	
0	1	2	1	1	1	1	1	1	
0.3	0.7	1	0.7	0.7	1	0.7	0.7	0.7	
MQI			2.45	2.45	3	2.45	2.1	1.75	

Horizontal out-of-plane loading								
NF	PF	F	A	B	C	D	E	F
0	1	2	0	1	1	0	0	0
0	1.5	3	1.5	0	0	1	0	0
0	1	2	1	1	1.5	1.5	1	1
0	0.5	1	0	0.5	1	1	1	0
0	0.5	1	0.5	1	0.5	0	1	0.5
0	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5
0.5	0.7	1	0.7	0.7	1	0.7	0.7	0.7
MQI			2.45	2.8	4.5	2.8	2.45	1.4