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OMA Tests and FEM Updating in Peruvian Archaeological Heritage: Chokepukio y
Modal Identification Tests on Archaeological Heritage: The Case of Chokepukio.

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Resumen

Los modelos numéricos son herramientas útiles para comprender el comportamiento de las estructuras. Sin embargo, contar con un modelo que se ajuste a la realidad es difícil debido a las variables que están en juego y a las simplificaciones que se asumen al construirlo. Para que un modelo sea confiable debe ser calibrado. Esta calibración se realiza comparando ciertos parámetros (por ejemplo las propiedades dinámicas) del comportamiento de la estructura real con los resultados del análisis numérico. Para identificar qué parámetros son los que tienen mayor influencia en el comportamiento de las estructuras es necesario llevar a cabo un análisis de sensibilidad.

En este trabajo se presentan dos artículos publicados en congresos internacionales que muestran la calibración del modelo numérico de una estructura histórica ubicada en el sitio arqueológico de Chokepukio (Cusco-Perú). Esta estructura, que data de la época pre-inca (900-1300 dC), es un muro de albañilería de piedra asentada con mortero de barro. Los parámetros modales experimentales de la estructura se obtuvieron llevando a cabo una campaña experimental aplicando la técnica OMA (Operational Modal Analysis). El proceso de calibración se llevó a cabo utilizando un algoritmo de optimización de los parámetros que tenían mayor influencia en la respuesta dinámica de la estructura los cuales fueron identificados a través de un análisis de sensibilidad.

El primer artículo titulado “OMA Tests and FEM Updating in Peruvian Archaeological Heritage: Chokepukio” fue presentado en el congreso del EVACES (Experimental Vibration Analysis for Civil Engineering Structures) realizado en la ciudad de Ouro Preto (Brasil, octubre 2013). En este artículo se desarrollaron tres modelos de elementos finitos usando el software SAP2000 y se calibró uno de ellos en base a los parámetros modales obtenidos en la campaña experimental. Los resultados de este trabajo sirvieron como herramienta preliminar para una posterior calibración automática.

El segundo artículo titulado “Modal Identification Tests on Archaeological Heritage: The Case of Chokepukio” fue presentado en el congreso del IMAC-XXXII (A Conference and Exposition on Structural Dynamics) realizado en la ciudad de Orlando–Florida (USA, febrero 2014). En este artículo se presentan tres modelos de elementos finitos desarrollados en el software Diana TNO y uno de ellos se calibró en base a los parámetros modales obtenidos en la campaña experimental.

Por último, se incluye un anexo que presenta una herramienta, desarrollada en el entorno de MatLab, para llevar a cabo un proceso automático de optimización en base a parámetros modales. Esta optimización se realiza minimizando el error de una función (función objetivo) que depende de las frecuencias y las formas modales de vibración, analíticas y experimentales. La herramienta de optimización automática consta de cinco módulos que incluyen: a) el ingreso de los datos de entrada,

b) la resolución de ecuaciones para establecer la función objetivo, c) la aplicación de matrices de ponderación, d) la construcción de la función objetivo y d) el proceso de optimización. En este anexo se incluyen cuatro ejemplos de aplicación de la herramienta propuesta que se presentan según su nivel de complejidad, desde una viga con un solo parámetro de calibración hasta una estructura real con cuatro parámetros de calibración.

Contenido

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OMA TESTS AND FEM UPDATING IN PERUVIAN ARCHAEOLOGICAL HERITAGE: CHOKEPUKIO

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ABSTRACT

The conservation of historical structures is of high importance for preserving the cultural heritage of humanity. The assessment of the structural behaviour of these types of buildings is particularly complex due to the difficulty of an accurate characterization of materials, boundary conditions, and damage state. In this paper, OMA tests are used to study a Pre-Inca stone masonry wall which is part of the archaeological site of Chokepukio in Cusco, Perú (~1100 A.D). The studied structure has 18 m length and 9 m height, and is made of irregular stone and mud mortar with bricks in multileaf configuration. The paper presents the details of the tests and the results of the data processing stage which was performed using the stochastic subspace identification method. The paper also discusses the process of finite element model calibration which was carried out by means of a sensitivity analysis and the use of optimization algorithms.

Keywords: Operational Modal Analysis, Archaeological sites, Stone Masonry, FE Analysis, Model Calibration

1. INTRODUCTION

The maintenance and preservation of historic structures is of high importance in order to preserve the cultural heritage of humanity. Understanding the structural behavior of this type of constructions is particularly complex due to the difficulty for characterizing the geometry, materials, and damage state, for identifying the structural system, as well as for creating reliable numerical models (Lourenço, 2006). The International Council of Monuments and Sites (ICOMOS), organization responsible for the cultural heritage conservation, dictates different strategies for studying historical constructions which consists on carrying out extensive diagnosis campaigns by means of non destructive tests, as well as laboratory and on site research (Roca et al., 2010). In this context, non-destructive testing becomes an important tool since it allows the evaluation of historical constructions without endangering its structure. The experimental vibration analysis, such as Operational Modal Analysis (OMA), is one of the most powerful non destructive techniques that allow the identification of the dynamic parameters of a structure. With the experimental results, an updating process can be performed in order to estimate optimum properties for the Finite Element (FE) models.

In this study, OMA tests are carried out in one of the last remaining traces of the archeological site of Chokepukio in Cusco, Perú. The results of these tests are used for calibrating the FE model of the studied structure which is the preliminary analysis for further studies of seismic vulnerability.

2. THE CHOKEPUKIO ARCHEOLOGICAL SITE

The archaeological site of Chokepukio is located 30km far away to the city of Cusco, Peru. A wide variety of remaining structures built with stone masonry and mud mortar were found in this archaeological site (see Figure 1). Unfortunately, the complex is severe damaged due to the pass of the time and the occurrence of earthquakes (Perú is located in one of the most active seismic zones of the world). The damages consist on loss of stone units and revetments due to the hard weather conditions and the presence of vegetation.

2.1 Historical Description

After the Wari's culture disappearance and before the Incas Empire, a small culture known as Lucre, was developed in the area of Chokepukio, Cusco. It is said that the remains left by the Lucre culture (Choquepukio) was built between 900 – 1300 AD and that it was considered as the main gathering centre of the late intermediate period of the Peruvian history. Niches for rituals and festivities found in Chokepukio indicate that the constructions had mainly religious purposes (McEwan et al. 2005). This archaeological site is located in the area of the confluence of two rivers: the Huatanay and the Vilcanota. This fact is an evidence of the worship that occupants had for water which is confirmed by existent reservoirs and canals that crossed their enclosures. So far, there are few vestiges of walls and foundations which give an idea of the size of Chokepukio in its time.

Figure 1: Panoramic View of one sector at the Chokepukio archaeological site

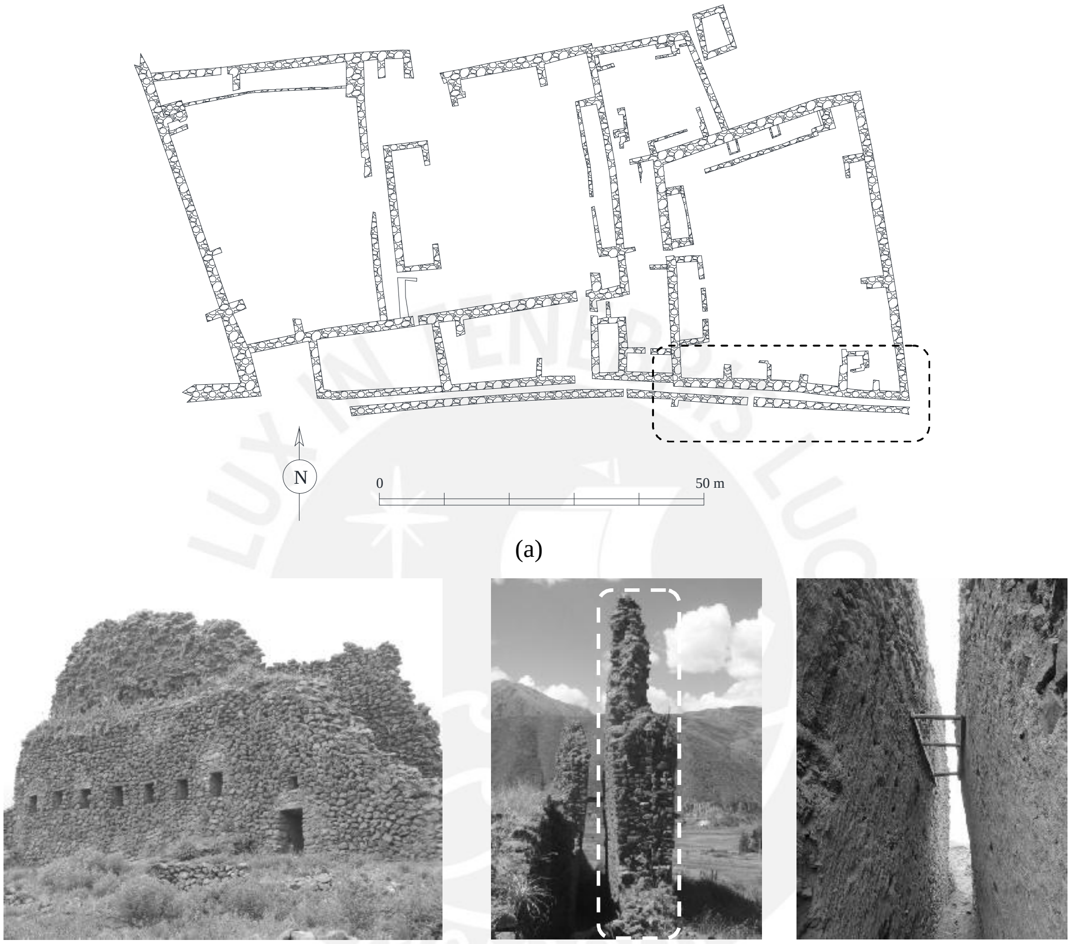
2.2 Architectural description

The archaeological site of Chokepukio presents a special architecture with walls forming enclosures around open spaces. This configuration maintains streets and narrow passageways connecting the access to the enclosures. Up to now, there were found vestiges of around ten groups of structures (called as "kanchas") which correspond to an urban settlement. In general, the perimeter walls are of around 12 m high and have trapezoidal and rectangular niches (closed windows) at different heights. The "rustic" and "simple" masonry found in Chokepukio is made of semi rounded stone with irregular joints of mud and straw mortar. In some cases, the original earthen coatings are still visible on the walls and the niches (McEwan et al. 2005).

2.3 Structural description

The archaeological site of Chokepukio was built with local material which is mainly Andesite stone. The masonry system is composed by irregular stones and mortar joints varying in thickness between 2.5 and 10 cm. The height of these structures is also variable ranging from 10 -12 m.

The selected area of study was a sector of the so called "Area A". The plant view of the studied area is shown in Figure 2a. As shown, the structural evaluation was carried out in the vestiges located at the corner of this sector which consisted on two walls connected with timber struts. This sector was selected as case study due to the well preservation state of the remaining structures (the original plaster is still on the interior wall's face of both of them – Figure 2d). In this case, only the front wall was instrumented for its structural disconnection with other parts. This wall, has an irregular geometry, is more than 20 m long and 9 m high, and its thickness varies from 1.20 m-1.80 m at the base and ~0.60 m at the top (see Figure 2b and Figure 2c). The different arrangements of the stone masonry that were used evidence the existence of two different masonry qualities. At the base, a more consolidated structure was built using bigger stones and mud mortar. On the other hand, the top part of the wall was made of smaller stones and thicker mud mortar joints.



(a)

(b) (c) (d)

Figure 2 : General views of the studied area: (a) plant view of the studied sector (McEwan et al. 2005); (b) elevation view of the instrumented wall, (c) section view; and (d) detail of the connection timber struts

The structural pathologies found in the case study are due to vegetal agents, the pass of the time, and the occurrence of earthquakes which caused deterioration in the lower and upper part. The studied wall presents also an inclination controlled with three wooden struts which served for connecting the structure to the existent wall behind it. The interaction between the two walls is observed in Figure 2c and Figure 2d.

3. OPERATIONAL MODAL ANALYSIS TESTS

In order to identify the dynamic response of the studied wall, an experimental campaign was carried out using ambient noise as the excitation source. This experimental campaign was conducted on December 2012. Sixteen measurement points were established in order to acquire as much data as possible. The transducers were four piezoelectric accelerometers with a sensitivity of 10 V/g and a dynamic range of ± 0.5 g together with an USB-powered 24 bits resolution data acquisition system. External scaffolding (not connected to the structure) was necessary to place the transducers along the wall as shown in Figure 3a. In addition ground vibrations were measured for further studies of soil-structure interaction.

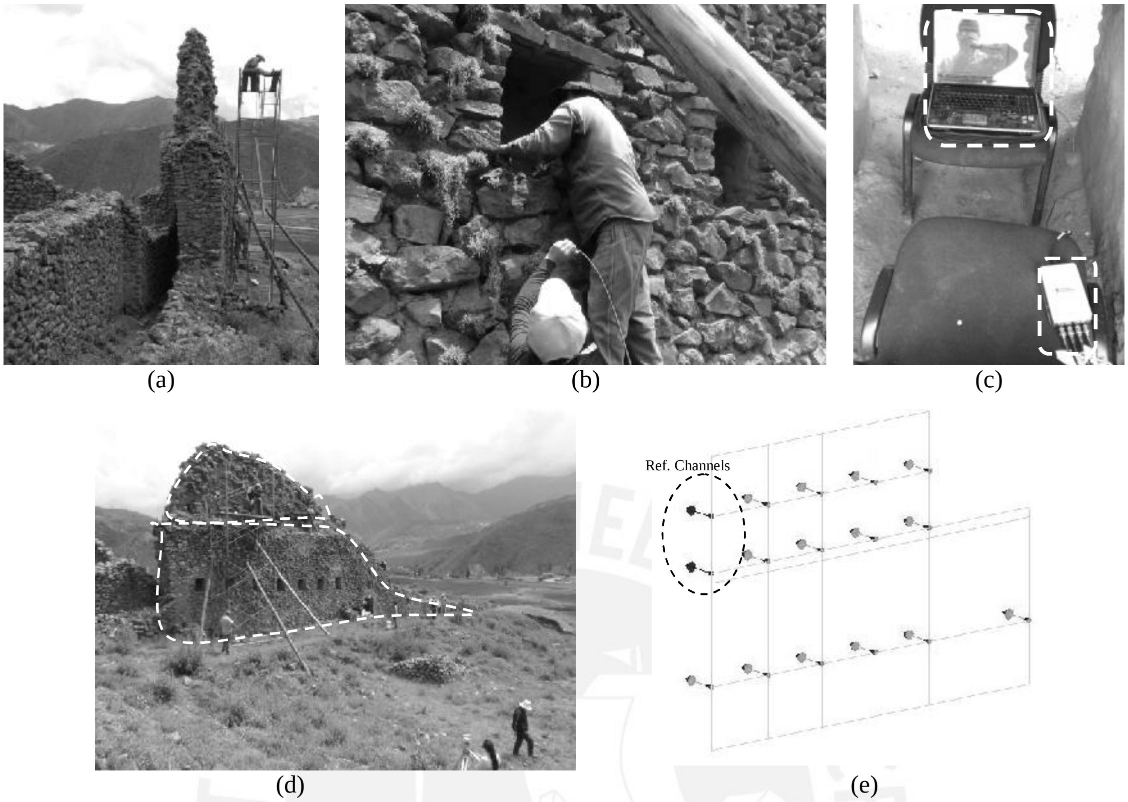


Figure 3: OMA tests at the Chokepukio archeological site: (a) and (b) location process of sensors; (c) central acquisition station; (d) and (e) instrumentation setup

The identification of the dynamic response was performed using time domain signal processing techniques by means of the SSI method, implemented in the ARTeMIS software (SVS, 2013). The stabilization diagram resultant from the application of this methodology is presented in Figure 4. As shown, at least four clearly aligned stable plots (indicating the first natural frequencies of the structure) at all the tests setups can be identified in the diagram. For the subsequent data interpretation stage and the numerical model calibration, only the results of the first four natural frequencies will be taken into consideration.

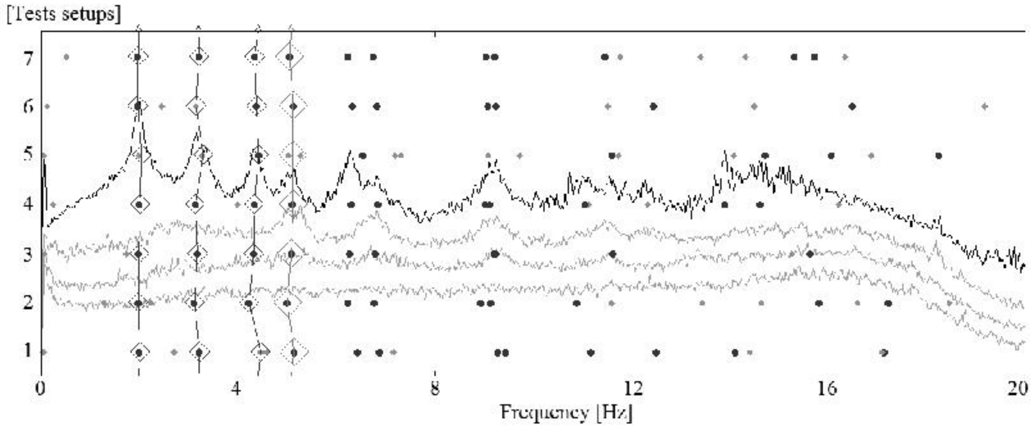
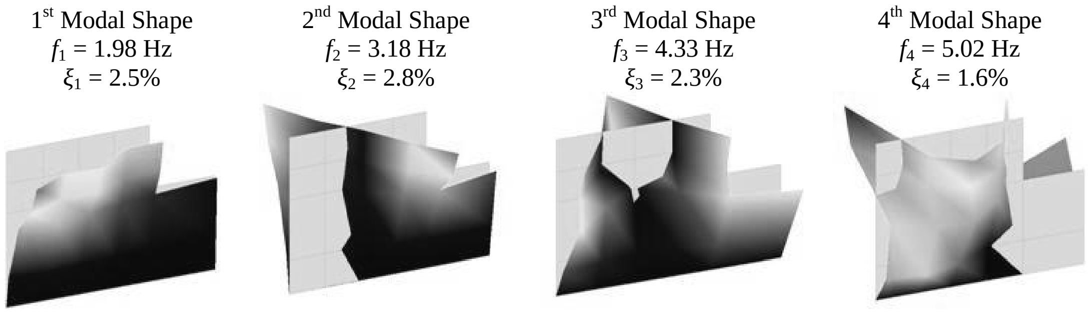


Figure 4 : Resultant stabilization diagram after the application of the SSI method for processing the acquired data

The experimentally identified dynamic behavior of the instrumented wall, by means of the first four natural frequencies, damping ratios and mode shapes, is presented in Figure 5.



1st Modal Shape $f_1 = 1.98$ Hz $\xi_1 = 2.5\%$

2nd Modal Shape $f_2 = 3.18$ Hz $\xi_2 = 2.8\%$

3rd Modal Shape $f_3 = 4.33$ Hz $\xi_3 = 2.3\%$

4th Modal Shape $f_4 = 5.02$ Hz $\xi_4 = 1.6\%$

Figure 5 : Experimental results of the tests at Chokepukio archaeological site

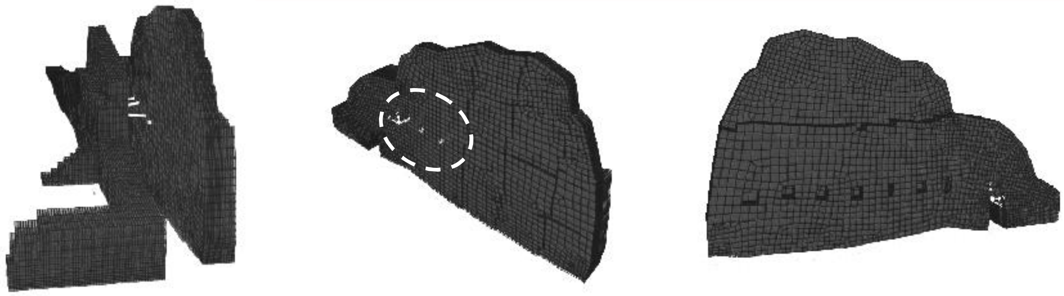
4. NUMERICAL MODEL AND UPDATING PROCESS

Computational models were developed using the SAP2000 (CSI, 2013). The models were created considering solid elements with homogeneous properties. Since laboratory tests haven't been performed and the mechanical properties of the constituent material are unknown, a bibliographic research was carried out for completing the FE model of the wall. Table 1 shows the mechanical properties of similar stone masonry. For the present study, the parameters given by Brignola, (2008) were chosen as base values.

Table 1: Mechanical properties of stone structures studies

Description	Wall typology	E [GPa]	Poisson ratio
Laboratory test (Porto et. al., 2003)	Irregular stone with lime mortar, sand(1:3) and water	0.3 – 5.1	
In-situ test (Porto et. al., 2003)	Irregular stone with lime mortar	0.1 - 1.3	
Laboratory test (Brignola, 2008)	Volcanic Stone with lime mortar and sand (e = 50 cm)	1.2	0.2
Laboratory test (Brignola, 2008)	Multi-leaf irregular stone lime mortar	0.8	0.2
Laboratory test (Manos, 2008)	Stone with lime mortar	2.5	0.2
Laboratory test (Almeida et al., 2011)	Irregular stone with lime mortar and sand (1:3)	0.2 - 0.3	0.2 - 0.3

In order to perform a sensitivity analysis, three structural conditions of the wall were tested. The first hypothesis was implemented taking into account the interaction between the wall that is being studied and the other one located behind it (Figure 6a). In the model implemented, the existent timber struts were represented by linear elements made of eucalyptus, with a modulus of elasticity of 5.4 GPa as stated in NTE E.010 (2006). The second hypothesis considered a partially decoupled system. For this, the struts were represented by springs with equivalent axial stiffness (Figure 6b). Finally, the third hypothesis considered that the existing walls are completely disconnected from each other (Figure 6c). In the last model implemented for this purpose, only the instrumented model was studied. In all the models, the specific weight of the structural system was set as 23.5 kN/m^3.



(a) (b) (c)

Figure 6 : Tested hypothesis: (a) first: numerical model of the two walls; (b) second: numerical model of the instrumented wall with springs representing the timber struts; and (c) third: numerical model of the wall considered as disconnected with the other one behind it

The first four natural frequencies and mode shapes resultant from the numerical modal analysis and the experimental results were compared using the Modal Assurance Criterion (MAC). This criterion establishes a relationship between two modal vectors ranging from 0-1. The closer the MAC value is to 1, the more consistent are the results (Allemang, 2003). The expression used to calculate MAC is defined by equation (1):

$$MAC = \frac{\left| \sum_{i=1}^{n} \varphi_i^{exp} \varphi_i^{FE} \right|^2}{\sum_{i=1}^{n} \left(\varphi_i^{exp} \right)^2 \sum_{i=1}^{n} \left(\varphi_i^{FE} \right)^2} \qquad (1)$$

where φ^{exp}, and φ^{FE}, are the experimental and numerical modal vectors, respectively.

The summary of the results, by means of the frequencies and MAC values calculated for the three working hypothesis are presented in Table 2. As shown, the frequencies have relatively good agreement in all the models. The maximum relative errors registered were of 14% in the 1st model, 19% in the 2nd model, and 14% in the 3rd model. The MAC ratios evidence as well a good correlation but higher variability for the third and fourth mode shapes.

Table 2 :Results of experimental and theoretical frequencies

	Experimental Frequency [Hz]	1° Model Frequency [Hz]	MAC	2° Model Frequency [Hz]	MAC	3° Model Frequency [Hz]	MAC
1st Mode	1.98	2.08 [5%]	0.99	1.95 [2%]	0.99	1.74 [12%]	0.99
2nd Mode	3.17	3.62 [14%]	0.96	3.78 [19%]	0.94	3.31 [4%]	0.97
3th Mode	4.33	4.43 [2%]	0.72	4.78 [10%]	0.59	4.47 [3%]	0.80
4th Mode	5.02	5.04 [<1%]	0.68	5.83 [16%]	0.79	5.73 [14%]	0.78

* (the relative errors are shown in brackets)

The subsequent optimization process of the FE model was carried out using an objective function, aiming at minimizing the difference between experimental and analytical results, as proposed in Ramos et.al. (2012). The optimization process was carried out only in the third working hypothesis considering the fact that its result reveal closer mode shapes to the ones obtained in the OMA tests (even if in frequencies the values had higher uncertainties).

In order to build the objective function, the Douglas-Reid approach (Douglas-Reid, 1982) was used. For this, base, lower, and upper values for pre-defined varying parameters were proposed. In this case, for choosing the varying parameters, a sensitivity analysis was carried out aiming at analyzing the influence of the material (the E-modulus and the specific weight) and the structural conditions (the boundary conditions and the localization of damage).

The results of the sensitivity analysis showed that the more significant parameters for optimizing were the E-modulus (which clearly affected the results of natural frequencies) and the specific weight of the material (which affected the mode shapes results). Aiming at obtaining a more refined numerical model and thus, better results in the calibration process, the existent two different masonry systems (one in the lower part and one in the upper part, coinciding with the change in section), were modeled with different materials.

Table 3 and Table 4 summarize the results of the calibration process. As shown, the final values obtained for the parameters that characterize the material (E-modulus and specific weight) evidence a difference in the quality of the masonry at the lower and upper part of the studied wall. The high correspondence between the results of the experimental campaign is also clearly evidenced since the frequencies and MAC values present small errors.

Table 3:Initial and final values for the obtained after the calibration process

Updating Parameters	$E_{lower\ wall}$ [MPa]	$E_{upper\ wall}$ [MPa]	$\gamma_{lower\ wall}$ [N/mm3]	$\gamma_{upper\ wall}$ [N/mm3]
Initial Values	800.0	800.0	269.0E-3	269.0E-3
Final Values	643.7	426.9	342.6E-3	316.5E-3

Table 4: Results of the modal analysis with the updated numerical model and comparison with the experimental data

	Experimental[Hz]	FEM[Hz]	Error	MAC
1^{st} Mode	1.98	1.82	7.8 %	1.00
2^{nd} Mode	3.17	3.42	8.0 %	0.98
3^{th} Mode	4.33	4.33	< 1 %	0.76
4^{th} Mode	5.02	5.67	13.0 %	0.81

5. CONCLUSIONS

This paper presents the details of the operational modal analysis tests carried out in a sector of the archeological site of Choquepukio in Cusco Perú. The paper aims at studying one of the remaining sectors of the site which is important for its good state of preservation and its location at the entrance of the complex. The results of the OMA tests in the instrumented wall show that the first four frequencies were experimentally identified with high reliability. On the other hand, the numerical model shows that the wall can be studied as a simplified system considering no interaction with the one located behind it. The results of the calibration process show that the dynamic behavior of the updated model has high correspondence with respect to what was measured in the field tests. These results are of high importance for carrying out future studies of seismic vulnerability evaluation.

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Modal Identification Tests on Archaeological Heritage: The Case of Chokepukio

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NOMENCLATURE

$f_{j,FE}$	Finite Element frequency	$\phi_{j,FE}$	Finite Element shape mode
$f_{j,exp}$	Experimental frequency	$\phi_{j,FE}$	Experimental shape mode
$W_{f,j}$	Weighting matrix for frequency	$W_{\phi,j}$	Weighting matrix for shape mode

ABSTRACT

In recent decades, the application of experimental modal identification tests in civil engineering structures is gaining interest for various purposes such as model calibration, quality control while the construction process, damage detection, and structural health monitoring of new buildings and bridges. The use of these tests in archaeological earthen sites is a novel area of application. The paper presents the results of operational modal analysis tests carried out on an archaeological site in Peru as part of an extensive research for assessing its structural vulnerability. The case study is related to the tests on one of the remaining stone masonry walls of Chokepukio archaeological site, which dates back to the 12th Century. The paper shows a brief summary of the historical condition of the site, the details of the tests carried out, the experimental data processing results, as well as the Finite Element model updating process using manual and automatic routines.

Keywords: Operational Modal Analysis, Archaeological sites, Stone Masonry, FE Analysis, Model Calibration

1. INTRODUCTION

Peru is located in the Pacific’s Ring of Fire, one of the most active seismic zones of the world, and thus, its cultural heritage is in permanent danger. The last seismic events that happened in the world such as the one in Chile (2010) and Iran (2003) have evidenced, once again, the fragility of the historical structures. The maintenance and preservation of these structures is of high importance in order to preserve the cultural heritage of humanity. Understanding the structural behaviour of this type of constructions is particularly complex due to the difficulty for characterizing the geometry, materials, damage state, identifying the structural system, as well as creating reliable numerical models [5]. The International Council of Monuments and Sites (ICOMOS) have published different strategies for studying historical constructions. These strategies evidence the necessity of a deep knowledge of the variables referred before which can only be assessed by extensive diagnosis campaigns by means of laboratory and on site research [9]. In this context, non-destructive testing becomes an important tool since it allows the evaluation of the constructions without endangering its structure. Experimental vibration analysis, such as Operational Modal Analysis (OMA), is one of the most powerful non-destructive techniques that allow the identification of the dynamic parameters of a structure. With the experimental results, an updating process can be performed in order to estimate optimum values for the variables required for developing a reliable Finite Element (FE) model. This paper is the preliminary stage of a broader seismic vulnerability study in the remaining traces of Chokepukio, an archaeological site located in Cusco, Peru. The paper starts by presenting a brief summary of the historical condition of the site, continue with the details of the OMA tests carried out in this archaeological site, and finish with the results of the calibration process of the FE model which was carried out using a sensitivity analysis and optimization routines.

2. THE CHOKEPUKIO ARCHEOLOGICAL SITE

The archaeological site of Chokepukio is located 30 km from the city of Cusco, Peru. A wide variety of remaining structures built with stone masonry and mud mortar were found in this archaeological site (**Fig. 1**). Unfortunately, this complex is severely damaged as a result of the pass of time, weathering, local/global settlements and the occurrence of earthquakes.

Fig. 1- General view of Archaeological Site of Chokepukio

2.1 Historical Description

After the Wari Culture disappearance, and before the Inca´s Empire, a group of small human settlements occupied Cusco. The Lucre Culture grew in the area of Chokepukio, south of the city. It is said that the remains left by this Culture were originally built between 1000 AD and 1450 AD and that Chokepukio was considered as the main gathering centre of the late intermediate period of the Peruvian history. This archaeological site is located in the area of confluence of two rivers. This fact may indicate the worship that occupants had for water, which is confirmed by the existence of reservoirs and canals crossing the site’s enclosures. The name of the site has local languages roots since Choke means “gold” and Pukio “wellspring” in Aymara and Quechua. The niches (closed windows in the walls) for rituals and festivities found in this site indicate that the constructions had religious purposes [6].

2.2 Architectural description

McEwan in 2005 divided Chokepukio in three principal sectors (A, B and C –see **Fig. 2**) according to the type of walls and occupation time. Sector A has the most density of standing structures and its walls enclose big areas (2600 m^2) with small rooms connected among them. This sector genuinely belongs to the late intermediate period. Sector B has less standing structures and its surrounded areas are smaller (1000 m^2), without any kind of communication. Its setting belongs to the Inca occupation. Finally, sector C has many small rooms with short walls which are, so far, mostly buried [6].

Chokepukio presents a special architecture with walls forming enclosures around open spaces. This configuration maintains streets and narrow passageways connecting the access to the enclosures. Nowadays, there have been found vestiges arranged in ten groups of structures (called as “kanchas”) which correspond to an urban settlement. In general, the perimeter walls are of 12 m high and have trapezoidal and rectangular niches at different heights. Chokepukio is characterized by presenting "rustic" and "simple" masonry which is made of semi rounded stone with irregular joints composed of mud and straw mortar. In some cases, the original earthen coatings are still visible on walls and niches [6].

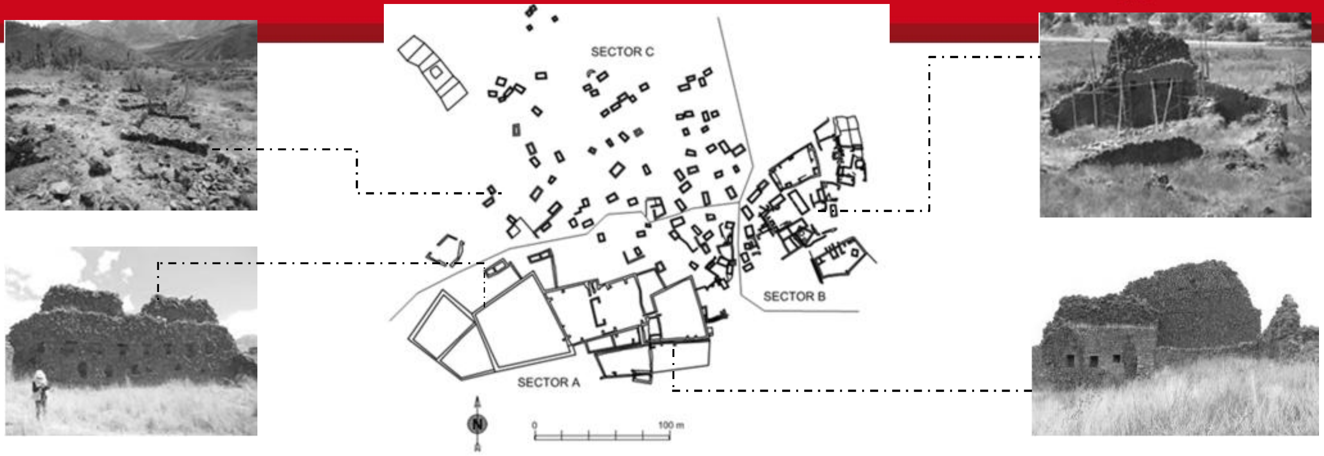
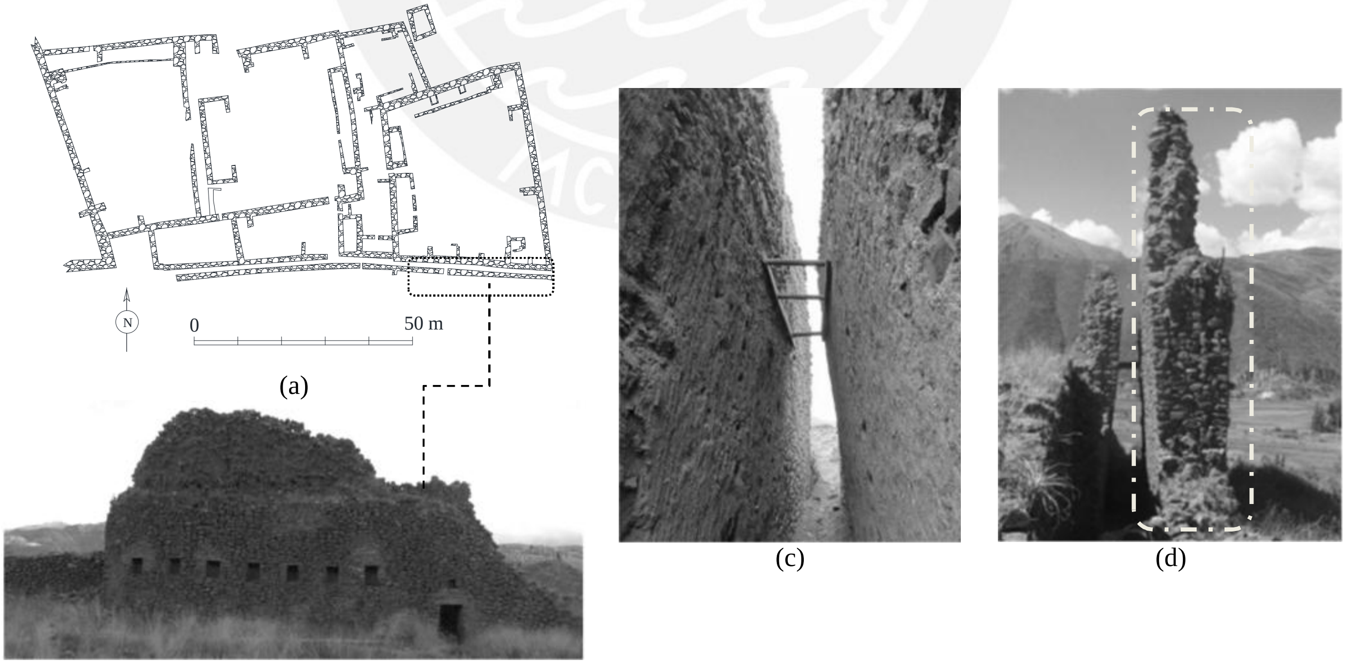


Fig 2 Sectors of Archaeological Site of Chokepukio

2.3 Structural description

The structures found in Chokepukio were built with Andesite stone which is the most available material at the zone. The masonry system is composed by small and irregular stones and mud mortar with variable thickness ranging between 2.5 and 10 cm. The height of these structures is also variable ranging from 10 to 12 m. Each wall of Chokepukio seems to be made in horizontal and vertical stages, which is evidenced by marked lines among some of the stone's courses. The mud mortar is a mixture of local soil, clay, straw, and cactus resin.

The structural evaluation was carried out in the vestiges located at the corner of the Sector A (**Fig. 3a**), which consist on two walls connected with timber struts (**Fig. 3c**). This sector was selected as case study due to the well preservation of the remaining structures (the original plaster is still on the interior wall's face of both walls – **Fig. 3c**). In this case, only the front wall was instrumented. This wall has an irregular geometry, with an average length and height of 20 m and 9 m, respectively. The thickness of the instrumented wall varies from 1.20 m-1.80 m at the base and 0.60-0.40 m at the top (see **Fig. 3b,** and **Fig. 3d**). At the lower part of the wall, a more consolidated structure was built using bigger stones and mud mortar. On the other hand, the upper part was made of smaller stones and thicker mortar. As shown in **Fig. 3d**, the change on materials coincides with the change on section in the height of the wall.



(a)

(c)

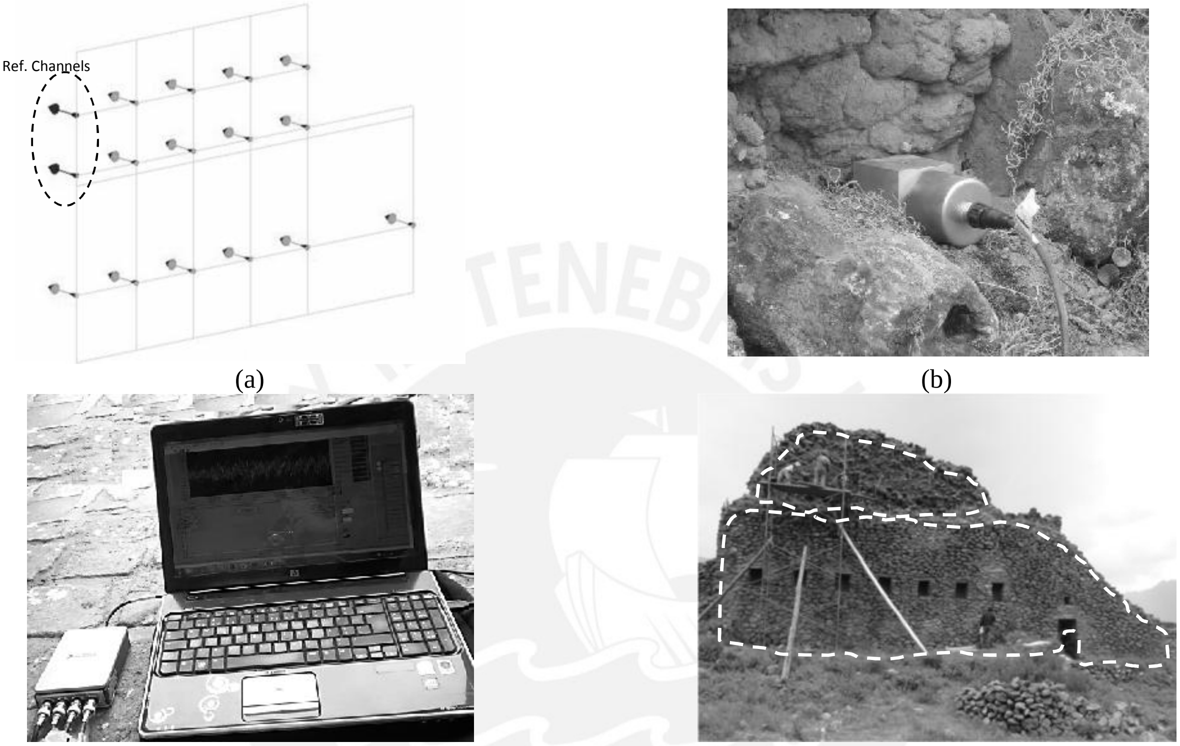
(d)

(b)

Fig. 3- General views of the studied area : (a) plant view of the studied sector [8], (b) elevation of the instrumented wall, (c) timber struts connecting the two studied walls and (d) section view of the instrumented wall

3. OPERATIONAL MODAL ANALYSIS TESTS

An experimental modal analysis campaign was carried out in Chokepukio using ambient noise as excitation source. As previously referred, one of the walls at Sector A was instrumented with sixteen measurement points to acquire as much data as possible (**Fig. 4a**). For this purpose, seven setups were considered using two sensors at the top of the wall as reference nodes. In the whole setups the sampling rate was 200 Hz and the acquisition time was 10 min. The transducers used for this study were four piezoelectric accelerometers (**Fig. 4b**) with a sensitivity of 10 V/g and a dynamic range of ± 0.5 g together with an USB-powered 24 bits resolution data acquisition system (**Fig 4c**). External scaffolding (not connected to the structure) was necessary to place the transducers along the wall as shown in **Fig. 4d**.

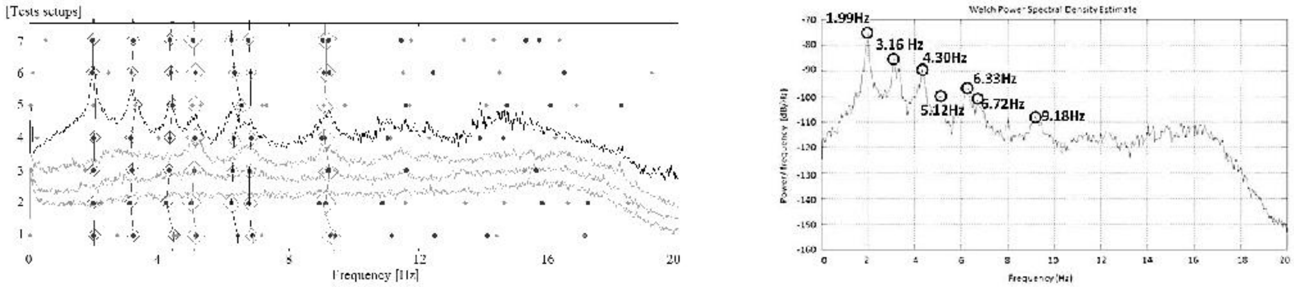


(a) (b)

(c) (d)

Fig. 4 - OMA tests at Chokepukio: (a) tests setup; (b) close up of a measurement node; (c) central acquisition station; and (d) general view of the instrumented wall and the process of fixing sensors

The date processing stage was carried out using the Peak Picking (PP), and the Stochastic Subspace Identification (SSI) methods. The PP process was carried out by using the welch routine [11] for building an averaged spectrum. On the other hand, the ARTeMIS software [1] was used for processing the data with the SSI method [7]. **Fig. 5** shows the results of the modal identification process of both methodologies. As shown, the perfectly aligned poles at the SSI method (**Fig. 5a)** and the clear peaks in the resultant Welch spectrum evidence a good identification of at least the first seven modes. Table 1 presents the summary of the natural frequencies estimated with both methods. As shown, the results of both are in high correspondence with errors of less than 2%.



(a) (b)

Fig. 5 – Data processing results: (a) stabilization plot of the SSI method; and (b) Welch spectrum for the PP method

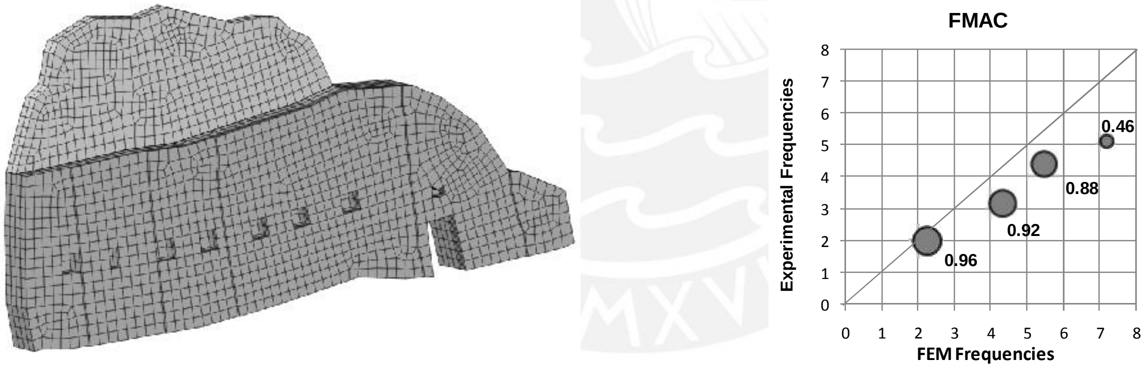
Table 1: Frequency error between the estimations from the Peak Picking and SSI methods

Mode	PP Frequency [Hz]	SSI Frequency [Hz]	Relative Errors [%]
1	1.99	1.99	0.22
2	3.16	3.16	0.23
3	4.30	4.37	1.60
4	5.12	5.09	0.41
5	6.33	6.35	0.31
6	6.72	6.79	1.03
7	9.18	9.19	0.11

4. NUMERICAL MODEL AND UPDATING PROCESS

The numerical analysis was performed using DIANA TNO release 9.4.4 [10]. For building a preliminary model (named as Model1), the mechanical properties of the materials were considered homogenous and were based on values proposed by Brignola et al. [3], and thus, the elasticity modulus and specific weight were set to 0.80 GPa and 2.690E-5 N/mm^3, respectively. The FE model was built using eight nodes isoparametric solid elements type HX24L. With these considerations, the resultant FE model has 7637 solids with 9862 DOF. The supporting conditions were considered as fully restrained at the base of the wall and no contact between the instrumented wall and the other one behind it. As shown in **Fig. 6a**, this preliminary model was built using two sections with different thickness according to the change of section in height.

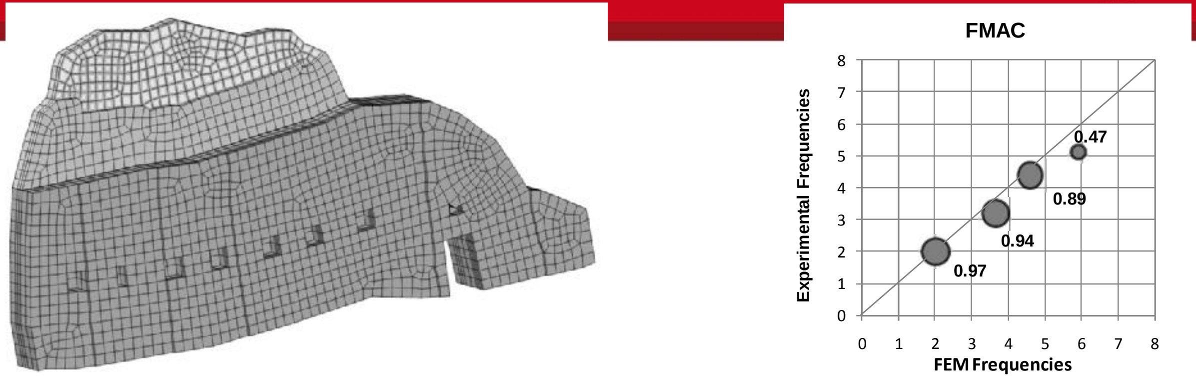
The numerical modal analysis and the updating process was carried out considering only the first four natural frequencies and mode shapes of the wall due to the complexity of the measured superior modes. In order to compare mode shapes, the Modal Assurance Criterion (MAC), which establishes a relationship between two modal vectors, was used. **Fig. 6b** shows the comparison between numerical and experimental results by means of frequency versus scaled MAC values (FMAC). In the FMAC, the distance of the dots from the 45º line indicates the frequency difference, while its size indicates the ratio of MAC values. If dots match the 45º line, and its size is one, means that the numerical frequencies and mode shapes are similar to the experimental ones [2]. The FMAC results for Model1 indicate that, neither the frequencies, nor the modal shapes, were accurately assessed by the numerical model (max. frequency difference 40% and min MAC 0.46).



(a) (b)

Fig. 6- Model1: (a) FE numerical model; and (b) comparison between numerical and experimental results

A sensitivity analysis was then carried out for improving the numerical results. Several variables such as the E-modulus, boundary conditions, geometrical properties and the specific weight were evaluated for this purpose. The conclusion of the study was that the variables with more influence were the E-modulus, specific weight, and the geometrical conditions (a third different section in height should be added). With these considerations, as presented in **Fig. 7a**, a new model (called as Model2) was built considering that the upper part of the wall had two different thicknesses. In this model, as in Model1, the mechanical properties of the materials were considered homogenous. The values used for the material in this model were 0.50 GPa and 2.350E-5 N/mm^3 for the elasticity modulus and specific weight, respectively. The results of the FMAC for this case **(Fig. 7b)**, indicates a better correspondence between the numerical and the experimental estimation of frequencies (max. difference of 15%). However, the modal shapes of the new model are still not accurate enough since the values of MAC are still remaining as low as 0.47.



(a) (b)

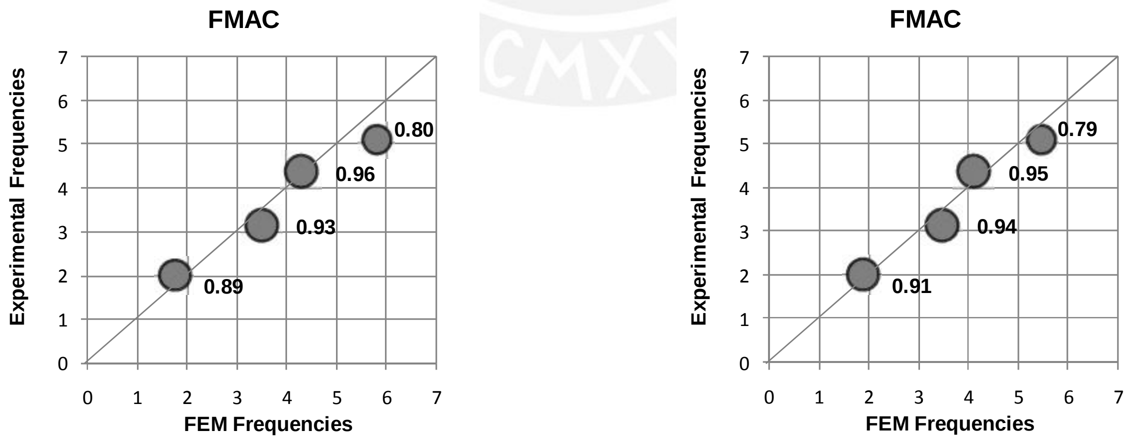
Fig. 7- Model2: (a) FE numerical model; and (b) comparison between numerical and experimental results

An optimization process was finally carried out on the two previous models (Model1 and Model2). This process was carried out aiming at minimizing frequency and modal shapes inaccuracies between experimental and numerical estimations. This process was based on an objective function defined by equation 1, as presented in Ramos et al. [8].

$$® = \frac{1}{2}\left[\sum_{j=1}^{m_w} W_{f,j}\left(\frac{f_{j,FE}^2 - f_{j,\exp}^2}{f_{j,\exp}^2}\right)^2 + \sum_{j=1}^{m_{\cdot\cdot}} W_{\cdot\cdot,j}\left(\ddot{}_{j,FE} - \ddot{}_{j,\exp}\right)^2\right] \qquad (1)$$

where $W_{f,j}$ and $W_{\varphi,j}$ are the diagonal weighting matrices for frequency and shape modes, respectively. These matrices could have different values according to the judgement of the analyser.

The Douglas-Reid approach [4] was used for creating the objective function. This approach states that base, lower, and upper values for pre-defined varying parameters need to be defined. For the original formulation, the number of the updating modes must be larger than the number of varying parameters to properly establish the equations. According to the results of the sensitivity analysis, the E-modulus and specific weight of the material were considered as varying parameters for the optimization process. Aiming at obtaining a more refined numerical model and better results in the calibration process, two materials (one in the lower and one in the upper part of the wall) were considered for Model1 and Model 2. The results of the FMAC (**Fig. 8**) show for both, Model1 and Model2, high correlation between experimental and updated models. The maximum difference in frequency is 13.5% for the Model1 and 9.8% for the Model2 while the minimum MAC is of 0.80 and 0.79 for the Model1 and Model2, respectively.



(a) (b)

Fig. 8 – FMAC comparison after the calibration process: (a) optimized Model1; and (b) optimized Model2

Table 2 and Table 3 summarize the results of the calibration process for Models 1 and 2. As observed, the final values for the varying parameters evidence a clear difference in the quality of the masonry at the lower and upper part of the wall. The results show that the lower part might have an E-modulus in the range of 750 – 1100 MPa. The result of the E-modulus for the upper part has less uncertainty as is clearly close to 300MPa. In case of the specific weight, the results of the optimization process of Model1 show high values close to 3.5N/mm3. This value might not be accurate taking into consideration what can be found in the field, and may indicate that the optimization of Model2 is more reliable. This is also confirmed when observing the results of frequencies. In this case, the optimized Model2 show frequencies values with errors of less than 10% in comparison to what was registered in the field campaign.

Table 2:Initial and final values obtained after the calibration process

Updating Parameters	$E_{lower\ wall}$ [MPa]	$E_{upper\ wall}$ [MPa]	$\gamma_{lower\ wall}$ [N/mm3]	$\gamma_{upper\ wall}$ [N/mm3]
Initial Values $_{Model1}$	800.0	800.0	2.690E-5	2.690E-5
Final Values $_{Model1}$	1056.1	300.0	3.432E-5	3.432E-5
Initial Values $_{Model2}$	500.0	500.0	2.350E-5	2.350E-5
Final Values $_{Model2}$	775.4	301.7	2.943E-5	2.943E-5

Table 3: Results of the modal analysis with the updated numerical model and comparison with the experimental data

	Experimental [Hz]	FEM_{model1} [Hz]*	FEM_{model2} [Hz]*	MAC_{model1}	MAC_{model2}
1st Mode	2.00	1.74 [13.0%]	1.86 [7.0%]	0.89	0.91
2nd Mode	3.16	3.49 [10.4%]	3.47 [9.8%]	0.93	0.94
3rd Mode	4.37	4.27 [2.3%]	4.10 [6.2%]	0.96	0.95
4th Mode	5.10	5.79 [13.5%]	5.43 [6.5%]	0.80	0.79

* The difference in frequency is indicated inside the brackets

For visualization issues, the first four mode shapes of the experimental, and the ultimate numerical model (optimized model2) are shown **Fig. 9**. As shown, the experimental and numerical mode shapes are almost the same in the whole cases. These results evidence the reliability of the optimized Model2 and confirm that this model can be used for a further stage of the structural evaluation which consists of verifying the response of the wall under seismic actions and finding an appropriate intervention technique.

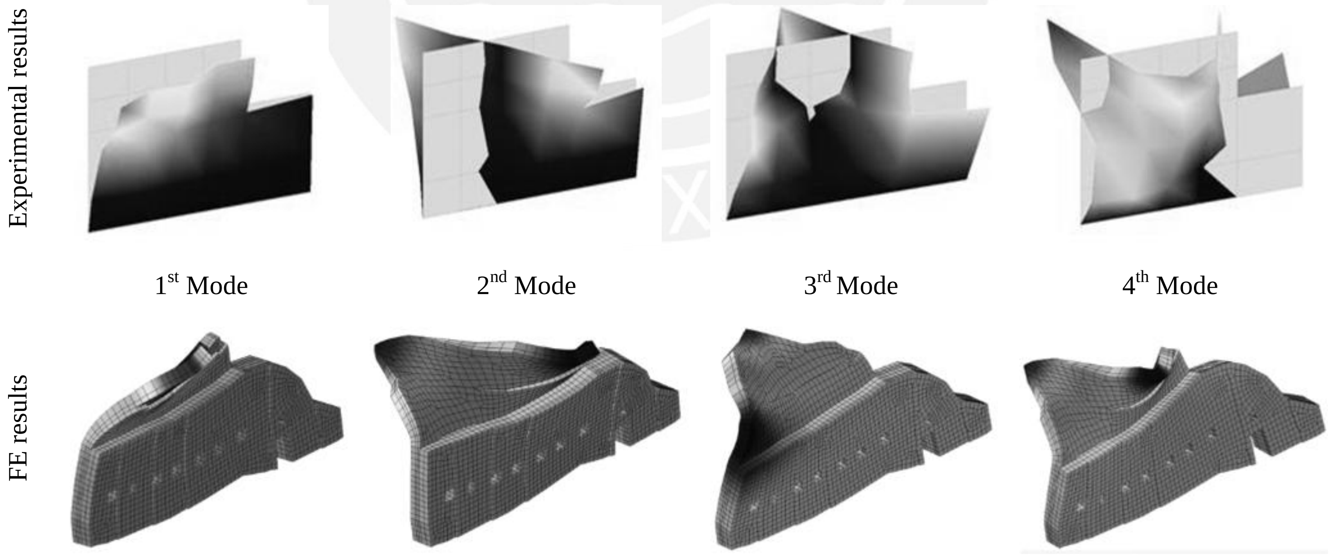


Fig. 9 – Mode shape comparison of the experimental and numerical results at the calibrated model

5. CONCLUSIONS

This paper remarks the relevance and feasibility of applying OMA tests to identify the behaviour of archaeological earthen-based structures. In this case study, one sector of the Chokepukio, an archaeological site dating back to the 12th century, was studied by means of experimental and numerical tools. The results of the OMA tests evidence clear spectrums and properly aligned stabilization plot which is an indication of the proper level of the ambient excitation in the tests as well as the reliability of the experimental campaign. The results of the numerical analysis indicate the importance of the calibration process for obtaining an accurate model. In this specific study, it was shown that the most important variables for the analysis were the mechanical properties of the materials and the accurate representation of the geometrical conditions. The calibration process of the numerical model was successful after carrying out a sensitivity manual analysis and an automatic optimization routine. The results allowed the identification of two different qualities of masonry coinciding, precisely, to what is observed in the field. Moreover, the obtained magnitudes for the E-modulus and specific weight of the materials coincide with what is reported in the literature for this kind of structural system. Once the ultimate and reliable FE model was obtained, the future stages of the work consist in the structural evaluation using numerical routines, such as limit analysis, for assessing the vulnerability of the studied structure due to earthquakes, and for planning appropriate intervention techniques.

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