

ON-SITE INVESTIGATION AND NUMERICAL ANALYSIS FOR STRUCTURAL ASSESSMENT OF THE ARCHAEOLOGICAL COMPLEX OF HUACA DE LA LUNA

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Abstract. *This paper presents the first round of on-site investigations and numerical analysis applied to the archaeological complex of Huaca de la Luna, aiming at its structural assessment. The studied complex is a massive adobe construction located in Trujillo, a northern city of Peru, which was built by the Moche Civilization from 100 AD to 650 AD. An on-site survey based on laser scanning was conducted in order to generate solid models of the monument as geometric input for numerical structural analysis, and to perform an initial diagnosis based on the deformation pattern of representative structural elements.*

Operational modal analysis tests were performed on substructures of Huaca de la Luna in order to characterize the local dynamic properties. It was possible to identify the natural frequencies and mode shapes of representative structural elements, namely adobe columns, which were used as indicators to support the structural diagnosis. Based on the experimental results, the influence of geometrical simplifications in the meshing of finite element (FE) models of the columns was evaluated. Nonlinear static analysis was applied to FE models of the columns to identify the critical accelerations leading to collapse, as well as the influence of the columns pedestal on the lateral capacity. A FE model of the entire Huaca de la Luna was developed and a linear static analysis of the complex under gravity load was performed, in order to evaluate zones with particular concentration of static displacements.

1 INTRODUCTION

Constructed heritage is fundamental for cultural identity of people and for place promotion. Peru presents a vast number of archaeological constructions left by ancient cultures. However, this country is located in one of the world regions with major seismic activity, the Pacific Ring of Fire. In effect, seismic hazard and the periodic occurrence of El Niño are the most influential factors that lead to loss of cultural heritage in Peru. Despite this situation, archaeological works in this country have been developed without considering engineering aspects, which is a matter of concern. It was only recently that interdisciplinary work has been undertaken to consider aspects of structural diagnosis and seismic safety of these constructions.

In effect, archeological remains are generally complex structures requiring for an engineering interpretation. The Peruvian archaeological remains can generally be divided in two categories, the massive adobe constructions which are mostly concentrated in the North Coast, and the stone building remains in the Andean region. Both kinds of remains are an ancient example of sustainability in construction, since they were built by exploiting the availability of local materials, respectively cohesive soil and stone. In the structural point of view, the two kinds of constructions are very different, and even within each category the typological variability is high. This work is focused on the study of structural typologies of adobe archeological elements through application to a paradigmatic archeological complex.

In the last decades, scientific approaches have been developed for structural assessment of ancient constructions that include on-site investigation, namely geometrical and damage surveys and non-destructive tests, to allow a reliable structural diagnosis of ancient constructions. In effect, on-site investigation along with numerical analysis is fundamental for a reliable and accurate structural evaluation. However, the application of these tools to each construction requires a different procedure. This paper presents the first round of on-site investigations and numerical approaches applied to Huaca de la Luna.

2 ARCHAEOLOGICAL COMPLEX OF HUACA DE LA LUNA

Huaca de la Luna is an archaeological complex built by the Moche civilization from 100 AD to 650 AD, and which is located in the Peruvian northern city of Trujillo. The complex was used as a ceremonial center and is considered as one of the most representative adobe archaeological sites. Huaca de la Luna is composed by three platforms and four squares (see Fig. 1a). The most extensive sector is known as Platform I and is located in the southwest corner of the complex. Platform I jointly with the identified Platform II, located in the southeast corner of the complex, were considered as one main structure named the Old Temple. A last platform constitutes the New Temple, which was used after the decease of the old one.

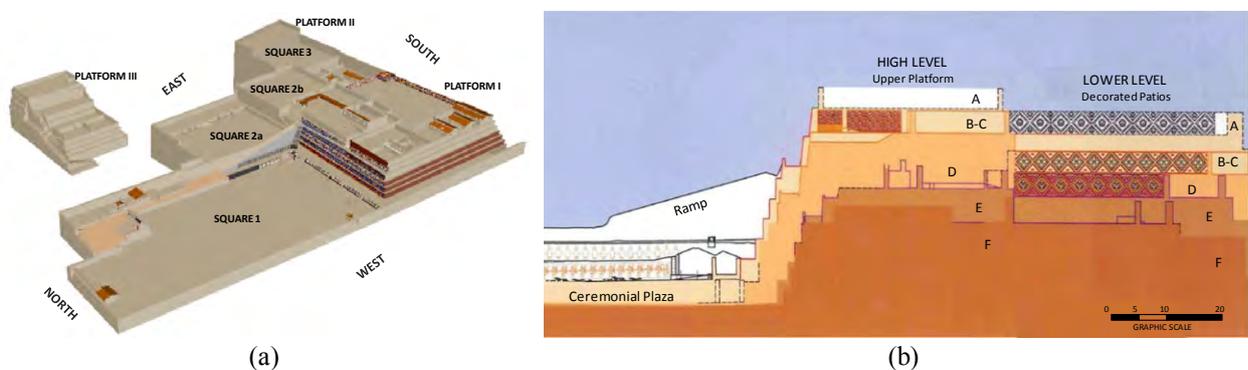


Figure 1: Huaca de la Luna: (a) distribution of main areas and (b) North-South section showing the construction stages.

The construction of Huaca de la Luna consisted on the overlapping of at least six building stages, named after the first letters of the alphabet. Architectonic spaces of previous stages were filled with columns of adobe in order to build a new one. These columns were separated through constructions joints, which may perform some structural function. Furthermore, archaeological evidence indicates that the architectural pattern was repetitive throughout the different construction stages (see Fig. 1b). Several hypotheses have been proposed to justify the constructive method of the Moche civilization. The most accepted explanation for the repetitive building is that this practice was based on the idea of renewal of power [1, 2].

Huaca de la Luna has been subjected to seismic activity and frequent occurrences of El Niño, which have contributed to its deterioration. However, because of the vast size of the archaeological complex, four areas were selected to study the local structural behavior. These areas are known as Corner Enclosure, North Façade, Hypostyle Halls and Unit 16. The first two areas were chosen because its structural elements present a severe deformation pattern. The North Façade, which is an enormous staggered frontispiece, and the Corner Enclosure, present remarkable features such as the iconographic designs represented on relief or mural paintings. These last two elements are shown in Figure 2a. In the remaining two areas, adobe columns were studied because of its severe damage and vulnerability to seismic events. The distribution of the selected areas is presented in Figure 2b.

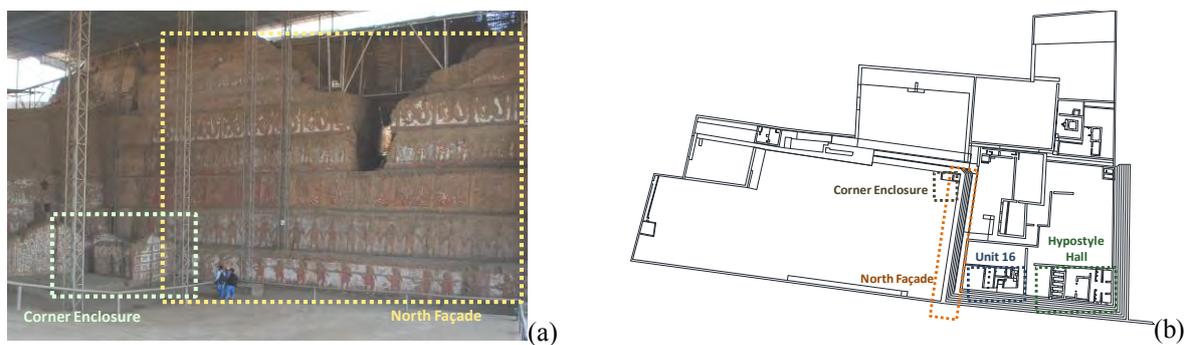


Figure 2: Studied areas: (a) North Façade and Corner Enclosure, and (b) location at Huaca de la Luna.

3 3D RECONSTRUCTION AS A TOOL FOR STRUCTURAL DIAGNOSIS

The development and application of digital techniques for surveying historical buildings and monuments has made possible the creation of accurate tridimensional models for multiple scientific applications. Examples of this are virtual reality inspections with exploration and immersion into the complexes, and the creation of 3D databases with topological-geometrical-textural information, designed for heritage documentation and archaeological-historical interpretations. Here, the application of these tools is focused on the generation of 3D solid models for engineering analysis.

3.1 3D acquisition and generation of solid models

A geometrical survey was performed to four sectors of Huaca de la Luna using a Faros Focus 3D time-of-flight laser scanner [3] with an acquisition rate of 976,000 points/sec and an accuracy of ± 2 mm. The survey protocol consisted on acquiring several scans around the selected areas of the monument, and the correspondent alignment using a point-based rigid registration performed in MeshLab [4]. The alignment was conducted on a computer system equipped with a 4-core Intel i5 processor at 2.30 GHz, 8 GB of RAM and ADM RadeonTM 6470M 512 MB RAM graphics card, running Microsoft Windows 7 64-bit. The geometry and texture of the four sectors are described in the resultant point clouds as illustrated in Figure 3.

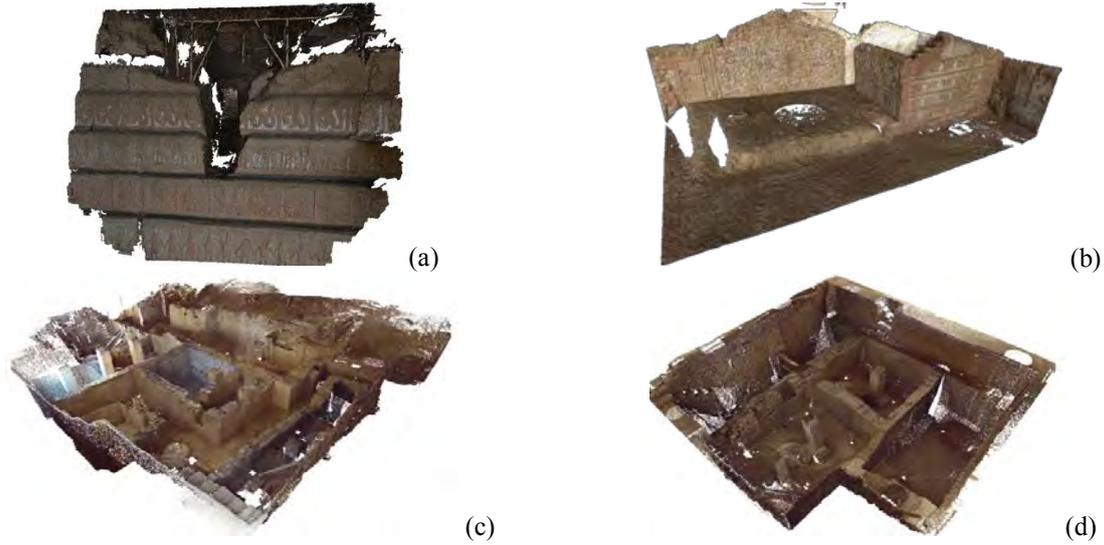


Figure 3: 3D point clouds of: (a) North Façade, (b) Corner Enclosure, (c) Unit 16 and (d) Hypostyle Hall.

Three columns from Hypostyle Hall and one from Unit 16 were selected for structural assessment. The columns were manually segmented using the software Cloud Compare [5] and converted from point clouds to triangle-based mesh models using the Poisson Surface Reconstruction algorithm [6]. The information about resolution and geometry of the columns is described in Figure 4. According to Zvietcovich et al. [7] these models are considered irregular, since they are not properly closed at the base (manifoldness). In order to convert these mesh models into regular solid models, an encapsulation procedure was implemented in Matlab [8].

This last procedure consists of three steps, as illustrated in Figure 5. First, a border detector algorithm is applied over the mesh of a column in order to find the opening at the base (see Fig. 5b). Subsequently, a linear fitting based on Least Squares optimization estimates the best plane equation from the border; this plane is triangulated and translated at certain depth from the initial border (see Fig. 5c). Finally, the mesh of the column is connected to the triangulated plane using a hole completion algorithm to create a regular and properly closed mesh (see Fig. 5d). This mesh is then converted into a solid model in a straightforward fashion in Matlab.

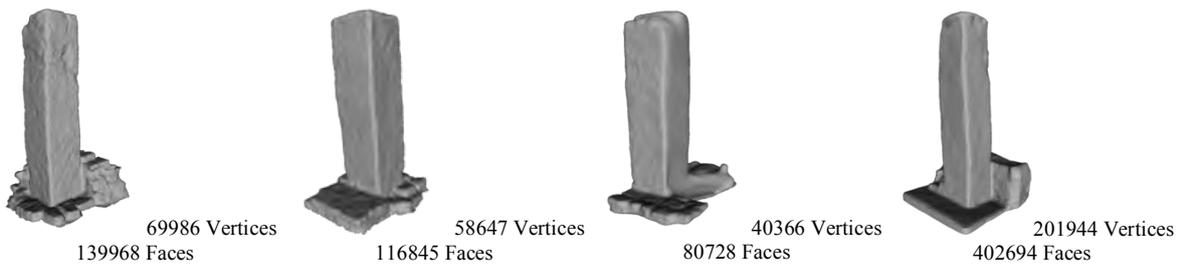


Figure 4: Triangle-based mesh models of the columns.

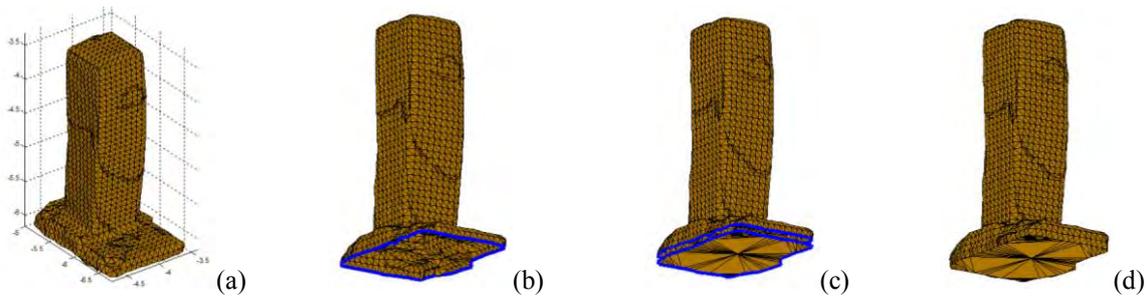


Figure 5: Encapsulation procedure: (a) triangle-based mesh, (b) detection of the border of the opening, (c) estimation of a plane and (d) junction of the plane with the mesh.

3.2 Deformation analysis of adobe walls

Accurate deformation measurements can be extracted from the point clouds of Huaca de la Luna. Structural elements from the Corner Enclosure and the North Façade were selected for diagnosis since they present a notorious deformation pattern. The point clouds were projected into a planar regular grid using cubic interpolation and maintaining its orientation with respect to the ground. It was possible to obtain three color-range images that describe the deformation. The frontal wall of the Corner Enclosure, which is parallel to the North Façade, presents a maximum relative deformation of 0.30 m (see Fig. 6a). This may indicate a detachment between this wall and the orthogonal one, which can compromise the stability of the structure. In addition, there is a similar relative deformation on the lateral walls with a maximum value of 0.28 m (see Fig. 6b). For the North Façade and because it is a staggered frontispiece, the points of each step were translated to the same reference plane. The color variation suggests that the right part of the façade is moving forward. The deformation ranges around 0.4 m and it could be as a result of a localized settlement in this sector of the monument (see Fig. 6c).

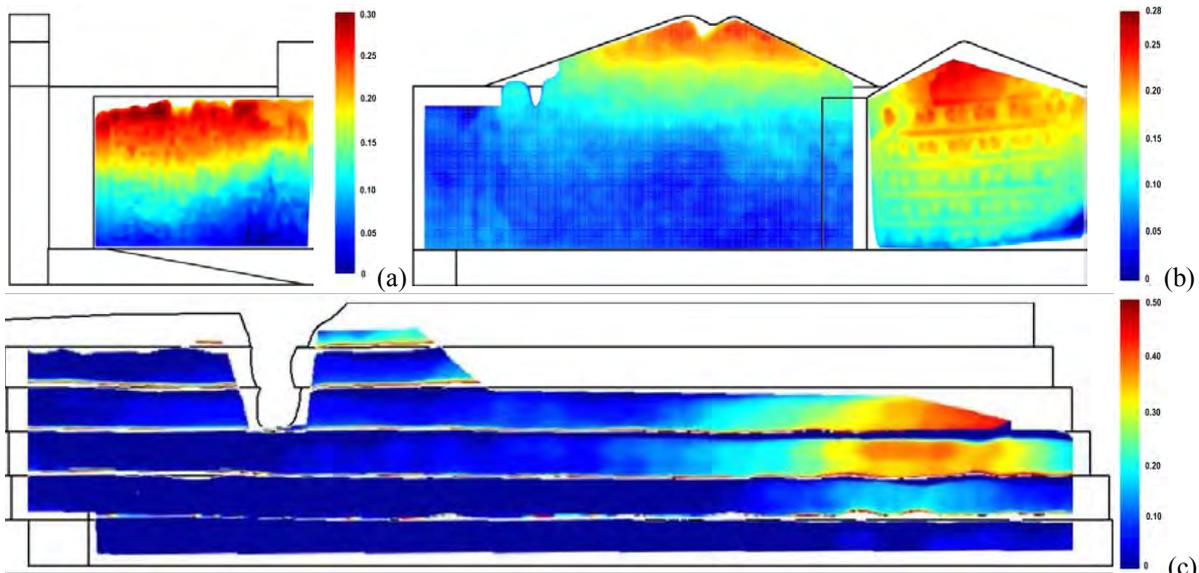


Figure 6: Depth range images: (a) frontal and (b) lateral walls of the Corner Enclosure, and (c) North Façade of Huaca de la Luna (color scale indicates the relative depth in meters).

4 OPERATIONAL MODAL ANALYSIS AND FINITE ELEMENT MODELING

An innovative approach to support the structural assessment of patrimonial constructions has been implemented, which is based on operational modal analysis (OMA). OMA is a powerful experimental technique for structural identification aiming at characterizing the dynamic properties of the structure (natural frequency, damping ratios and mode shapes). OMA tests fit into modern conservation philosophies, since they imply minimum intrusion by using ambient noise as excitation source. The application of this technique is complemented with the use of numerical models. In order to perform reliable analyses, the results obtained from the OMA are used as input for the updating of the models, as illustrated in Figure 7.

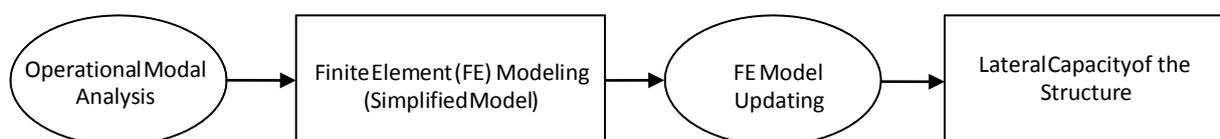


Figure 7: Simplified flowchart of proposed approach for the structural assessment of patrimonial constructions.

4.1 Experimental campaign and dynamic identification

OMA tests were conducted to four adobe columns of Huaca de la Luna, see Figure 8a-b. The tests consisted on the measurement of vibrations from ambient noise excitation. Four piezoelectric accelerometers with a sensibility of 10 V/g and a dynamic range of ± 0.5 g together with a USB-powered 24 bits data acquisition unit were used for the signal recording. In order to obtain enough resolution in frequency and good quality time domain signals, each recording lasted 600 seconds with a sampling rate of 200 Hz during tests. The used transducers and the acquisition unit are shown in Figure 8c-d. Four setups were established for recording and each setup “S” consisted of four components “Accel”. Two of these components were fixed as reference, whereas the other two were moved throughout the structural element to obtain the enough data to properly identify the dynamic properties. A total of ten points were measured according to the configuration in Figure 8e.

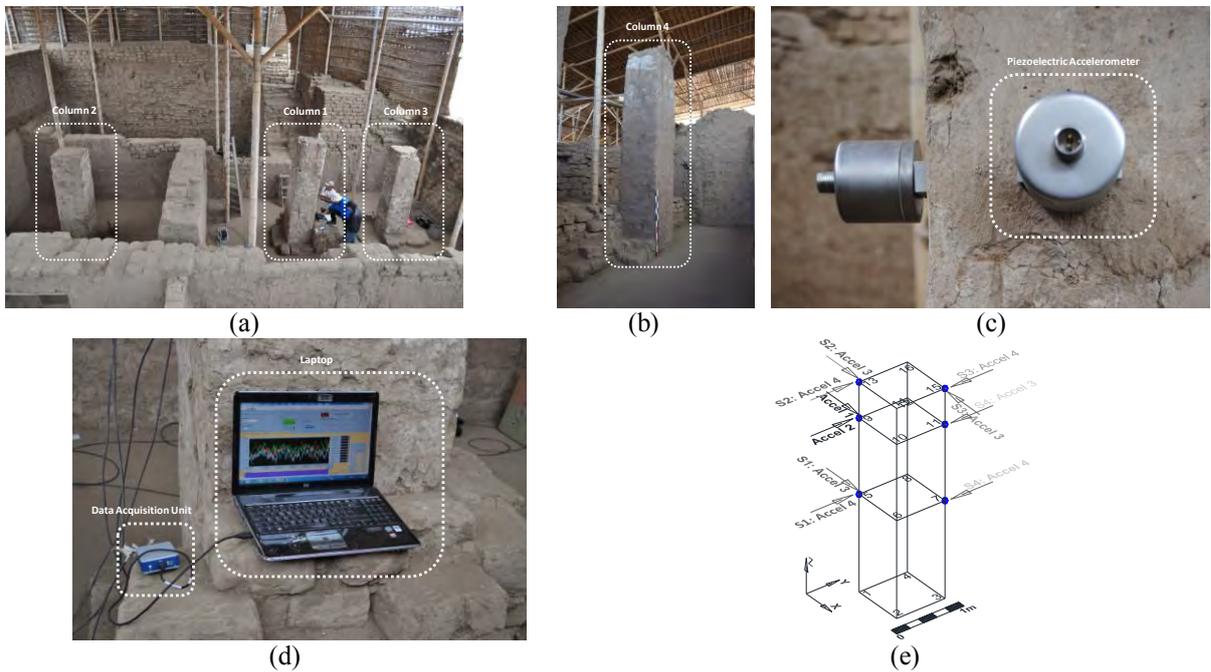


Figure 8: OMA tests at Huaca de la Luna: (a,b) adobe columns, (c) piezoelectric accelerometers, (d) data acquisition unit and portable computer and (e) measurement configuration of the columns.

The identification process was carried out using ARTeMIS [9]. In order to determine the dynamic properties of the columns, signal processing methodologies of Enhanced Frequency Domain Decomposition (EFDD) [10] and data-driven Stochastic Subspace Identification (SSI-data) [11] were used. Results of the application of these methodologies are exemplified in Figure 9, referring to Column 2. The average of the normalized singular values of spectral density matrices from the EFDD shows the presence of notorious peaks that represent at least the first three natural frequencies (see Fig. 9a). On the other hand, from the selection and link of stable poles from the SSI-data methodology it was possible to identify the first four natural frequencies (see Fig. 9c). In both cases, the first two frequencies are ranging between 5 Hz and 6 Hz, respectively, whereas the third one is around 13 Hz. The existence of several stable poles on the stabilization diagram (Fig. 9b) and the numerous peaks (Fig. 9c) at different frequencies denotes complexity in the identification process. Since SSI-data is considered a more reliable methodology, its results were adopted for further analysis. Agreement in frequencies, damping ratios and modal shapes was taken into account during the identification process.

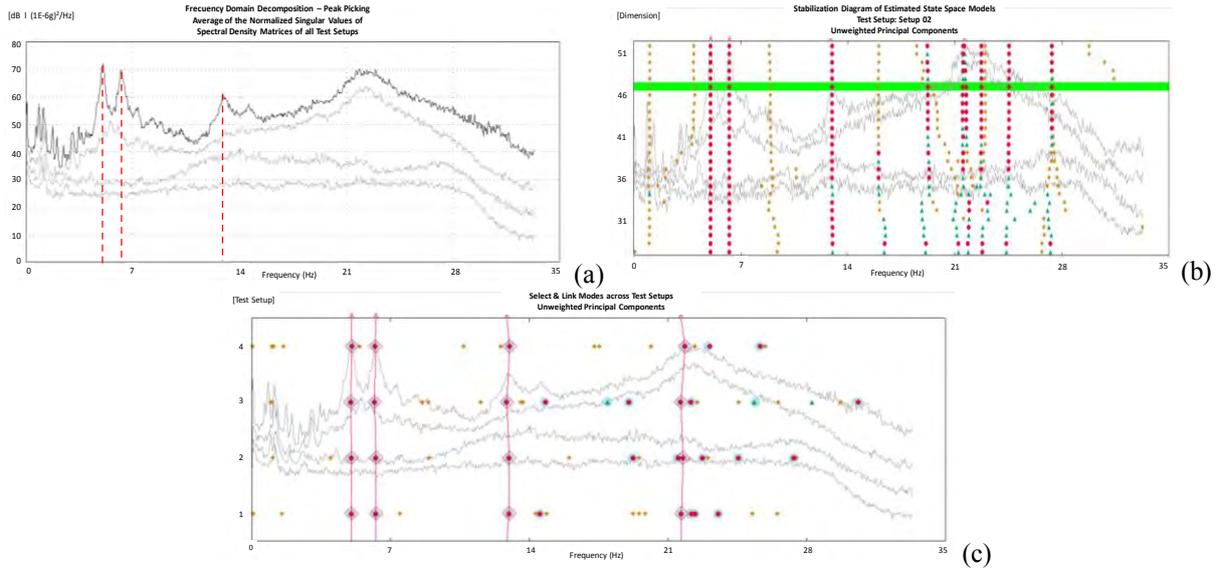


Figure 9: Identification of the dynamic properties of adobe column: (a) average of the normalized singular values of spectral density matrices, (b) stabilization diagram and (c) selection and link modes.

For Columns 1 to 3, it was possible to identify four vibration modes, whereas for the last column, an additional mode was estimated. The modal response of the columns is shown in Figure 10. For all columns, the first two vibration modes correspond to translational (bending) movements in both directions (first fundamental mode in each direction). The third mode clearly represents a torsional motion. Finally, for Column 4, the fourth and fifth modes represent the second fundamental mode in each direction. It can be observed in Figure 10 that the natural frequencies of the first two modes for all columns range around 5 Hz and 6 Hz, respectively. The difference on these values is mainly caused by the variability of the columns section and apparent predominance of damage in one of the directions. In addition, frequencies from the third mode present high variability from 12.6 Hz to 19.0 Hz. This reinforces the idea of the existence of localized damaged through the columns. The same tendency is repeated for higher vibration modes.

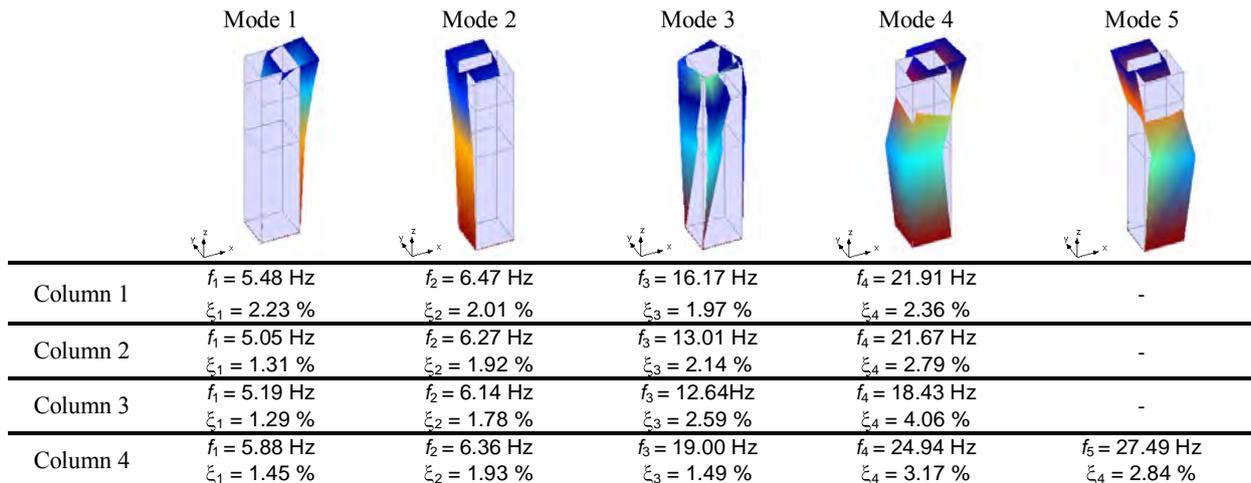


Figure 10: Dynamic properties of the adobe columns at Huaca de la Luna.

4.2 Finite element modeling

The numerical analysis of the columns was performed using DIANA [12]. For the analysis, two simplified finite element (FE) models of one of the columns were considered in order to

determine the influence of the geometrical simplification on the modal response of the column. Two models of Column 4 were developed using hexahedral irregular and regular FE elements, resulting respectively in irregular and regular models (see Fig. 11). The irregular model presents a more precise geometry since it was created from the on-site 3D survey. In order to evaluate the accuracy of the FE models, the approximation between numerical and experimental results from modal analysis was assessed. A sensitivity analysis was also carried out to evaluate the effect of lateral boundary conditions and elastic modulus on natural frequencies and mode shapes. An average value of 17 kN/m^3 was assumed for specific weight [13], whereas the elastic modulus was ranged between 200 MPa and 500 MPa. In addition, the column was considered fixed to the ground (see Fig. 11b). For the sensitivity analysis two conditions were assumed for the interaction between column and lateral adjacent adobe infill: (1) no interaction and (2) a pinned connection (see Fig. 11c).

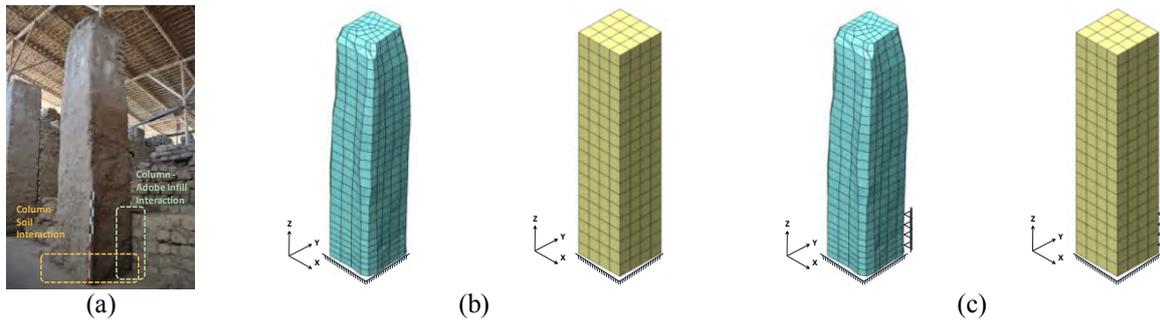


Figure 11: Finite element modeling of Column 4: (a) real structure, (b) condition 1 and (c) condition 2.

An eigenvalue modal analysis was conducted to the FE models in order to determine its dynamic properties. Experimental and numerical mode shapes were compared through the Modal Assurance Criterion (MAC) [14]. This criterion establishes the correlation between two modal vectors and the MAC ratio ranges between 0 and 1. The closer the ratio is to the unity, the more approximated the two modal vectors are. The MAC ratio is given by Equation 1, in which φ_e and φ_a correspond to the modal shapes of the experimental and analytical models [14].

$$MAC_{(a,e)} = \frac{|\varphi_a^T \varphi_e|^2}{(\varphi_a^T \varphi_a)(\varphi_e^T \varphi_e)} \quad (1)$$

After the sensitivity analysis, a value of 300 MPa for the elastic modulus was calibrated. Considering this E-modulus value, the comparison of dynamic properties of all models relatively to the experimental ones was made, which is summarized in Table 1. It can be observed that considering no interaction between the column and the adobe infill (condition 1) the approximation is poor. The mode shapes present a reduced similarity regarding the first two vibration modes, and the numerical-based frequencies are low. On the other hand, considering the interaction between the column and the adobe infill (condition 2) the approximation is better. Frequency values are higher since the column presents a more rigid pedestal connection. Frequencies are better approximated in general and all MAC ratios are above the acceptable value of 0.75. However, there is a considerable difference of mode shapes from the regular and irregular models. Figure 12 shows the first five vibration modes of the irregular model of Column 4. It can be observed that the first two modes correspond to translational movement in both directions (first fundamental mode), while the third one clearly represents a torsional motion. The fourth and fifth vibration modes correspond to the second fundamental bending mode in each direction.

Table 1: Varying parameters for the optimization process.

Mode	Regular Model				Irregular Model			
	Condition 1		Condition 2		Condition 1		Condition 2	
	Frequency (Hz)	MAC	Frequency (Hz)	MAC	Frequency (Hz)	MAC	Frequency (Hz)	MAC
Mode 1	3.67	0.66	4.85	0.78	3.81	0.55	5.42	0.99
Mode 2	3.67	0.66	5.08	0.77	3.92	0.65	5.73	0.98
Mode 3	16.53	0.91	19.49	0.88	17.56	0.94	21.68	0.97
Mode 4	19.81	0.58	25.10	0.79	20.19	0.87	26.80	0.98
Mode 5	19.81	0.73	25.84	0.89	20.60	0.78	27.64	0.97

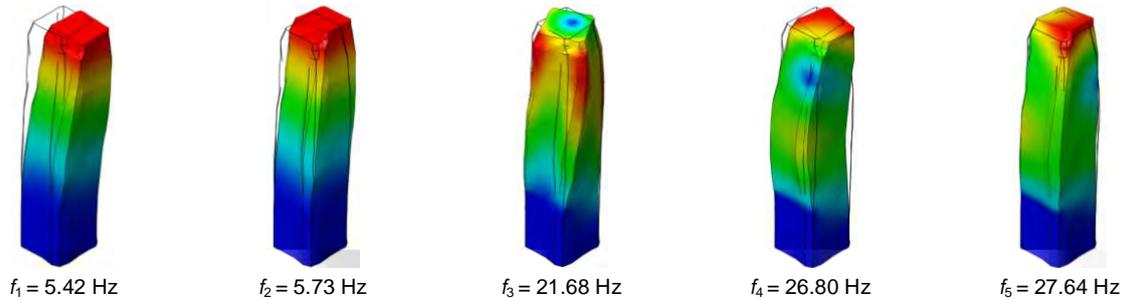


Figure 12: Finite element models of the columns at Huaca de la Luna.

Since there is a significant difference of results and approximation by considering irregular and regular simplified FE models of Column 4, it was decided to create irregular representations of the remaining columns. Figure 13 shows the FE models of the three columns left. A similar procedure to that for the updating of Column 4 needs to be applied to these elements in order to calibrate to the experimental results.



Figure 13: Finite element models of columns at Huaca de la Luna.

5 NON LINEAR STATIC ANALYSIS

Pushover analysis is a simpler alternative approach to dynamic analysis for estimating the seismic response of a structure, which avoids to consider a seismic spectrum input and allows significantly to reduce the computational effort. The analysis is performed by applying an incremental lateral loading to the structure until collapse. Pushover is usually used to assess the performance of buildings through displacement verifications and allows also identification of critical zones in constructions that are more susceptible to failure.

Here, pushover was conducted to the adobe columns at Huaca de la Luna, to evaluate the hinge formation and the lateral capacity. For the material behavior it was adopted the total strain model available in DIANA [12]. The mechanical properties were extrapolated based on the calibrated E-modulus of 300 MPa: compressive strength f_m as $E/400=0.75$ MPa; tensile strength f_t as $f_m/10=0.075$ MPa; compressive fracture energy, considering a ductility factor μ of 1.0 mm [15], as $\mu f_m=0.75$ N/mm; and tensile fracture energy, by extrapolating from experimental results in literature [16, 17], as 0.004 N/mm. Parabolic and exponential tendencies were assumed for the material laws in tension and compression, respectively [15] (see Fig. 14). The pushover was applied considering a lateral force distribution proportional to the mass.

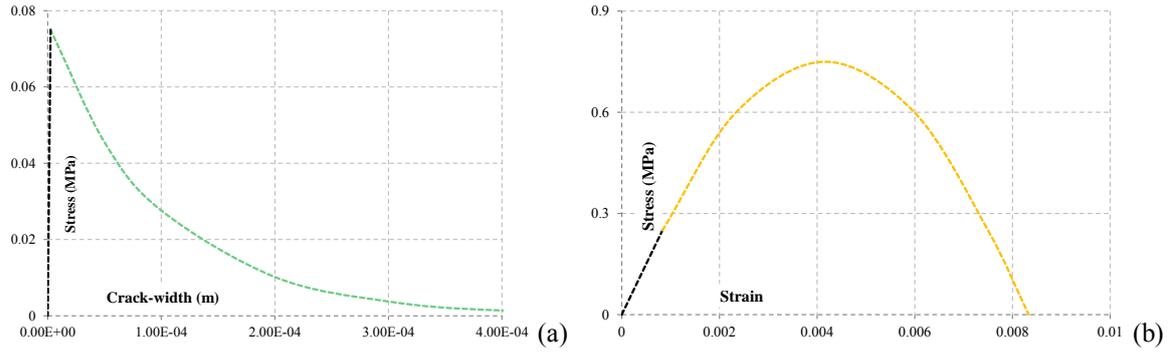


Figure 14: Material laws for adobe masonry in (a) tension and (b) compression.

The lateral loading was applied in both directions and positive and negative senses, because the boundary conditions from the pedestal of the columns are heterogeneous. Columns 1 to 3 were considered with the original geometry of the pedestal and were fixed at the base. For Column 4 the pedestal was simulated through pinned supports, according to the calibrated model presented in Section 4.2. The hinging of the columns was always around its base and the resulting capacity curves are presented in Figure 15. The strength curve of Column 1 indicates that this element withstands a lateral load of 0.25g and 0.30g in +X and -X, and of 0.20g and 0.30g in +Y and -Y, respectively. These values stress the influence of the pedestal geometry of the columns in the lateral capacity. This aspect is confirmed referring to Columns 2 and 3, even if in this case the influence from the geometry of the pedestal was expected to be lower. For these columns, the lateral strength ranges from 0.17g to 0.26g. Column 4 present a lateral load capacity of 0.23g in X direction, and of 0.34 g and 0.16g in +Y and -Y, respectively. In this case, there is a significant variation on the capacity curves for positive and negative senses of Y direction, due to different boundary conditions of the column base.

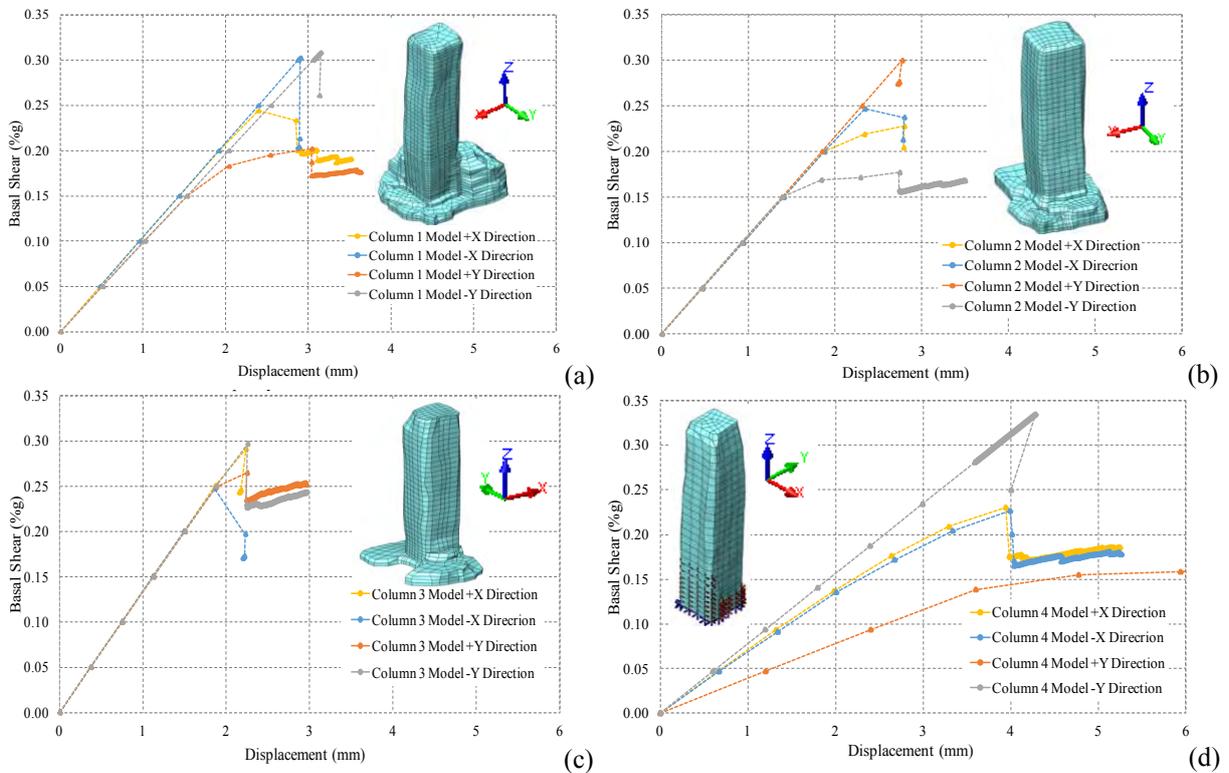


Figure 15: Capacity curves of: (a) Column 1, (b) Column 2, (c) Column 3 and (d) Column 4.

A finite element model of the entire Huaca de la Luna has been developed, which is presented in Figure 16a. As an ongoing study, a linear analysis is being carried out in order to evaluate the behavior of the archaeological complex under gravity load. As a first approximation the construction is considered fixed at the base, but a future investigation has been planned to investigate the foundation characteristics. The plots in Figure 16b-c illustrate the deformed shapes with horizontal deformation components separated in X and Y directions. It can be observed from Figure 16b that the right side of the complex presents a significant deformation compared to the rest of the structure, which is mostly due to lateral expansion of the adobe fabric. In addition, Figure 16c shows that the North Façade is also experiencing notorious deformation.

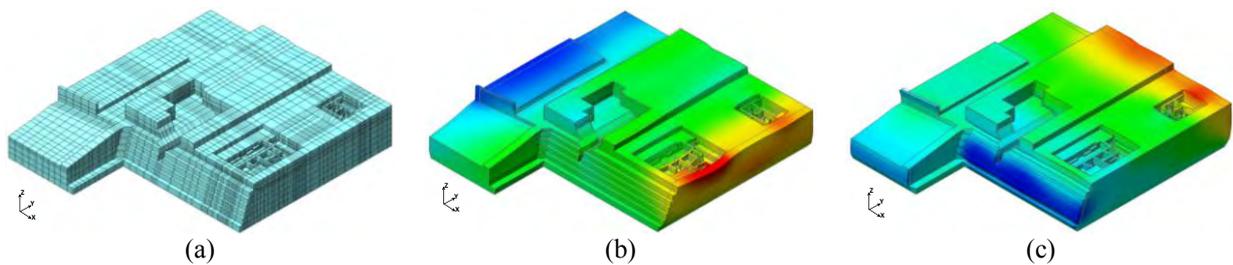


Figure 16: Linear analysis under gravity load of Huaca de la Luna: (a) FE model, (b) deformed shape in X direction and (c) deformed shape in Y direction.

6 CONCLUSIONS

A preliminary structural diagnosis of an adobe archeological complex, the Huaca de la Luna, was performed through on-site investigations and application of non-destructive tests. First of all, a 3D surface reconstruction by a time-of-flight laser scanning and a post-processing stage using computational geometry tools, were carried out. The range image, which was calculated from the 3D point cloud, allows to identify anomalous deformations in the complex: the Corner Enclosure presents excessive deflection in one of the ornamented walls, ranging from 0.28 m to 0.30 m; and the North Façade presents significant deformation at its right central part around 0.30 m. Thus, these elements may present structural damage and weakness that can lead to collapse in case of seismic events. An extensive spatio-temporal analysis is recommended to monitor the deformation of those areas, in order to obtain a deeper diagnosis of damage and to support retrofit interventions.

From the in-situ dynamic tests and operational modal analysis to adobe columns, it was possible to identify the main dynamic properties (principal vibration modes and corresponding natural frequencies, ranging from 5 Hz to 28 Hz in adobe columns) of typical adobe elements at Huaca de la Luna. This restates the fact that operational modal analysis is a reliable tool for structural diagnosis of patrimonial adobe constructions. It was also evidenced that geometric representativeness in finite element modeling places an important role when analyzing the structural behavior of substructures. In this study, the accuracy of adopted simplified regular models of adobe columns was limited concerning the modal identification (MAC ratios lower than 0.9). In addition, the definition of the boundary conditions and the E-modulus of the adobe (adjusted around 300 MPa) presented a major influence on the modal response.

Moreover, pushover analysis was applied to evaluate the hinge formation and the lateral capacity of adobe columns, which is in future to be confronted with dynamic time-history analysis. The peak strength in the capacity curves allows to identify the critical acceleration level leading to collapse, ranging from 0.16g to 0.34g. Column 4 results to be the most vul-

nerable, because of its high slenderness but also depending on the boundary conditions. The obtained collapse accelerations denote seismic vulnerability of the columns, since the reference peak ground acceleration demand for Trujillo is 0.45g [18]. On the other hand, a finite element model of the entire Huaca de la Luna was developed and analyzed under gravity load, and which is a first modeling approach for further analytical investigations.

REFERENCES

- [1] S. Uceda, A. Paredes eds., *Arquitectura y función de la Huaca de la Luna*. Instituto Nor Peruano de Desarrollo Económico y Social, Trujillo, 1994.
- [2] S. Uceda, El poder y la muerte en la sociedad Moche. L. Millones, M. Lemlij eds. *Al final del camino*, SIDEA, Lima, 1996.
- [3] FARO Laser Scanner Focus 3D X-130. FARO Technologies Incorporation, USA; URL: <http://www.faro.com/home>.
- [4] MeshLab, Visual Computing Lab. Institute of the National Research Council of Italy, ISTI-CNR; URL: <http://meshlab.sourceforge.net>.
- [5] Cloud Compare, 3D point cloud and mesh processing software. EDF R&D, Paris; URL: <http://www.danielgm.net/cc>.
- [6] M. Kazhdan, M. Bolitho, H. Hoppe, Poisson surface reconstruction. *Proceedings of the 4th Eurographics Symposium on Geometry Processing*, Cagliari, CD-ROM, 2006.
- [7] F. Zvietcovich, B. Castañeda, R. Perucchio, R. Morales, S. Uceda, A methodology for updating 3D solid models of complex monumental structures based on local point-based meshes. *Proc. of the Digital Heritage International Congress*, CD-ROM, 2013.
- [8] Matlab, High-level language and interactive environment for numerical computation. MathWorks, Massachusetts; URL: <http://www.mathworks.com/products/matlab>.
- [9] SVS, ARTeMIS Modal Pro User Manual, Release 1.5. Structural Vibration Solutions, Aalborg, 2013.
- [10] R. Brincker, C. Ventura, P. Andersen, Damping estimation by frequency domain decomposition. *Proceedings of the 19th International Modal Analysis Conference*, Kissimmee, CD-ROM, 2001.
- [11] P.V. Overschee, B.D. Moor, Subspace algorithms for the stochastic identification problem. *Automatica*, **29**(3), 649-660, 1993.
- [12] TNO, Displacement method ANALyser, Release 9.4, User's Manual. TNO DIANA BV, Delft, 2013.
- [13] I. Vásquez, Monitoreo de la resistencia mecánica y características físicas en adobes arqueológicos de distinto tipo de suelo. *Proyecto Arqueológico Huaca de la Luna: Informe Técnico 2010*, Trujillo, 2010.
- [14] R.J. Allemang, The modal assurance criterion – twenty years of use and abuse, *Sound and Vibration*, **37**(8), 14-23, 2003.
- [15] P.B. Lourenço, Recent advances in masonry structures: Micromodelling and homogenization. U. Galvanetto, M.H. Ferri Aliabadi eds. *Multiscale Modeling in Solid Mechanics: Computational Approaches*, Imperial College Press, 2009.
- [16] R. van der Pluijm, Out of plane bending of masonry: Behaviour and strength. PhD thesis, Eindhoven University of Technology, Eindhoven, 1999.
- [17] J. Almeida, Mechanical characterization of traditional adobe masonry elements. MSc thesis, University of Minho, Guimarães, 2012.
- [18] SENCICO, Norma técnica E.030: Diseño sismorresistente ('Peruvian seismic code'). Ministerio de Vivienda, Construcción y Saneamiento, Lima, 2006.