Operational Modal Analysis Tests on Peruvian Historical Buildings: The Case Study of the 19th Century Hotel Comercio

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SUMMARY:
The paper presents the preliminary round of in-situ experimental tests carried out at the “Hotel Comercio”, a historical construction located at Lima´s Historical Centre. The building is a three story republican-type construction built at the 19th Century with a composite structure of adobe and “Quincha”. The experimental works consisted on modal identification tests aiming at identifying the dynamic characteristics of the building using the environmental noise as source of excitation. Outstanding results were obtained in terms of modal properties since the first two translational modes and subsequent seven local modes were properly identified. The results confirm the expected different behaviour of the quincha panels and the adobe in terms of flexibility. An important contribution of the paper is the introduction of these tests as a tool for better understanding the structural behaviour which may also allow assessing the real damage condition of the buildings, as well as the seismic resistance.

Keywords: Adobe, Quincha, Damage, Operational Modal Analysis, Stochastic Subspace Identification

1. INTRODUCTION

Peru is located in the centre of the pacific coast of South America which is one of the most active seismic zones of the world (known as “pacific ring of fire”) due to the subduction process of the Nazca and the South American Plates,. The actual capital of Perú, Lima, was the main city of the Spanish Viceroyalty from 1531 to 1821 and because of the beauty of the constructions in its urban area, as well as the whole history involved, its Historical Centre was included in the UNESCO heritage list in 1991. Lima has suffered the occurrence of several strong earthquakes along time being the most destructive one the event of 1746 (ML 8.6) which almost destroyed the whole city and killed thousands of people (Walker, 2008). For these reasons, the architectural style and the constructions typology of the buildings in the city had changed numerous times and resulted in improved “earthquake resistant” structural systems.

The present work aims at performing a first assessment of the structural condition of the “Hotel Comercio” which is a construction from the 19th century located in front of the Government Palace, one block from the main square of Lima. When performing structural diagnosis on historical buildings it is mandatory to consider the modern conservation criteria of minimum intervention and preservation of the original construction. In these buildings, the task of creating accurate numerical models is difficult to achieve since the existing properties and conditions of the buildings are unknown. So far, there are several experimental methods that are used on existent structures which allow the assessment of local information and/or the estimation of their global properties. In this respect, one the most powerful methods for the quantitative diagnosis of structures are the so called experimental modal identification tests. There are broad applications of these dynamic tests for structural evaluation such as analytical model updating, damage detection, quality control of materials and structural systems, etc.

The importance of this work relies in its innovative character since represents a first attempt for performing operational modal analysis in Peruvian earthen historical construction. The paper starts with a general description of the architecture, the construction systems, and the structural characteristics of the building, which includes the survey of actual damage condition. The following section is dedicated to the explanation of the theory of the Operational Modal Analysis and comprises the description of the general characteristics of the tests, the description of the measurement systems, as well as of the details of the available signal processing methods. The experimental field campaign and its results are following discussed in detail. Finally the conclusions and future works are stated.

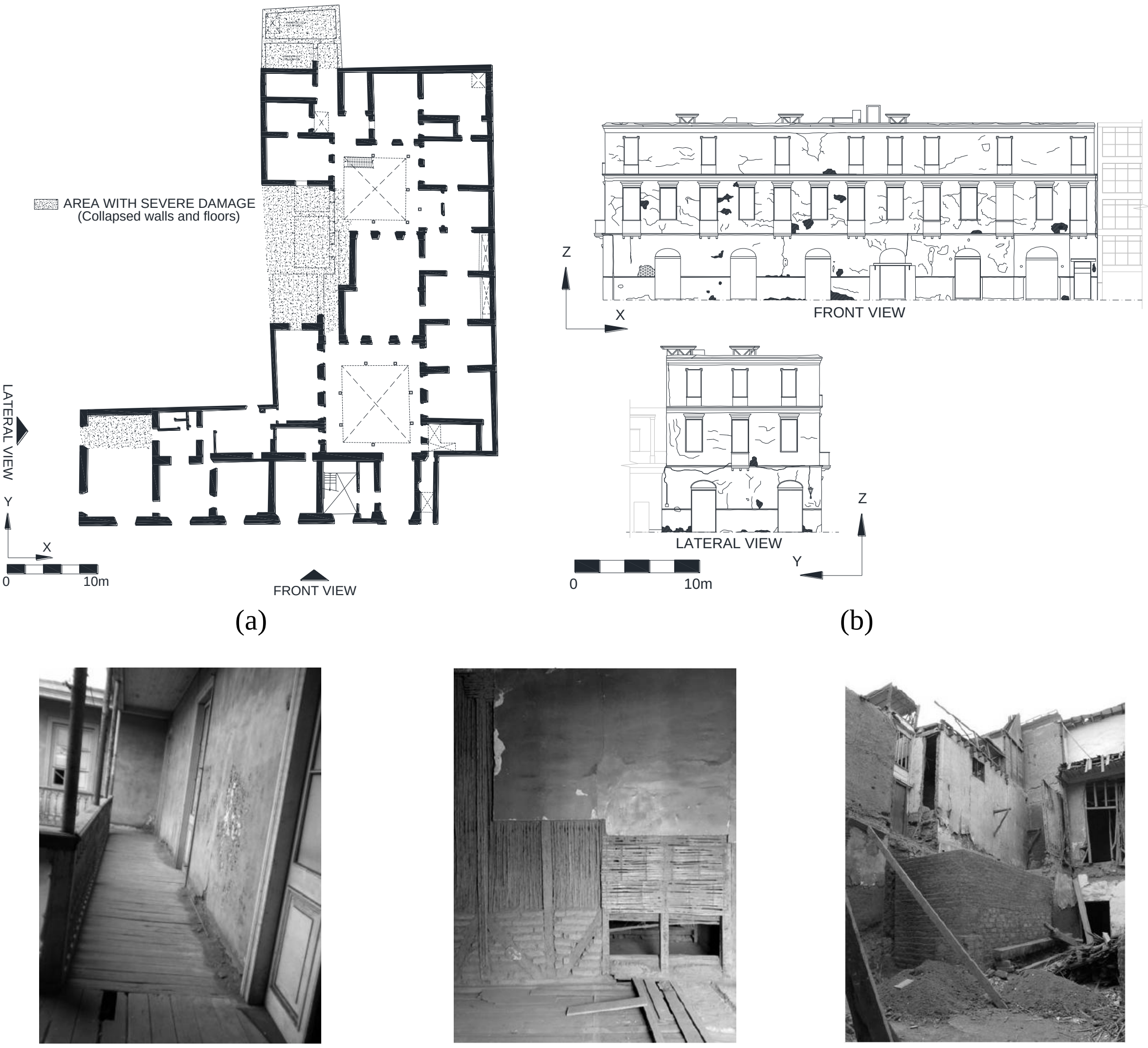
2. ARCHITECTURAL AND STRUCTURAL DESCRIPTION OF THE BUILDING

The "Hotel Comercio" is a three story construction considered as a Peruvian National monument since 1980. The construction is of adobe walls at the first floor and a composite system of mud, wood and canes (known as Quincha) at the second and third floors. The building has 1480 square-meter footprint and is of 14 m height. According to Galvez (1943), it was built in the middle of the 19th Century and was used as a Hotel until the decade of the 1980_s. So far, the building is unoccupied and only the spaces at the corner of the first floor are open to the public. Figure 1 shows the location of the building as well as some pictures that illustrate how its condition changed in the last century.

Figure 1. Location and general views of the Hotel

The structure of the first floor is composed of adobe walls of 0.90 m thickness in the façades and 0.80 m in the interiors. In the area of arches and openings, there were used clay bricks. The resultant system was covered with 30 to 40 mm of mud plaster and 2 mm thick gypsum finish coat. In the second and third floors, the structure is flexible and composed of panels of "Quincha" which are small wood frames with diagonals filled with mud and canes. The panels are then covered with a 35 mm thick mud and straw layer, followed by a 25 mm mud layer, and a 4 mm gypsum finish coat. The structure of the floor is of wood arranged in a double layer configuration, and the roof is also of wood covered by a thick layer (105 mm) of mud and a compacted soil. The building is settled on a rocky soil and its foundations are of stone bricks masonry with lime and sand mortar with 0.50 to 0.80 m depth (Cancino and Lardinois, 2011).

In the last years, severe damage has evidenced in the building due to different factors that caused its degradation, such as the occurrence of small-medium earthquakes, the unused condition, as well as the lack of conservation and preservation works. Figure 2 presents a general overview of the damage condition of the building. As shown, even in the façade walls, which receive a continuous treatment of re-plastering and re-painting for the aesthetic of the Lima's Historical Centre, light pattern of cracks and some humidity marks are visible (see Figure 2b). The condition of these walls does not reflect the actual situation of the building since inside there are zones with collapsed walls, floors, corridors, and stairs (see Figure 2a and Figure 2c). In general, the plaster of large zones of walls inside is in bad condition (some walls has not plaster any more) which causes problems of humidity in the walls, and deterioration of the wood and canes.



(a) (b)

(c)

Figure 2. Damage condition of the building: (a) plant view of the first floor; (b) elevation view of the front façades; and (c) pictures of the condition at the interior of the building

3. STRUCTURAL SYSTEM IDENTIFICATION USING EXPERIMENTAL DYNAMIC SIGNATURES

As stated by Farrar and Worden (2007), experimental modal identification tests are used to study civil engineering structures since the early 1980_s. These tests aim at characterizing the dynamic properties of the structures by measuring their in-situ response and their results are used as a tool for performing analytical models calibration, quality control, damage detection, etc. Most of the modal identification studies are related to large and flexible structures by means of bridges and tall buildings. In case of historical constructions, there are also numerous applications (mainly in stone and clay brick masonry buildings) such as churches and temples (Baptista et al., 2004; Casarin and Modena, 2007; Jaishi et al., 2003; Ramos et al., 2010b), towers (Gentile and Saisi, 2004; Ivorra and Pallarés, 2007; Rebelo et al., 2007; Schmidt, 2007), arch bridges (Costa et al., 2004), and minarets (Ramos et al., 2006).

Experimental modal analysis tests are classified depending on the excitation source in two different groups namely, Input-Output and Output-Only techniques. Input-Output techniques are based on the estimation of a set of Frequency Response Functions (FRF_s) relating an applied excitation (input) to the corresponding response along the structure (output). The most common types of equipments used to excite small and medium size structures are impulse hammers, and electro dynamic shakers. In case of larger structures, heavier equipments such as eccentric mass vibrators and servo-hydraulic shakers are used (Cunha et al., 2006). Artificial excitation of civil engineering structures generally requires a large amount of specialized equipment and trained personnel, which make these tests expensive and difficult to carry out. The technological developments in the fields of sensors and data acquisition equipments made possible the designing of a new experimental modal identification process where the dynamic characteristics of the structures are obtained by using only the ambient noise as exciting source. These types of tests are called as Output-Only techniques (also known as Operational Modal Analysis - OMA) and the interest of their application for studying civil engineering structures is exponentially increasing since the late 1990_s (Doebling et al., 1997).

OMA is based on the premise that ambient noise (wind, traffic, etc) adequately excite structures in the frequencies of interest since it is a Gaussian white noise stochastic process. Due to the nature of the excitation, the structural response includes not only the modal contributions of the ambient forces and the system itself, but also the contribution of the noise signals from undesired sources. Therefore, the measurements reflect the response from the structural system and the ambient forces and thus, the signal processing algorithms must be able to separate them. As shown in Cunha et al. (2006), Output-Only modal identification data processing methods are divided in two groups namely, nonparametric methods (Peak Picking, Frequency Domain Decomposition, Enhanced Frequency Domain Decomposition, Random Decrement, PolyMax), mostly developed in frequency domain, and parametric methods (Stochastic Subspace Identification, Least Square Complex Exponential, Ibrahim Time Domain), developed in time domain.

There is no one method that can be applied as a recipe for the whole case studies because of the fact that their precision depends on the specific characteristics of the environmental noise and the structure itself, as well as the quality of the measurements systems and the experience of the personal performing the study. However as reported by Ramos et al. (2010a), the main drawback of non parametric methods is that their results depend on the quality of the environmental noise. This drawback is overpassed by the use of parametric methods which results are in general of good quality and reliability due to the robust numerical algorithms used for performing the signal processing. Among the whole available nonparametric and parametric data processing methods, the most used ones are the Frequency Domain Decomposition (FDD), the enhanced Frequency Domain Decomposition (EFDD), and the Stochastic Subspace Identification (SSI) methods (these methods were also used in the present work).

As shown in Figure 3, in the FDD method (Brincker et al., 2000), the spectral density functions matrix is, at each discrete frequency, decomposed in singular values and vectors using the Singular Value Decomposition (SVD). By doing so, the spectral densities functions are decomposed in the contributions of different modes that, at each frequency, contribute to its response. Brincker et al. (2001) improved the FDD method by presenting the EFDD method, which is closely related with the previous one but includes additional procedures to evaluate the damping and to get enhanced estimates of the frequencies and mode shapes. According to the EFDD method, the selection of the autospectra corresponding to each mode is performed by using the Modal Assurance Criterion – MAC (Allemang and Brown, 1982). Those SDOF auto-spectral density functions are then transformed into the time domain using the Inverse Fast Fourier Transform (IFFT), resulting in autocorrelation functions for each mode. Based on those autocorrelation functions, frequencies and dampings are estimated from the zero crossing times and the logarithmic decrement, respectively (Rodrigues et al., 2004).

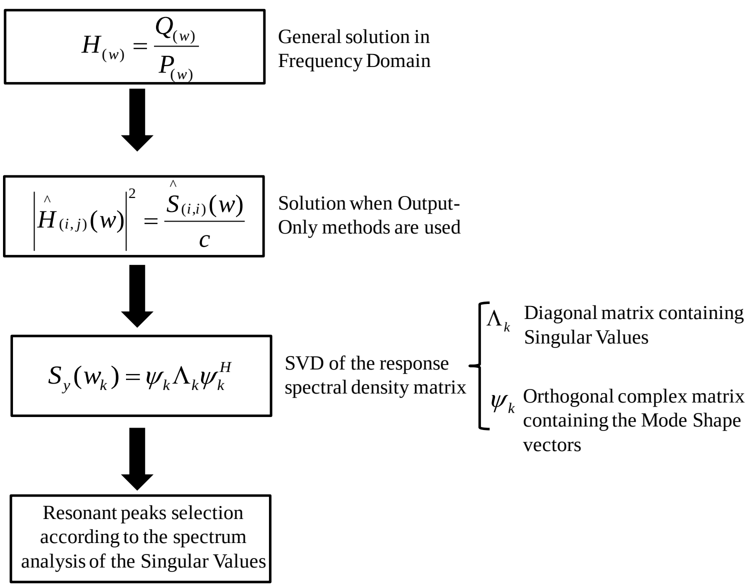


Figure 3. Flow chart of the FDD method

The Stochastic Subspace Identification (SSI) method was originally proposed by Van Overschee and De Moor (1991) and then modified (SSI-Data method) by Peeters and De Roeck (1999). The Data-Driven Stochastic Subspace Identification method (SSI-Data) is based on the stochastic space model theory from output-only measurements and so is focused in the identification of the state matrix A and the output matrix C that contains the modal information of the studied system. The SSI method uses robust numerical techniques such as QR-factorization, and singular value decomposition (SVD). The QR-factorization results in a significant data reduction whereas the SVD is used to reject system noise. The summary of the method is presented in Figure 4.

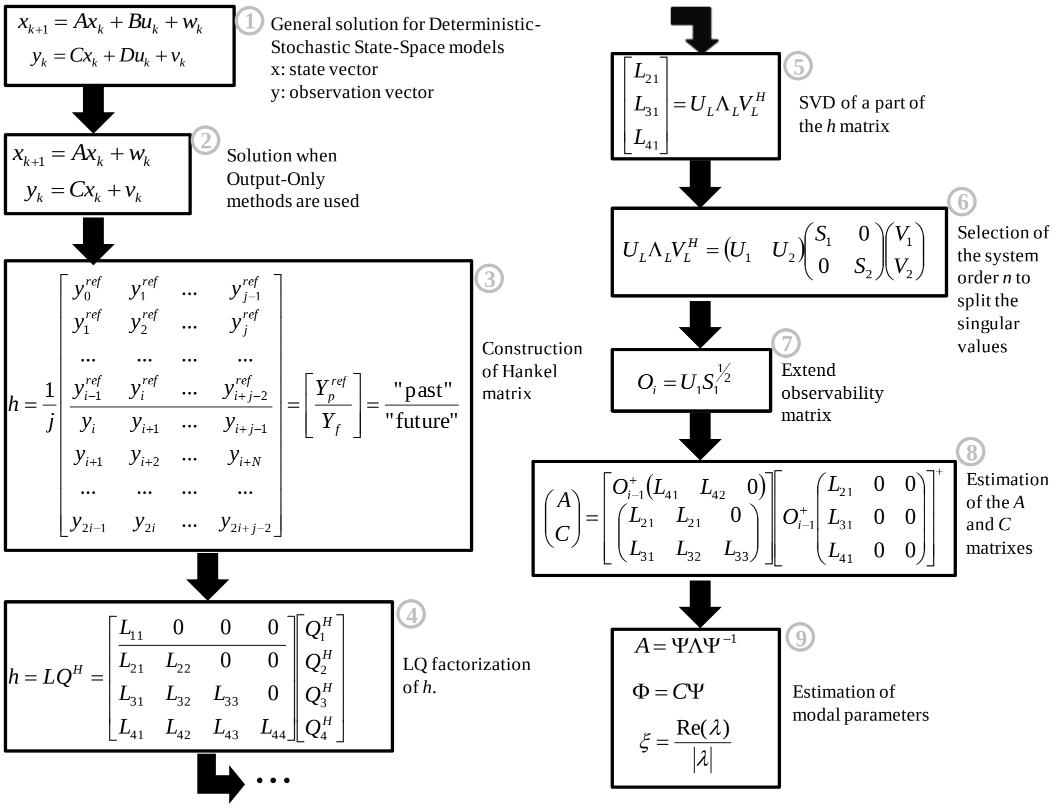
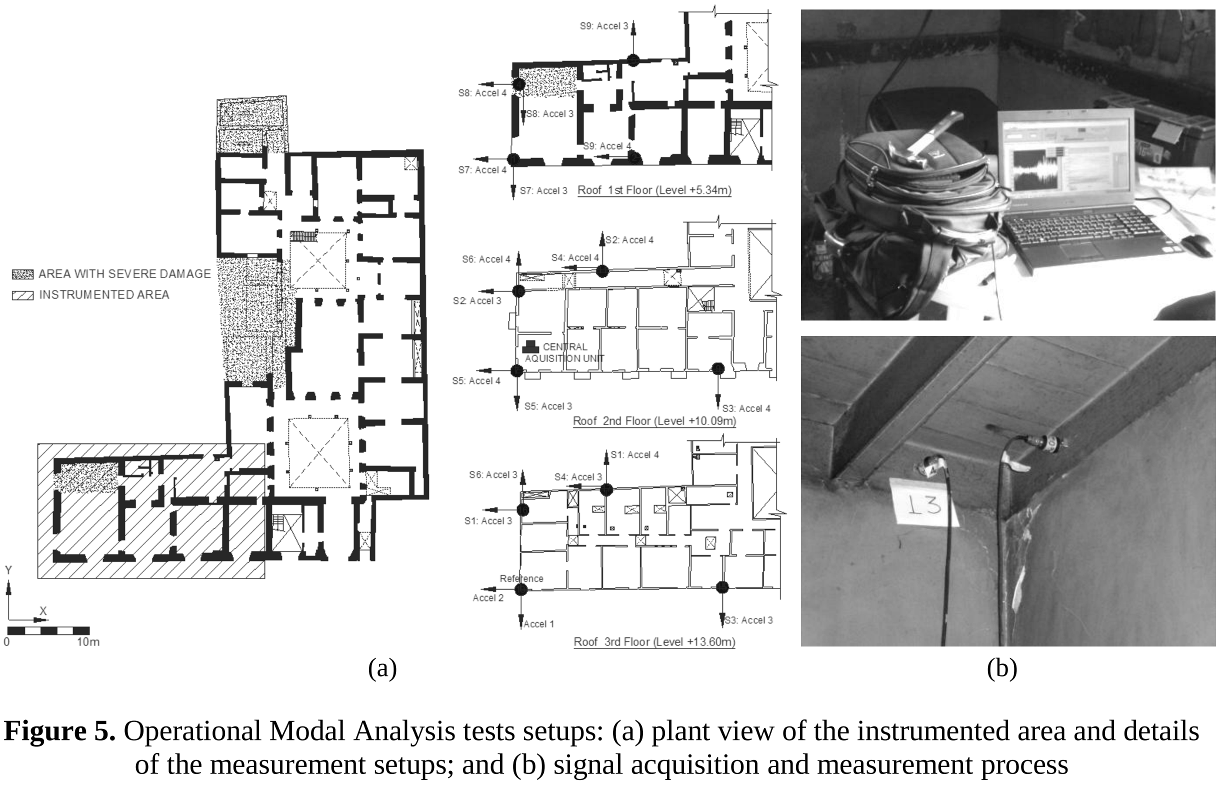


Figure 4. Flow chart of the SSI-DATA method

The measurements systems used for performing dynamic monitoring studies can be understood as composed of three parts: the measurement transducers, the data acquisition system and, in some cases, the remote transmission unit. In case of the measurement transducers, velocity or accelerometers are commonly used due to the fact that they offer appropriate characteristics for civil engineering testing namely, enough resolution, sensing range and sensing frequency. The Data Acquisition (DAQ) system is the electronic device designed to collect the information that is acquired by the transducers, as well as the adjustment of the signal using modification processes. The main tasks that signal modification processes comprise are signal conditioning (amplification and filtering), signal conversion (analog-to-digital ADC, digital-to-analog or, frequency-to-voltage), and synchronization among sensing nodes. From the experience of the authors, and as is documented in Aguilar (2010), when OMA tests are carried out, high resolution and high sensibility transducers are required, as well as sensors with moderate range of measurement capabilities in frequency and time domain. In these cases (OMA tests), sensors with sensitivity of over 1 V/g, with a frequency range of DC - 100 Hz, and a measurement range of as much as ± 1 g are of interest. On the other hand, the DAQ systems must be of high resolution (ADC$_s$ with over 16 bits) and the acquisition process should consider moderate sampling frequencies which is selected taking in consideration the Shannon theorem (Shannon, 1949).

4. OPERATIONAL MODAL ANALYSIS TESTS AT THE HOTEL COMERCIO

OMA tests were carried out in the Hotel on September 2011 aiming at characterizing the modal properties of the building. Due to the complexity of the structure (neighbouring constructions are surrounding the building, presence of large damaged areas, and variability of materials) only the left appendix at the corner of the building was studied (see Figure 5a). Four piezoelectric accelerometers with 10 V/g of resolution and ± 0.5 g of measurement range were used together with an USB-powered 24 bits resolution DAQ. As shown in Figure 5a, due to reduced number of transducers, the acquisition process was carried out considering nine measurement setups. The reference nodes and the central acquisition unit were located on the ceiling and over the base of the second floor, respectively. The signal acquisition process considered a moderate sampling rate of 200 Hz and a sampling time of 10 min aiming at obtaining good quality time domain signals with enough resolution in frequency domain. Figure 5b illustrates the acquisition and measurement processes.



(a) (b)

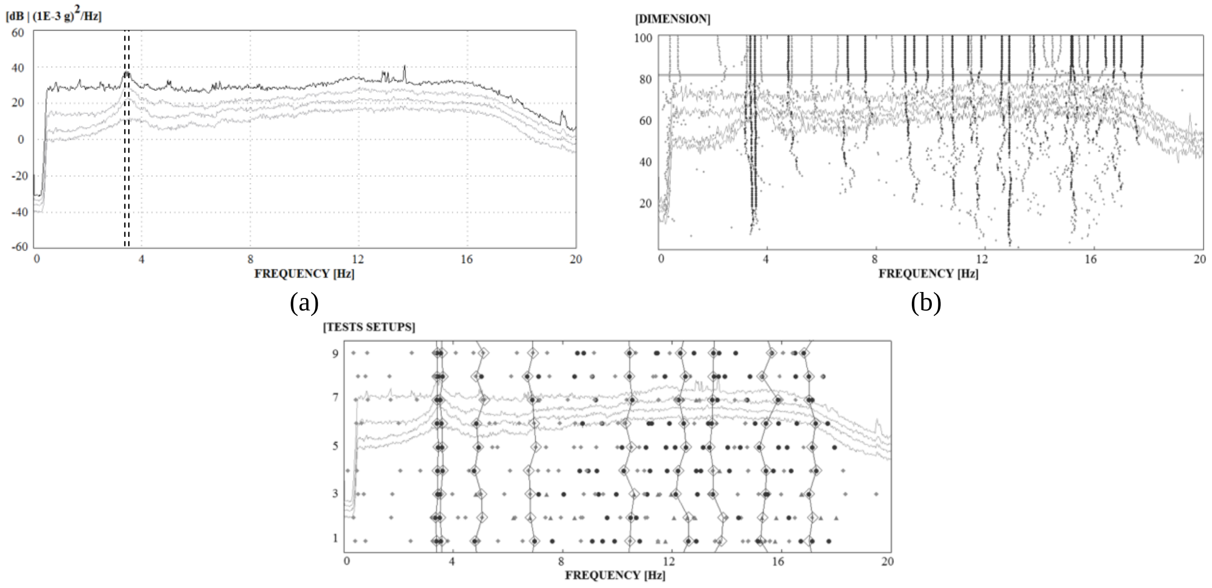
Figure 5. Operational Modal Analysis tests setups: (a) plant view of the instrumented area and details of the measurement setups; and (b) signal acquisition and measurement process

Table 1 shows the time domain results by means of the registered maximum accelerations and Root Mean Square (RMS) values. As shown, in the tests carried out it was registered a maximum peak value of 4 mg while the higher RMS was of around 0.5 mg (*g* is the acceleration of gravity). These results evidence the low amplitude level of excitations that are normally registered in OMA tests and explain the importance on appropriate choosing the characteristics of the measurement system.

Table 1. Peak acceleration values and RMS during the Operational Modal Analysis tests

	Peak Acceleration [mg]				**RMS [mg]**			
	CH 01	**CH 02**	**CH 03**	**CH 04**	**CH 01**	**CH 02**	**CH 03**	**CH 04**
Setup 1	1.247	0.609	3.026	0.596	0.0738	0.0964	0.2411	0.1173
Setup 2	1.858	1.117	2.357	1.622	0.1053	0.1251	0.3169	0.1589
Setup 3	1.475	0.934	1.182	0.884	0.0785	0.0996	0.0877	0.1009
Setup 4	0.476	0.824	0.718	0.715	0.0714	0.1037	0.1273	0.1127
Setup 5	0.681	0.887	1.918	2.684	0.0699	0.1061	0.2258	0.2849
Setup 6	0.555	0.611	1.689	0.789	0.0645	0.0976	0.199	0.1135
Setup 7	0.641	0.966	1.825	2.235	0.1031	0.1411	0.3042	0.3582
Setup 8	0.742	1.05	2.505	2.594	0.1353	0.1667	0.4173	0.4618
Setup 9	0.767	1.087	3.361	3.953	0.1299	0.1608	0.5101	0.5427

The modal identification process was carried out using the Artemis software (SVS, 2009). The dynamic properties of the building were calculated using different modal identification methodologies namely the FDD, EFDD, and the SSI-data methods. The results of the singular values of the spectral density matrices and the stabilization diagrams are presented in Figure 6. The frequency domain results (Figure 6a) indicate two closely separated peaks around 4 Hz (which certainly correspond to the first two natural frequencies of the structure) and other sharp peaks in higher frequencies which evidence that undesired noise was also recorded. The results of the SSI method (Figure 6b) indicate the complexity of the identification process since several columns of stable poles appear at different frequencies throughout the whole measurement setups. The final selection of the proper model order as well as the columns of stable poles (Figure 6c) was carried out considering consistency not only in frequency but also in damping and modal shapes results.



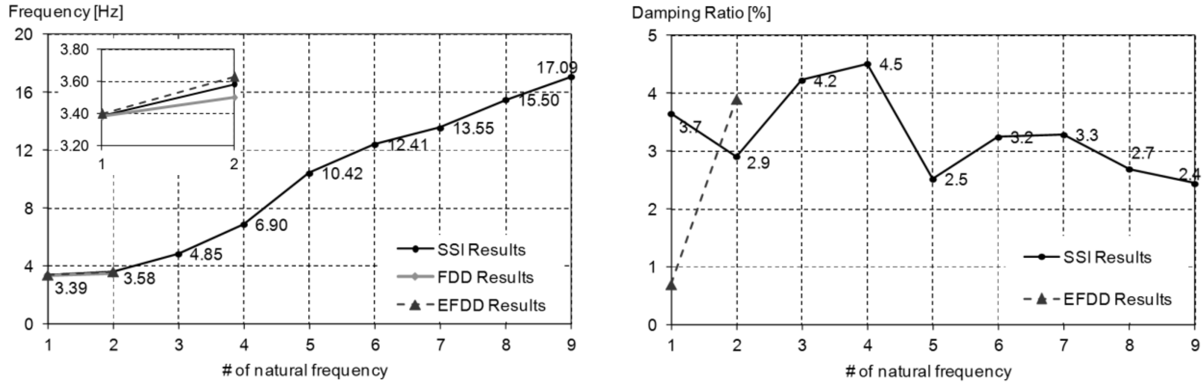
(a)

(b)

(c)

Figure 6. Data processing details: (a) average of the normalized singular values of the Spectral Density Matrices - EFDD method; (b) stabilization diagram of Setup 01 - SSI method; and (c) selection and linking process across all tests setups - SSI method

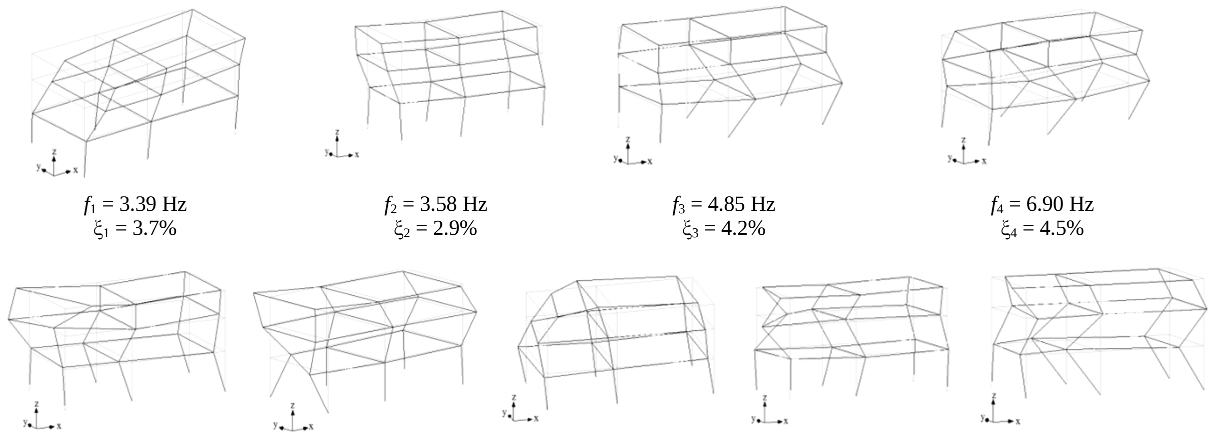
Figure 7 shows the results of the identified natural frequencies and damping ratios with the three methodologies. As shown, with the FDD and EFDD methods there were only identified the first two frequencies of the structure while the SSI method resulted in an improved identification of nine natural frequencies. In case of the first two frequencies, it is feasible to observe the small variability of the results on the three methods (see Figure 7a). Less reliable results were obtained for the damping ratios (see Figure 7b) which confirm the uncertainties on this value and the difficulties on properly identifying this parameter by the use of OMA. Despite of this, the results of damping ratios are coherent varying in the range of 2% to 5% in the whole cases.



(a) (b)

Figure 7. Modal identification results: (a) identified natural frequencies; (b) identified damping ratios

The modal shape results are presented in Figure 8. These results confirm the complexity of the structure and confirm the fact that the existent damage affects the behavior of the whole system. The first two mode shapes are clearly global translational modes parallel to the façades Y-Y and X-X, respectively (see Figure 5). In these modes, it is evidenced the effect of the neighboring constructions, as well as the different behavior of the first adobe floor (rigid part with almost without movement) and the others second and third Quincha levels (which shows high flexibility). The third and fourth mode shapes indicates and unexpected behavior since the façade wall parallel to the Y-Y side is not moving in consistency to the back part. This phenomenon may indicate that the diaphragm conformed by the floors of the building are not properly connecting the walls. The results of the fifth to the ninth mode corroborate this effect and shows mainly complex modes of the façade.



$f_1 = 3.39$ Hz
$\xi_1 = 3.7\%$

$f_2 = 3.58$ Hz
$\xi_2 = 2.9\%$

$f_3 = 4.85$ Hz
$\xi_3 = 4.2\%$

$f_4 = 6.90$ Hz
$\xi_4 = 4.5\%$

$f_5 = 10.42$ Hz
$\xi_5 = 2.5\%$

$f_6 = 12.41$ Hz
$\xi_6 = 3.2\%$

$f_7 = 13.55$ Hz
$\xi_7 = 3.3\%$

$f_8 = 15.50$ Hz
$\xi_8 = 2.7\%$

$f_9 = 17.09$ Hz
$\xi_9 = 2.4\%$

Figure 8. Experimentally identified modal shapes of the Hotel

The results of the tests evidence a structural problem that should be studied in detail in further studies. In these studies, in addition to the solutions for repairing the areas with evident damage, it should be studied the condition of the façade wall parallel to the Y-Y axis in Figure 5.

5. CONCLUSIONS

The present study consisted in the structural evaluation of a 19th Century adobe and quincha construction located at Lima´s Historical Centre. The studied building was a Hotel unoccupied since the 1980_s which is subjected to severe damage due to the lack of restoration and preservation works along time. The main objective of the study consisted on carrying out Operational Modal Analysis tests for assessing the real dynamic behaviour of the building which was used as input information to evaluate the actual structural damage.

The tests carried out consisted on taking twenty uniaxial measurements along the three levels of the structure using four high sensibility piezoelectric accelerometers, and one high resolution data acquisition equipment. The modal identification process was carried out using different techniques namely the Frequency Domain Decomposition, the Enhanced Frequency Domain Decomposition, and the Stochastic Subspace Identification methods.

The results indicate that in case of damaged structures (such as the one presented in this study), the measurement of a dense grid of nodes is important to proper characterize their dynamic properties. In the specific case of this study, one of the façade walls was fully instrumented with twelve uniaxial accelerometers which allowed the identification of seven complex modes. The complexity of the results evidence severe structural problems in the building. Future works may consider a detailed analysis of the diaphragms as well as the performance of in-situ tests for assessing the real condition of the walls and other structural elements. It would be also of interest a second series of modal identification tests, this time considering measuring more degrees of freedom with a dense mesh of sensors.

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