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EXPERIMENTAL MODAL IDENTIFICATION OF AN EXISTENT EARTHEN RESIDENTIAL BUILDING

Rafael Aguilar[1], Luis F. Ramos[2], Daniel Torrealva[3] and C. Chácara[4]

ABSTRACT

The paper presents the preliminary round of in-situ experimental tests carried out at “Hotel Comercio”, a historical construction located at the historical centre of Lima (capital of Peru). The building is a three story republican-type construction built at 19th Century with composite structure of Adobe and “Quincha”. The experimental works consisted on Operational Modal Analysis (OMA) tests aiming at identifying the dynamic characteristics of the building using the environmental noise as source of excitation. The severe damage at the Hotel, as well as its complex boundary conditions made the dynamic identification process hard to carry out. The experimental results showed coupled global and local modes. The expected different behaviour of the Quincha panels and the Adobe in terms of flexibility was also verified. The Finite element model of the building was implemented and a preliminary numerical model updating was carried out. The modal comparison of the numerical and experimental results evidenced that few modes were accurately assessed by the analytical approach. An important contribution of the paper is the introduction of OMA as a tool for better understanding the structural behaviour which may also allow assessing the real damage condition of the buildings.

Keywords: Adobe, Quincha, Damage, Operational Modal Analysis, Finite Element Model Updating

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 [18]. 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.

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[1] Associate Professor, Engineering Department, Pontifical Catholic University of Perú, raguilar@pucp.pe

[2] Assistant Professor, Civil Engineering Department, ISISE, University of Minho, Portugal, lramos@civil.uminho.pt

[3] Full Professor, Engineering Department, Pontifical Catholic University of Perú, dtorrea@pucp.edu.pe

[4] Undergraduate student, Civil Engineering, Pontifical Catholic University of Perú, c.chacara@pucp.pe

The present work aims at performing a first experimental and analytical assessment of the structural condition of "Hotel Comercio" which is a construction from 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 experimental modal identification tests.

The importance of this work relies in its innovative character since represents a first attempt for performing operational modal analysis in Peruvian earthen historical constructions. 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 Operational Modal Analysis tests and comprises the description of their general characteristics, the description of the measurement systems and experimental setups, as well as the discussion of the experimental results. The characteristics of the numerical modelling and the results of a preliminary manual calibration process are next presented. 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, timber, and canes (known as Quincha) at the second and third floors. The building is surrounded by other buildings since is part of a bigger block, has 1480 square-meter footprint and is of 14 m height. According to Galvez [8], it was built in the middle of 19th Century and was used as a Hotel until the decade of the 1980_s. So far, the building is unoccupied and only the corner of the first floor is open to the public. Figure 1 shows the location of the building, and two pictures that illustrate the changes of its condition in the last century.

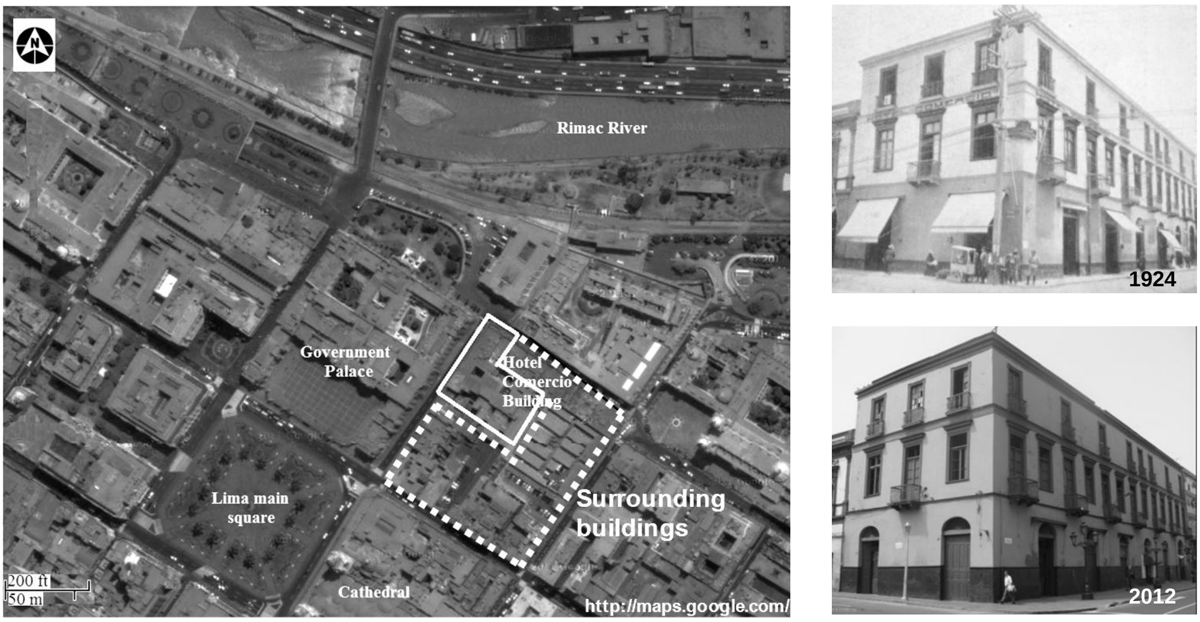
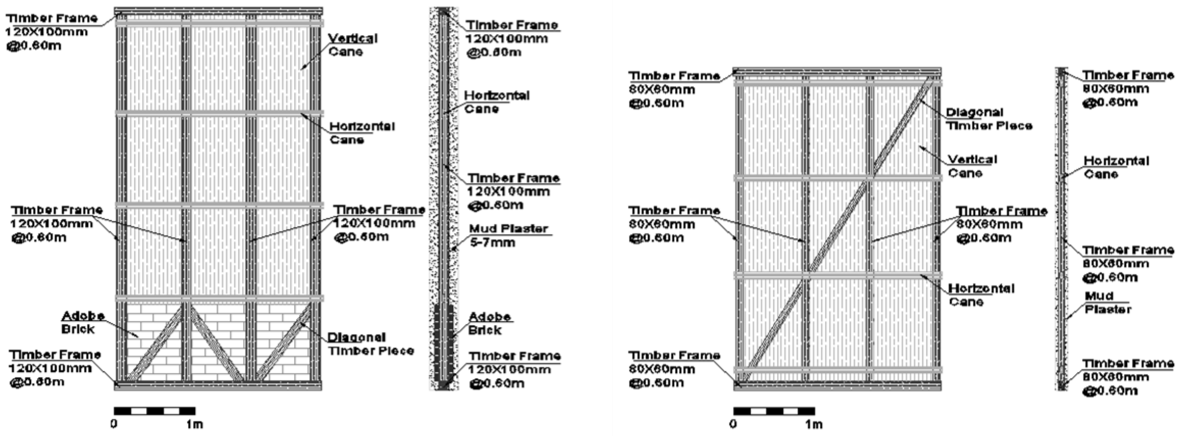


Figure 1 Location and general views of the Hotel

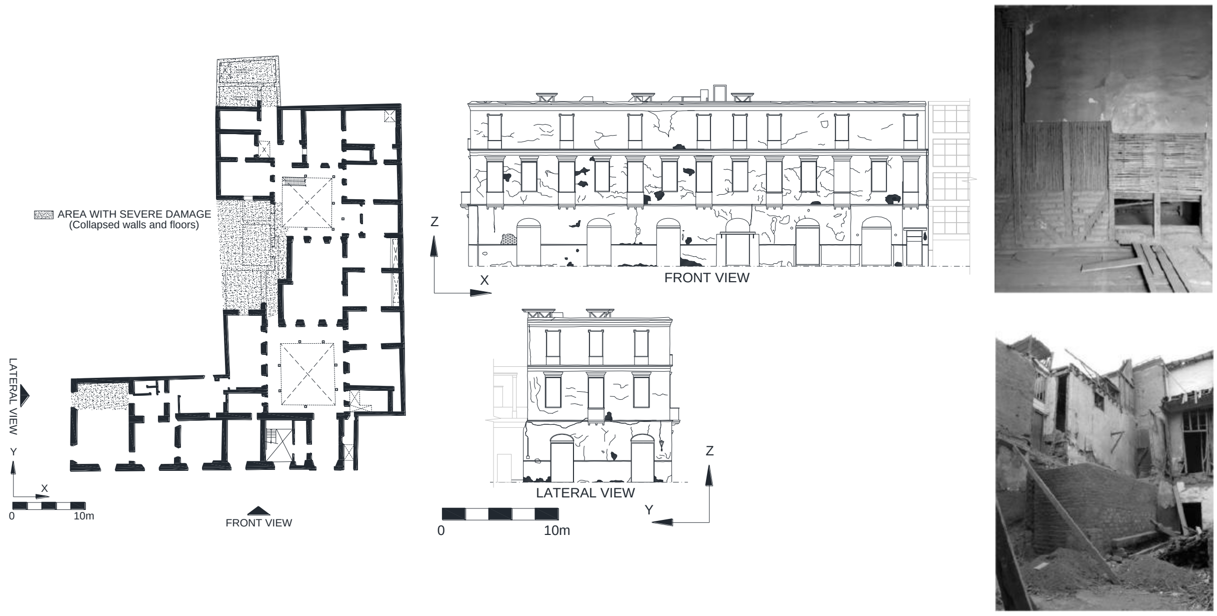
According to Cancino and Lardinois [2], the building is settled on a rocky soil and its foundations are of stone bricks masonry with lime and sand mortar with 0.50 to 0.80 m depth. The structure of the first floor is composed of Adobe walls with an average thickness of 0.90 m in the façades and 0.80 m in the interiors. There were used clay bricks in the arches and openings and the resultant system was covered with 30 to 40 mm mud plaster and 2 mm thick gypsum finish coat. In the second and third floors, the structure is composed by a series of "Quincha" panels which are timber frames with diagonals filled with mud and canes. The thickness of the panels has high variability and the section is composed by a first mud/straw layer, followed by mud, and a gypsum finish coat (details are presented in Figure 1). The structure of the inter-story system varies throughout the building and in general is composed of wood arranged in a double layer configuration. The roof is also of wood covered by a thick layer (105 mm) of mud and compacted soil.



(a) (b)

Figure 2 Typical structural configuration of the Quincha: (a) panel at the 2nd level; (b) panel at the 3rd level

In the last years, severe damage has evidenced in the building due to the occurrence of small-medium earthquakes, the unused condition, and 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 3 Damage condition of the building: (a) plant view of the first floor [adapted from 2]; (b) elevation view of the front façades [adapted from 2]; and (c) interior of the building

3. OPERATIONAL MODAL ANALYSIS TESTS AT THE HOTEL COMERCIO

3.1. Basic concepts

As stated by Farrar and Worden [7], 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 [1; 3; 11; 13], towers [9; 10; 15; 16], arch bridges [4], and minarets [14].

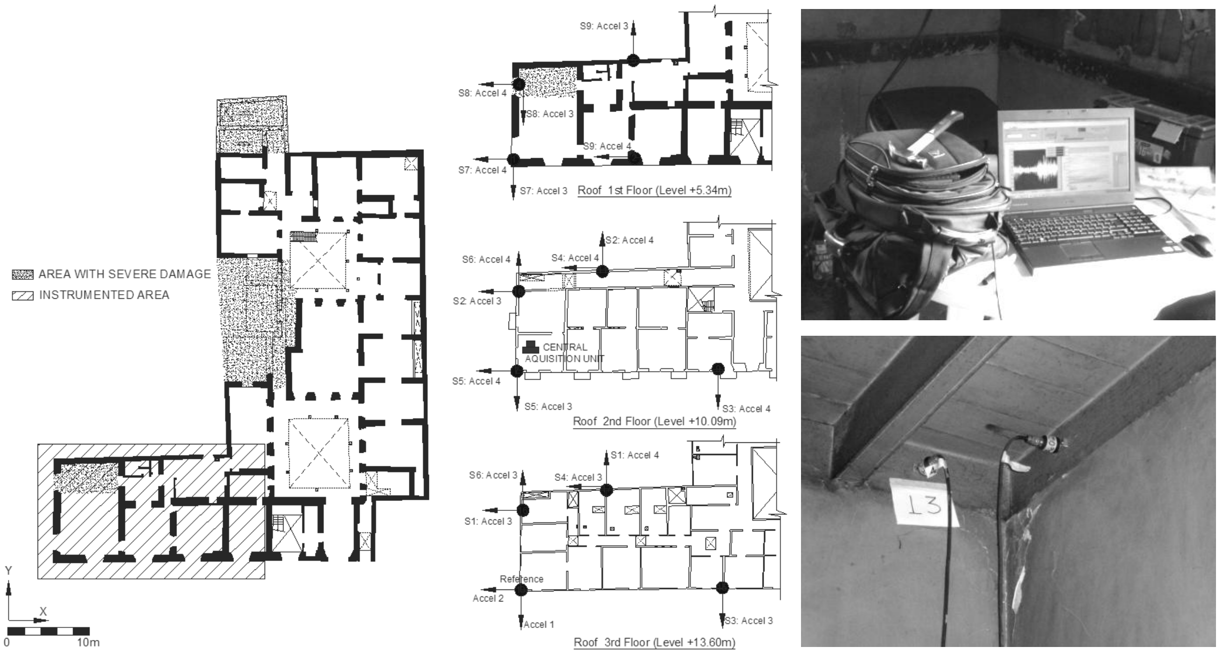
Experimental modal analysis tests are classified depending on the excitation source in two different groups namely, Input-Output and Output-Only (also known as Operational Modal Analysis – OMA) techniques. Input-Output techniques are based on the estimation of a set of Frequency Response Functions (FRFs) relating an applied excitation (input) to the corresponding response along the structure (output), while OMA is based on the premise that ambient noise (wind, traffic, etc) adequately excite structures in the frequencies of interest. 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. Parametric (Stochastic Subspace Identification, Least Square Complex Exponential, Ibrahim Time Domain) and Non Parametric (Peak Picking, Frequency Domain Decomposition, Enhanced Frequency Domain Decomposition, Random Decrement, PolyMax) methods are used for processing the acquired data in these tests Cunha et al. [6]. As reported by Ramos et al. [12], 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.

3.2. Experimental test design

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, the presence of large damaged areas, and the 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.

3.3. Experimental results

Table 1 shows the time domain results by means of the registered maximum accelerations and Root Mean Square (RMS) values. As shown, the maximum peak value registered was 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 and the data processing method.



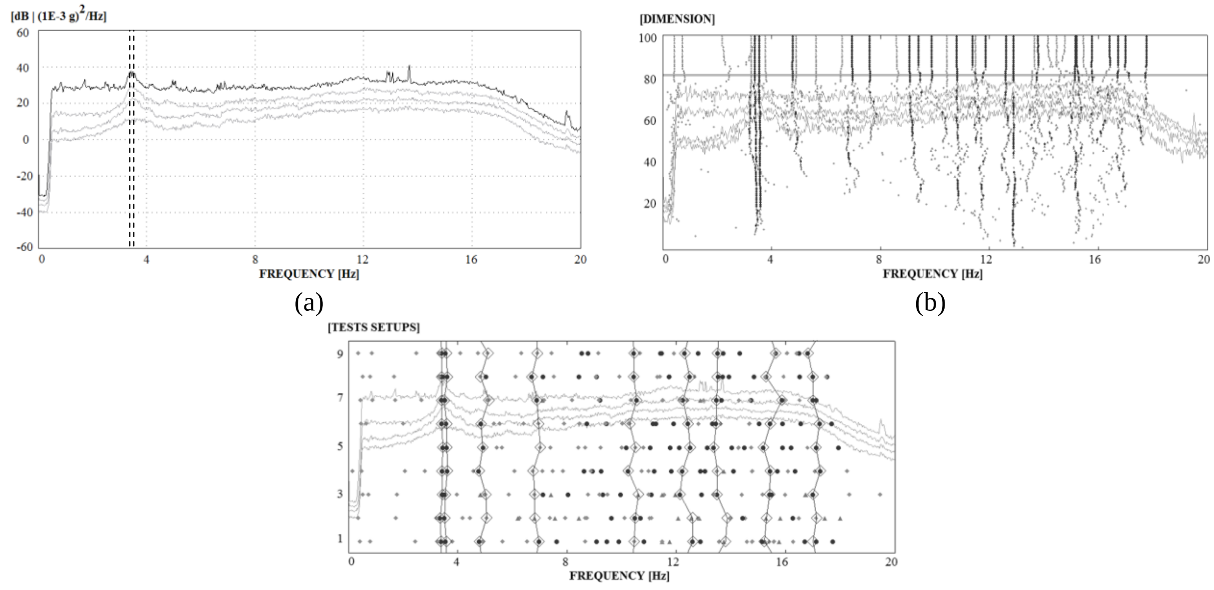
(a) (b)

Figure 4 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 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 [17]. 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 and other sharp peaks in higher frequencies which evidence the presence of undesired noise. 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.

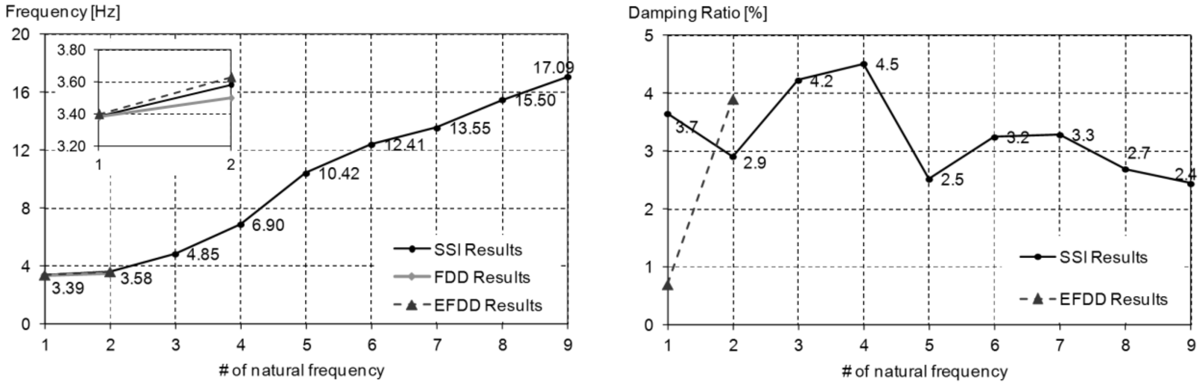


(a) (b)

(c)

Figure 5 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

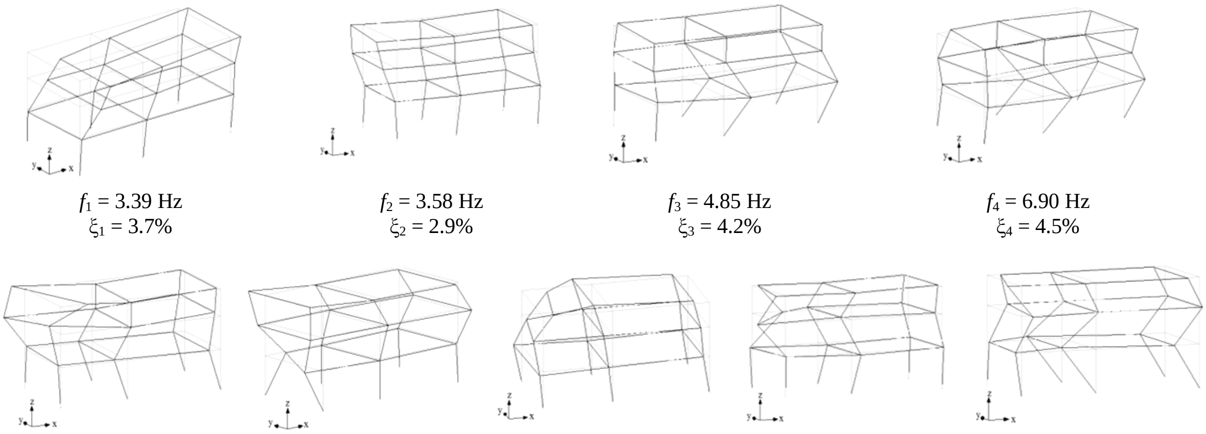
Figure 6 shows the results of the identified natural frequencies and damping ratios with the three methodologies. As shown, the FDD and EFDD methods allowed the identification of only the first two frequencies while the SSI method resulted in an improved identification of nine natural frequencies. In case of the first two frequencies, it is feasible to observe the small variability of the results on the three methods (see Figure 6a). Less reliable results were obtained for the damping ratios (see Figure 6b) 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 6 Modal identification results: (a) identified natural frequencies; (b) identified damping ratios

The modal shape results are presented in Figure 7. These results evidence the complexity of the structure and confirm the fact that the existent damage affects the behaviour of the whole system. The first two mode shapes seem global translational modes parallel to the façades Y-Y and X-X, respectively (see Figure 4). In these modes, it is evidenced the effect of the neighbouring constructions, and the different behaviour of the first Adobe floor (rigid part with almost no movement) and the others second and third Quincha levels (which shows high flexibility). The third and fourth mode shapes indicates an unexpected behaviour 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 diaphragms 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. 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 4.



f_1 = 3.39 Hz
ξ_1 = 3.7%

f_2 = 3.58 Hz
ξ_2 = 2.9%

f_3 = 4.85 Hz
ξ_3 = 4.2%

f_4 = 6.90 Hz
ξ_4 = 4.5%

f_5 = 10.42 Hz
ξ_5 = 2.5%

f_6 = 12.41 Hz
ξ_6 = 3.2%

f_7 = 13.55 Hz
ξ_7 = 3.3%

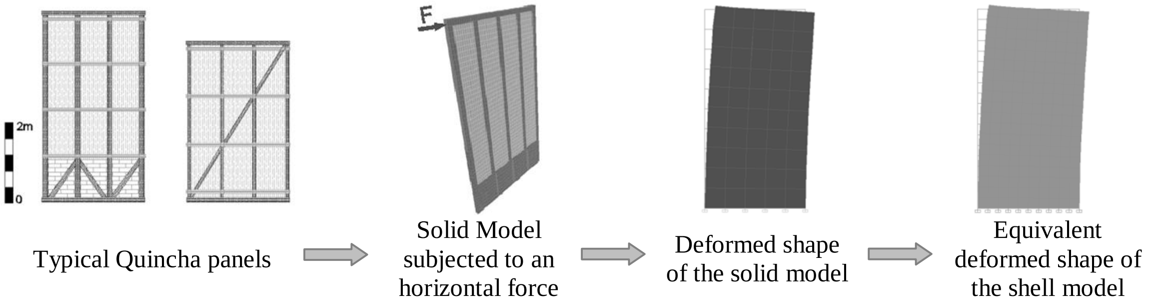
f_8 = 15.50 Hz
ξ_8 = 2.7%

f_9 = 17.09 Hz
ξ_9 = 2.4%

Figure 7 Experimentally identified modal shapes of the Hotel

4. NUMERICAL MODEL OF HOTEL COMERCIO

The numerical model of the Hotel was built in SAP2000 [5] aiming at having a better understanding of the uncertainties of the measured structural behaviour. Only the instrumented area was modelled using shell elements for the Adobe and Quincha walls, and frame elements for the inter-story system. The Elasticity Modulus (E-modulus) of the Quincha at the second and third floor was estimated using a solid model of a typical panel. From these solid models, the E-modulus and the effective bending thickness of the shell elements were assessed using deflection equations. Figure 8 shows the process of the analytical determination of the mechanical properties of the Quincha. The results show that the E-modulus of the Quincha is 2.7 GPa and 4.2 GPa in the second and third floor, respectively; the specific weight if of around 10 kN/m3 in both floors, and the effective thickness is almost the same in perpendicular directions. The detailed results are presented in Table 2.



Typical Quincha panels → Solid Model subjected to an horizontal force → Deformed shape of the solid model → Equivalent deformed shape of the shell model

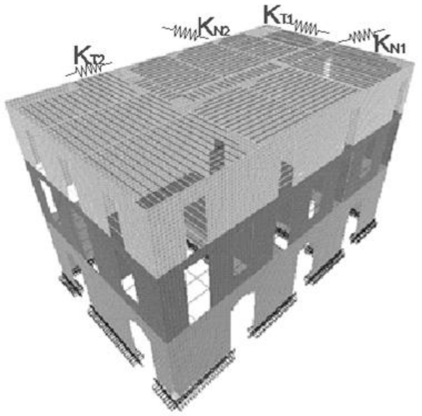
Figure 8 Quincha modelling process

Table 2 Mechanical characteristics of the materials at the Hotel

		First story (Adobe)	Second story (Quincha 2nd floor)	Third story (Quincha 3rd floor)
Modulus of Elasticity	(GPa)	0.65	2.70	4.20
Membrane Thickness	(m)	1.00	0.30	0.15
Bending Thickness	(m)	1.00	0.27	0.13
Specific Weight	(kN/m3)	16	10	10

The initial FE model of the Hotel Comercio was created considering no neighbouring constraints conditions. The modal results of this model evidenced a similarity (Modal Assurance Criterion Ratio – MAC = 0.697) between the first numerical mode and the second experimental one. For calibration purposes, it was decided not to consider the first experimental mode since what was registered corresponded to a local behaviour. The rest of the numerical modes presented complex behaviour and thus, for practical purposes, it was decided to carry out a preliminary manual calibration considering only one mode.

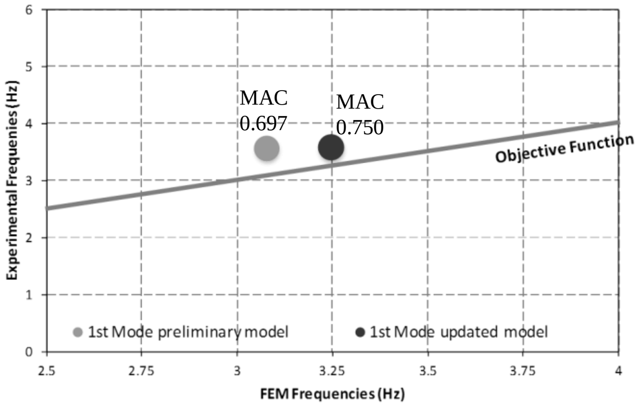
Joint springs were defined in the numerical model to simulate the missing part of the Hotel, and the neighbouring conditions (see Figure 9a). The model calibration process consisted in tuning the stiffness of the springs verifying the correspondence of frequencies and modal shapes between analytical and experimental results. The preliminary manual updating evidenced the contribution of the normal stiffness in the missing part and in the interaction limit with the other neighbouring buildings (Figure 9b). As shown in the MAC and frequency comparison plot (Figure 9c), even if the results show small differences in frequencies (11%) and acceptable MAC values of 0.75, the process is still not completed. Further works might be oriented in an extensive experimental campaign aiming at measuring more nodes in the structure and the implementation of automatic routines with an optimization algorithm for a proper calibration of the numerical model.



(a)

Initial Model		Updated Model	
Spring Stiffness (kN/m)	1st frequency (Hz)	Spring Stiffness (kN/m)	1st frequency (Hz)
k_{N1}= 0	3.077	k_{N1}= 50	3.172
k_{T1}= 0		k_{T1}= 0.1	
k_{N2}= 0		k_{N2}= 2000	
k_{T2}= 0		k_{T2}= 0	

(b)



(c)

Figure 9 Numerical analysis of the Hotel Comercio: (a) FE model; (b) stiffness properties; and (c) MAC – Frequency comparison plot of the first natural frequency

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. The tests carried out consisted on twenty uniaxial measurements along the three levels of the structure using four high sensitivity 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 experimental 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 behaviour. 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 a second series of modal identification tests, this time considering measuring more degrees of freedom with a dense mesh of sensors.

In this type of structures, the numerical modelling is also hard to implement, not only for the difficulty on representing the actual damage and assessing the materials properties, but also for a proper representation of the real boundary conditions of the building (neighbouring constructions, also severely damaged, are located all around the building). Further works in this area might consider the development of more refined models and the implementation of automatic calibration routines.

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