Environmental and Dynamic Remote Monitoring of Historical Adobe Buildings: The Case Study of the Andahuaylillas Church in Cusco, Peru

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Abstract. Constant survey of historical constructions is very important to ensure their conservation. In the case of ancient buildings, their use, the materials aging, vibrations, environmental effects (temperature, rain, snow) and seismic events are all possible causes of deterioration and damage. A continuous Structural Health Monitoring can provide useful information for automated condition evaluations of the health-state of historic buildings; however, it is known that the effects of environmental conditions such as the variation of temperature and humidity can make this assessment difficult. Therefore, continuous monitoring of environmental conditions and dynamic parameters is needed to develop suitable models to assess the current health-state. Additionally, historical structures could be located in a place where the harsh local conditions (viability, electricity, internet connection, etc.) or the distance from the inhabited centers can make monitoring activities challenging. This paper reports an innovative dynamic and environmental remote monitoring system implemented on the historical adobe church of San Pedro of Andahuaylillas, built in the sixteenth century, suitable example of Andean historical earthen constructions, strategically located on an Inca road system, 60 km south of Cusco. Firstly, the monitoring methodology is discussed, and subsequently, the case study is presented. The data is recorded locally and is automatically sent to Lima (1200 km away from Cusco) where the dynamic data is automatically processed to identify the modal parameters of the church. Preliminary results of a 6-month monitoring campaign is finally shown.

Keywords: Structural health monitoring · Real-time assessment
Remote control · Adobe structures · Environmental effects

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1 Introduction

Cultural heritage earthen buildings are vulnerable to external actions, as earthquakes, tsunamis, environmental conditions and others, and, often, they are under high risks. Furthermore, the heritage earthen buildings present an important cultural, economic and historic asset of a nation. Peru is characterized on the one hand by a large number of these buildings that are an important part of the historical and cultural heritage of inestimable value, and on the other hand, by high seismicity. For all these aspects, Peruvian cultural heritage earthen buildings need an indispensable intervention but also an accurate diagnosis to respect the modern restoration principles.

In this context, Structural Health Monitoring (SHM) has seen an increasing interest because it perfectly fits modern principles of restoration and conservation and it is considered a useful tool to increase the knowledge of a historical building, in order to understand its structural behavior and its structural health condition [1]. Moreover, a SHM system applied to cultural heritage earthen buildings may also allow validating FEM models and control the effectiveness of strengthening interventions [2].

In a SHM, the study of the environmental effects on the dynamic behavior is a crucial step [3]. Several studies have reported that temperature and humidity variation may significantly affect the dynamic results and if the effect of these environmental variations is not taken into account, no correct structural diagnosis may occur, making this tool unreliable [4].

The paper reports the results obtained during a long-term monitoring of a symbolic Peruvian cultural heritage earthen building, the Church of San Pedro Apostol de Andahuaylillas, located in Cusco (Peru). The church construction dates back to the 16th century, was built by Spanish Jesuits and is considered an emblematic example of South American baroque architecture. The monitoring system was installed on March 2017 and is continuously acquiring the dynamic behavior of the monument using force-balanced accelerometers and environmental conditions using temperature and humidity sensors.

The paper is organized as follows: Sect. 2 describes the developed tool for the environmental and dynamic remote monitoring, Sect. 3 describes the case study and the obtained results, and Sect. 4 concludes the paper.

2 Description of the Monitoring System

2.1 Data Acquisition

The dynamic monitoring system of the Church of San Pedro Apostol de Andahuaylillas is composed by four EpiSensor ES-U2 uniaxial force balance accelerometers [5] (bandwidth range from DC to 200 Hz, a dynamic range of 155 dB+, a sensitivity of 10 V/g and an operating temperature range from −20 °C to 70 °C) and by an Obsidian 8x [6], a multi-channel recorder with 24-bit resolution (see Fig. 1a and b). The system is equipped by an external battery and a charger maintainer to ensure the continuous operation even in the event of an electrical cut. The dynamic data acquisition parameters were set to 200 Hz of sampling rate, 900 s of sampling time and the recurrence of events of 1 h.

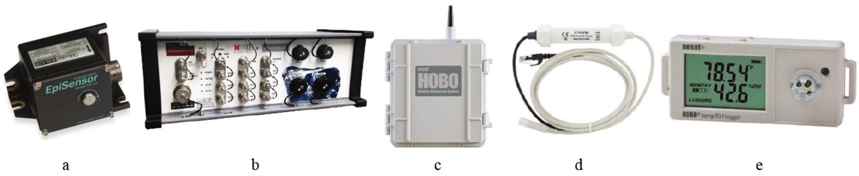

Fig. 1. Monitoring system installed in the church: (a) EpiSensor ES-U2 accelerometer sensor; (b) Obsidian 8x acquisition system; (c) HOBO RX-3000 Data Logger; (d) S-THB-M008 temperature/humidity sensor; and (e) UX100-011HOBO environmental sensor.

The monitoring system to record the environmental parameters of the Church of San Pedro Apostol de Andahuaylillas is composed by a HOBO RX-3000 Data Logger [7] with two S-THB-M008 temperature and humidity sensors [8] (see Fig. 1c and d) and, additionally, by two UX100-011 HOBO digital temperature and humidity sensors [9] (see Fig. 1e). The S-THB-M008 sensors have a temperature range between −40 °C to 75 °C, a humidity range between 0–100%, a temperature resolution of 0.02 °C and humidity resolution of 0.1%. The UX100-011 HOBO sensors have an air temperature range between −55 °C to 150 °C, a relative humidity range between 0% to 99%, a temperature resolution of 0.024 °C and humidity resolution of 0.05%. Four sensors were placed in different locations of the church to record the external ambient temperature and humidity and the internal ambient temperature and humidity of the church in three specific points (near the entrance to the church, in the middle of the main nave and, finally, behind the main altar). The use of the HOBO RX-3000 Data Logger was justified by the possibility with this tool of a remote and on-line monitoring of the recorded parameters in real time. On the contrary, the UX100-011 HOBO sensor is a static tool and needs an in-situ user-interaction to manage data. The environmental parameters were recorded with a time recurrence of 1 h.

Dynamic and the environmental monitoring acquisition started on March 2017 and they are active to current time. In this work, only the first six months of recorded data will be presented which implies the report of 4100 recording events.

2.2 Data Transmission

The data transmission process is composed of three steps; the first is the creation of small files, the second is the sending by a Entel 3G USB Modem with a 3 GB plan line, the third step is the saving an in-situ safety copy of the recorded data to avoid data loss.

The Obsidian 8x was used for recording the dynamic properties and the HOBO RX-3000 Data Logger for recording the environmental factors, and were programed to send automatically the recorded information by a safe File Transfer Protocol (FTP). The devices are connected by an Ethernet cables with the Entel 3G USB to directly send the file from Andahuaylillas (Cusco) to PUCP laboratory of Lima (1200 km away from Cusco). Furthermore, the Obsidian 8x was programed to send and save in-situ the files in .mat format, a binary file of limited size.

2.3 Data Processing

The recorded files arrive in almost real time to the PUCP laboratory workstation for storing and processing. The modal parameters (natural frequencies, damping ratios and modal shapes), the maximum and the root mean square values of each acquired signal are obtained. The methodology for the automatic estimation of the modal parameters considers four steps: (i) the pre-processing of recorded data to obtain the dynamic properties, (ii) application of the SSI-Data method and automatic cleaning of the resultant stabilization diagram, (iii) the automatic choice of the most representative modal values, and (iv) the modal tracking. Firstly, digital signal pre-processing of recorded data is applied (decimation and filtering) and subsequently, the Data-Driven Stochastic Subspace Identification (SSI-Data) method [10] is developed to obtain the dynamic properties (frequency, damping and modal shape). Generally, the stabilization diagram (a plot of model order vs eigenfrequencies for a wide range of model orders) is used to facilitate the final selection of the modal parameters of the system. In this work, an automatic analysis of the stabilization diagram is applied and soft and hard validation criteria [11] and hierarchical clustering methodology [12] with an automatic threshold [13] are used to clean the stabilization diagram. Subsequently, an algorithm for the automatic choice of the most representative values of the estimated parameters is developed with the use of the modal shape complexity criteria. Finally, an automatic tracking of the evolution in time of the identified modal parameters [14] is proposed with a self-adaptable filter time-window to obtain the real modal parameters of the structure. Figure 2 shows the main steps of this tool.

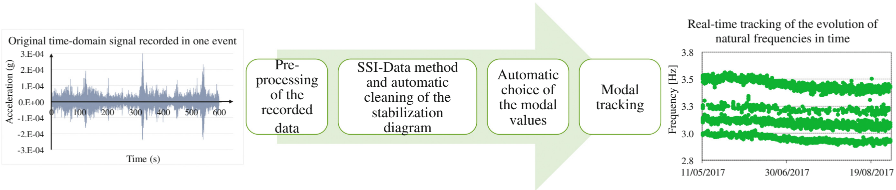

Fig. 2. Summary of the proposed methodology for the automatic estimation of the modal parameters.

2.4 Real Time Visualization

A Web Platform was implemented for the online visualization of the dynamic processed data and environmental recollected data in real time. Firstly, the software Bitvise Client (Bitvise Limited, Texas, USA) sends real time the data stored in the PUCP laboratory workstation to the web server by a secure SSH connection. Then, the data are stored in a SQL database, administered by MySQL (Oracle Corporation, California, USA), managed under the services of Amazon Web Servers (Amazon, Washington, USA). Finally, the data are graphed on the Web Page using HTML, CSS and Java-Script codes.

3 Case Study: San Pedro Apostol Church of Andahuaylillas

The San Pedro Apostol church of Andahuaylillas is considered as one of the most emblematic colonial adobe churches in Peru (Fig. 3a). It is located at the main square of the village of Andahuaylillas, about 41 km southeast of the city of Cusco and it is included into the Andean Baroque Route, a route that has been established as a scenic road dedicated to several churches belonging to the Andean baroque artistic movement [15]. The church of Andahuaylillas covers a total area of 27 m × 61 m and, in particular, the temple develops around an enlarged nave with plan dimensions of 12 m × 58 m. The main nave is connected to the presbytery, the baptistery, the bell tower, the choir loft and several side chapels (Fig. 3b and c). The structure is composed mainly of adobe walls with an average thickness of 2 m and an average height of 10 m and of 12 m in the main nave and in the presbytery, respectively. Additionally, the longitudinal walls of the nave are restrained by wooden tie-beams and (un-tensioned) steel tie-roads, which are distributed along the nave and have a stone masonry basement 1 m high. The roof structure of the church is composed by triangular arrangements of wooden elements known as 'par y nudillo' and the church has lateral buttresses located in the front facade and side walls. Different conservation works, especially in the last 50 years, have been carried out in the whole church which did not completely solve the structural problems of the building; especially the ones regarding its seismic vulnerability [16].

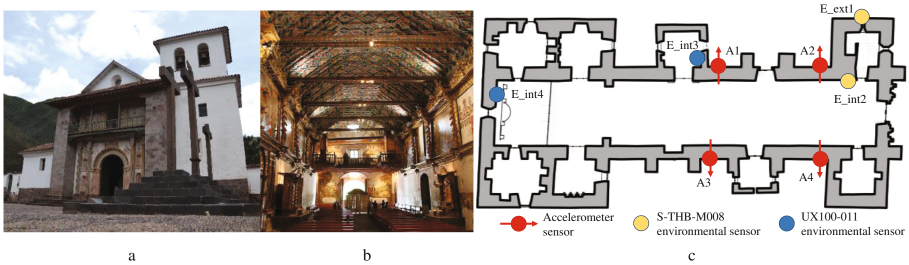

Fig. 3. Church of 'San Pedro Apostol' of Andahuaylillas: (a) Exterior view; (b) Interior view; and (c) A1, A2, A3, A4 accelerometers location (red dots) and E_ext1, E_int2 S-THB-M008 environmental sensors location (yellow dots) and E_int3, E_int4 UX100-011 environmental sensors location (blue dots).

Because of the importance of the building and the need to increase the knowledge about the real structural behavior of the structure, a long-term monitoring was implemented. Figure 3c shows the location of the installed sensors. In particular, the four acceleration sensors (the A1, A2, A3 and A4 red dots in Fig. 3c) were located at the top of the walls of the main nave; the two S-THB-M008 environmental sensors (the

E_ext1 and E_int2 yellow dots in Fig. 3c) were located outside and in the church choir and the two UX100-011 environmental sensors (the E_int3 and E_int4 blue dots in Fig. 3c) were located in a side chapel and behind the main altar. In this way, it is possible to monitor the external ambient temperature and humidity and the internal ambient temperature and humidity distribution in different points of the buildings.

As an example, Fig. 4a shows the recorded data of the A2 sensor during the schedule events on 20/07/2017 at 10:00 am. Each event has a 900 s of sampling time and the structure is only excited by ambient noise. The recorded file is sent to the PUCP laboratory where it is automatically processed. Subsequently, the SSI-data method is applied and a preliminary stabilization diagram is obtained (Fig. 4b). Then, the stabilization diagram is filtered and, finally, the most representative modal values of each event are selected with an automatic procedure.

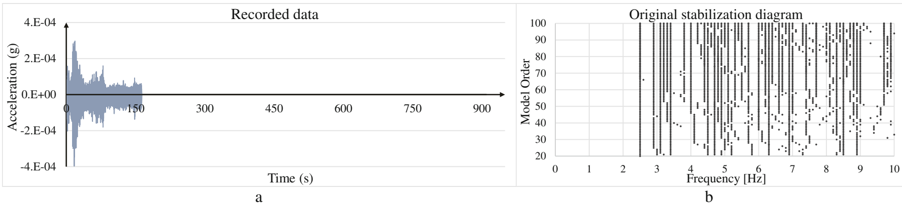

Fig. 4. Data processing: (a) Recorded data of the A2 sensor during the events on 20/07/2017-10:00; and (b) Stabilization diagram.

For a clearer visualization of the natural frequency evolution in time, a further cleaning stage is needed. For this purpose, an automatic tracking of the evolution in time of the identified modal parameters is applied and the results are shown in Fig. 5. The results indicate that, with this methodology, it is possible to follow the time-evolution of the modal parameters of an adobe historical church in real-time. Figure 5 shows the first five frequencies of the church obtained automatically by the developed modal algorithm in the range of 2 Hz–4 Hz. Furthermore, a frequencies variation was detected between 30/05/2017 and 19/06/2017, with a clear decrease of the frequencies values, probably due to changes in environmental conditions.

The results of the time evolution of the environmental parameters are shown in Figs. 6 and 7. Figure 6a shows the external ambient temperature recorded by E_ext1 sensor and Fig. 6b shows the internal ambient temperatures recorded by E_int2, E_int3, E_int4 sensors. The results indicate a constant trend of the data, with a clear attenuation of the daily variation in the case of internal ambient temperatures in comparison with the external ambient one. Similar attenuation is present between external ambient humidity and internal ambient humidity (Fig. 7a and b). In this case, a clear decrease of the humidity values was detected between 30/05/2017 and 19/06/2017 with an explicit similarity with the trend of the frequencies.

Finally, the processed data is sent to the Web Platform for the online visualization

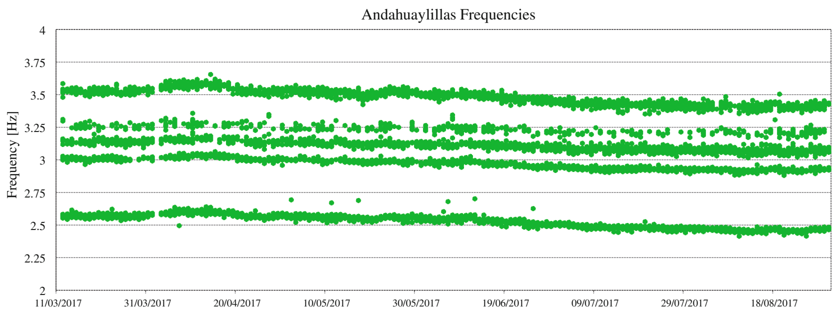

Fig. 5. Time evolution of the first five natural frequencies of the church.

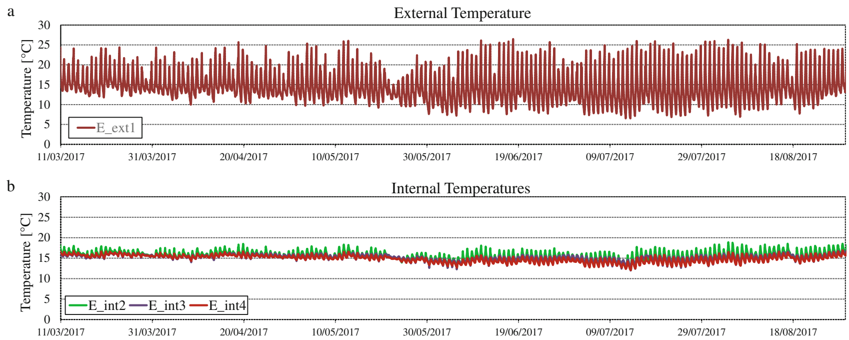

Fig. 6. Time evolution of the temperature values: (a) External ambient temperature recorded by E_ext1 senor; and (b) Internal ambient temperatures recorded by E_int1, E_int2 and E_int3 sensors.

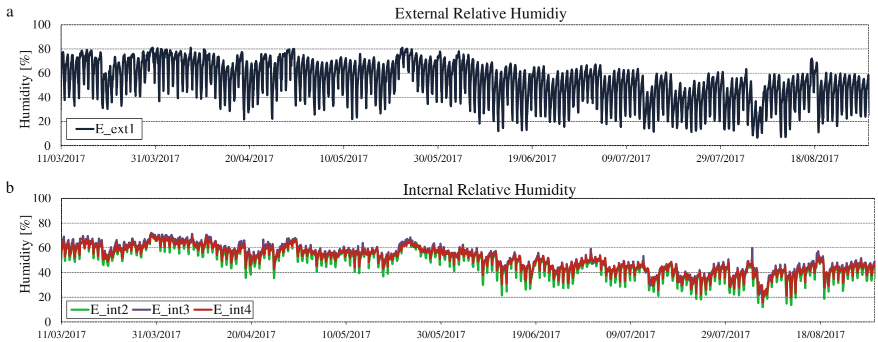

Fig. 7. Time evolution of the humidity values: (a) External relative humidity recorded by E_ext1 senor; and (b) Internal relative humidity recorded by E_int1, E_int2 and E_int3 sensors.

of the dynamic processed data and environmental recollected data in real time. Figure 8 shows a view of the main page of the Web Platform for the structural health monitoring of the San Pedro church of Andahuaylillas and San Juan Bautista church of Huaro, where this system was preliminary installed.

Fig. 8. View of the main web page with the results of the remote monitoring system

4 Conclusions

The present paper shows the long term monitoring applied to the San Pedro Apostol adobe Church of Andahuaylillas in Cusco (Peru) and the tool to display in real-time the obtained data. The simple four steps of the developed methodology (acquisition, sending, processing and real-time visualization of the data) were successfully evaluated and allowed to compare remotely different parameters, in this case frequencies and environmental factors. The direct and real-time comparison of different parameters may allow to assess the health state of the structure and to understand the main parameters that most affect certain trends or behaviors. The high accuracy of the developed system makes it a useful tool for monitoring complex masonry structures and for reducing uncertainties regarding their structural performance through time. Furthermore, the free online access to this information allows a greater diffusion of these diagnostic techniques and, moreover, an active participation of the users in the cultural heritage management. The great simplicity and the easy repeatability make the developed remote monitoring system a useful tool for the conservation and protection of the cultural heritage earthen buildings.

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