Structural Evaluation of Stone and Earthen Peruvian Architectural and Archaeological Heritage through Experimental Modal Analysis

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Abstract
In recent decades, the application of experimental modal identification tests in civil engineering structures is gaining interest for various purposes such as model calibration, quality control while the construction process, damage detection, structural health monitoring, etc. The use of these tests in archaeological sites as well as earthen heritage buildings (which are in general massive) is a novel area of application. The paper presents the results of operational modal analysis tests carried out on archaeological and architectural heritage buildings in Perú as part of an extensive research for assessing their structural vulnerability. The first case study is related to the tests on one sector of the Chokepukio archaeological site, which dates back to the pre-Inca period of Peru (12th Century). The second case study is related to the tests carried out at the St. Peter Apostle Church of Andahuaylillas (16th Century), which is considered as one of the most representative earthen churches of South America for the beauty of its internal paintings. In both cases, the paper shows the details of the tests, measurement procedures, data processing results, and finite element model updating process, as well as a general discussion on the importance on carrying out in situ tests as part of the structural evaluation process of existent structures.

Keywords: Archeological Heritage, Architectural Heritage, Structural Analysis, In-Situ NDT tests, Operational Modal Analysis

1. Introduction

Peru is located in the Pacific’s Ring of Fire, one of the most active seismic zones of the world, and thus, its cultural heritage is in permanent danger. The last seismic events that happened in the world such as the one in Chile (2010) and Iran (2003) have evidenced, once again, the fragility of the historical structures. The maintenance and preservation of these structures is of high importance in order to preserve the cultural heritage of humanity. Understanding the structural behavior of this type of constructions is particularly complex due to the difficulty for characterizing the geometry, materials, damage state, identifying the structural system, as well as creating reliable numerical models [6]. The International Council of Monuments and Sites (ICOMOS) have published different strategies for studying historical constructions. These strategies evidence the necessity of a deep knowledge of the variables referred before which can only be assessed by extensive diagnosis campaigns by means of laboratory and on site research. This paper shows the application of operational modal analysis tests (where the excitation source is only the environmental noise) in two case studies of archaeological and architectural heritage, respectively. The paper starts with a brief overview of the structural intervention process in earthquake prone regions. Then, the details of the experimental campaigns are shown and the process of numerical model calibration. Finally, the importance of in-situ Non-Destructive-Tests (NDT) as a powerful tool for understanding the structural behavior of heritage buildings is highlighted.

2. Seismic Protection of Historical Buildings

The taking action process for the protection of historical heritage in seismic areas requires the performance of four stages: 1) identification and quantification of threat; 2) state and vulnerability evaluation of the structure, 3) risk quantification to which the system is exposed; and 4) intervention and monitoring measurement planning.
In countries located on the western coast of South America, the seismic hazard is originated from the subduction process of the Nazca and South American plates. This process generates earthquakes of great magnitude in zones with coastal interaction and between these two plates. Through studies known as seismic hazard, it is possible to identify seismic sources which imply knowing the location and geometry of every one of them. Once the identification is achieved, it is necessary to establish the level of activity and to transfer its vibratory effect to the place where the studied structure is located. Usually, the latter is carried out using attenuation curves and standardized weighting processes of the effect of the different sources, considering local topography effects as well as soil characteristics.

On the other hand, the seismic vulnerability is defined as the damage propensity that the structure presents. The study of this particular vulnerability, as stated in [6], is a complex process that takes into consideration historic recollision phases (usage, architectonic changes, and behavior under severe events), survey on the current state of the structure (acknowledge of geometry, material, and structural system), characterization of the damage state (identification of existing pathologies, and determination of the in-situ structural response), and the structural response due to severe events and localized phenomena. The application of this last stage consists in the use of simple models, such as approximations based on the opinion of experts as well as experience, or more sophisticated tools, such as advanced computational models, in order to estimate the structural response. In any of these alternatives, the validation of the utilized tools should be of high importance.

One of the most powerful tools for quantifying the current behavior of structures is known as experimental modal analysis tests. These tests consist in the instrumentation of the structure and the measurement of a time varying parameter (displacement, velocity or acceleration) in order to estimate its dynamic properties (natural frequencies, damping ratios and vibration modes). Experimental modal analysis tests, used alone or integrated into ongoing monitoring processes, have been used in Civil Engineering since the 80’s as a numerical model updating tool, quality control during construction and damage detection. These tests have been carrying out in masonry historical construction (fired brick bell towers and churches, stone and brick masonry monasteries) since the last decade. The application of these tests in earthen constructions and archaeological heritage is a new area that is been studied in Peru.

3. Operational Modal Analysis Tests at the Archeological Site of Chokepukio

The archaeological site of Chokepukio is located 30 km from the city of Cusco, Peru. This site corresponds to a vestige of the Lucre culture (beginning of the Inca Empire) and its construction took place between 900 AD and 1300 AD. Chokepukio archaeological site presents a special architecture with walls forming enclosures around open spaces. This configuration maintains streets and narrow passageways connecting the access to the enclosures. Currently, as shown in Figure 1, there have been found vestiges arranged in groups that correspond to an urban settlement. Mostly, the perimeter walls are 12 m high and have trapezoidal and rectangular niches at different heights. The masonry found in Chokepukio is made of semi rounded stones with irregular joints of mud and straw mortar that range between 25 and 100 mm [5]. Unfortunately, this complex is severely damaged due to the seismic activity and the lack of suitable maintenance activities. The damage constitutes the partial or total destruction of most of the complex, the loss of supporting elements and the presence of vegetation.

Dynamic tests were conducted to one of the vestiges placed on the corner of sector A. The vestiges consist of two walls that support each other by means of wooden struts. This sector was chosen as study case due to the good conservation state of the remaining structures (original coating can be appreciated on both walls). The instrumentation was carried out in one of the walls (see Figure 1). The instrumented wall has an irregular geometry with an average length and height of 20 m and 9 m, respectively; and a thickness that varies from 1.20 m to 1.80 m at the bottom and from 0.60 m to 0.80 m at the top of the wall. The different arrangement of the stone units may indicate two types of masonry, at the lower and upper part of the wall, respectively. The lower part of the wall presents a more consolidate structure with bigger stones and smaller mud mortar joints, whereas the upper one is made of smaller stones and thicker joints.
Aiming at characterizing the dynamic response of the wall, an experimental campaign that consisted in the application of operational modal analysis tests was carried out. Sixteen measurement points were established throughout the wall. The transducers used consisted on four piezoelectric accelerometers with a sensitivity of 10 V/g and a dynamic range of ± 0.5 g (Figure 2a) together with an USB-powered 24 bits resolution data acquisition system (Figure 2b). The identification of the dynamic response was carried out using signal processing methodologies in frequency (Peak Picking method), and time domain (SSI method). The preliminary results in the frequency domain (Figure 2c) show that the first seven natural frequencies range between 2 Hz and 10 Hz. The results of frequencies from the SSI methodology are in good agreement with the ones obtained before and, due to the robustness of this last method, its results were chosen as final values modal identification process.

Next, a numerical analysis was carried out using DIANA TNO. For this, a Finite Element (FE) model was implemented considering the mechanical properties of the materials as homogenous. The values used for the material in this model were of 0.50 GPa and 2.350E-5 N/mm$^3$ for the elasticity modulus and specific weight, respectively. The results of the initial model showed discrepancies between the numerical and the experimental results, and thus, a FE model updating process was then performed using the first four vibration modes for
comparison purposes. The optimization was developed through the implementation of an objective function, whose purpose was to establish a difference between experimental and numerical results, as proposed in [6]. The objective function was created according to the Douglas-Reid method [3] for which, upper and lower boundary values were defined for the variable parameters. The selection of the varying parameters was carried out based on a sensibility analysis in order to assess the influence of the material (modulus of elasticity and specific weight) and the structural conditions (boundary conditions and localized damage). The results of the sensitivity analysis showed that the most influential parameters for optimization purposes are the E modulus (affecting natural frequencies) and specific weight of the material (affecting mode shapes). In order to accomplish a more refined model and consequently better results in the updating process, the possibility that the two existing materials were different (one at the lower, and one at upper part of the wall) was taken into consideration. Table 1 summarizes the results of the updating process. As presented, the final values obtained for the parameter that characterized the material evidenced differences on the quality of the lower and upper masonry, which is in good agreement to what is actually found in the field. The final comparison of experimental and updated vibration modes (Figure 3) highlights the high reliability of the FE model.

Table 1: Initial and final values obtained after the calibration process

<table>
<thead>
<tr>
<th>Updating Parameters</th>
<th>$E_{\text{lower wall}}$ [MPa]</th>
<th>$E_{\text{upper wall}}$ [MPa]</th>
<th>$\gamma_{\text{lower wall}}$ [N/mm³]</th>
<th>$\gamma_{\text{upper wall}}$ [N/mm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Values</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model2</td>
<td>500.0</td>
<td>500.0</td>
<td>2.350E-5</td>
<td>2.350E-5</td>
</tr>
<tr>
<td>Final Values</td>
<td>775.4</td>
<td>301.7</td>
<td>2.943E-5</td>
<td>2.943E-5</td>
</tr>
</tbody>
</table>

![Figure 3. Experimental and numerical results after the numerical calibration process](image)

4. Operational Modal Analysis Tests at Saint Peter Apostle Church of Andahuaylillas

The village of Andahuaylillas is located in the Andes of Perú, 40 km from the city of Cusco. This town still maintains a typical layout of the early colony with narrow stone streets, and one story adobe houses (which originally had thatched roofs which were replaced by tiles in the late 1800’s).

The construction of Saint Peter Apostle of Andahuaylillas church began in the 1610’s. The architecture of the temple presents renaissance characteristics influenced by the “Manierist” style such as the mural ornamentation on walls [2]. The church consists of a main rectangular nave, a bell tower, and four lateral chapels. The main nave and the bell tower are made of adobe walls with an average thickness of 2 m. The foundation of the church is made of stone masonry with mud mortar 0.50 m height underground 1 m over the ground level. The adobe walls are coated with a gypsum layer with varying thickness. The roof system of this church is made of a “A shape” (par y nudillo) timber structure, and a decorated ceiling underneath. The covering is made of traditional
fired clay tiles [7]. Figure 4a and 4b show the main façade and an inner view of the church, respectively.

During the last 40 years, several conservation works have been carried out in the church. However, these interventions have been purely esthetic, and haven’t proven to be a real solution to the structural problems that are visible nowadays. So far, the adobe walls, especially from the presbytery, triumphal arch, and the chapel, present a severe cracking pattern. Other damaged areas (especially in the timber supporting structure) are the chorus, the facade and the balcony. The timber and steel tie beams located in the main nave are highly deteriorated as well.

![Figure 4. Andahuaylillas church: (a) main facade; (b) inner view; (c) cracks on the triumphal arch](image)

In order to evaluate the structural conditions, and the current state of damage of this construction, an experimental campaign was performed by instrumenting the bell tower in order to measure its dynamic response (Figure 5a). Sixteen uniaxial points were established for measurement (Figure 5b) considering as sampling time and rate as 10 minutes and 200 Hz, respectively. Figure 5c shows the results of the modal identification process. As shown, the first two modes clearly correspond to translational movement of the tower in orthogonal directions, whereas the third one corresponds to a torsion mode.

![Figure 5. Experimental tests conducted to Andahuaylillas church: (a) placement of transducers for measurement; (b) measurement configuration; (c) results of the first three vibration modes](image)

The FE model of the church was then built using DIANA TNO. In this model, the adobe walls, buttresses and tie beams were represented through solid elements, whereas floors were modeled using shell elements instead. The effect of the roof, and the tympanum was modeled through horizontal and vertical equivalent applied forces that represent the weight and the pressure upon walls. As shown in Figure 6, the current stage of the numerical analysis is the updating process; and as a first step for the sensitivity analysis, the influence of the wooden tie beams was studied. The preliminary results of the first three vibration modes clearly indicate the influence of these elements (behavior of the longitudinal walls in numeral models with and without tie beams), and the importance of the updating process. Further work leads to the study on the behavior of the church including the representation of the current state of damage, and non-linear analysis (taking into consideration the energy dissipation capacity of the material) aiming at estimating its behavior in seismic events. Once these
analyses are concluded, a strategy for a proper intervention of the monument can be finally designed.

**Figure 6.** Results of the modal analysis of the church (first three vibration modes)

### 5. Conclusions

In-situ experimental modal analysis tests are a powerful tool for the study of architectonical and archaeological heritage. This type of measurements is appropriate when assessing the behavior of historical monuments since it does not involve damage or deterioration to the structure. These techniques can not only be applied to the study of its structural behavior, but also for assessing the effect of vibrations from external factors such as buses, neighboring excavations or tourism activity. In the specific case of the Chokepukio archeological site, and the Andahuaylillas church, it has been shown that a good way to obtain a better understanding of the structural behavior of these monuments is through the use operational modal analysis. This has also allowed probing the importance of complementing the numerical modeling, and seismic vulnerability studies with data collected in the field of the real structural response.

### 6. References