Geomatics' procedures and dynamic identification for the structural survey of the church of 'San Juan Bautista de Huaro' in Perú

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ABSTRACT: This paper presents the feasibility of combining geometrical survey and in-situ non-destructive testing for the structural assessment of historical earthen constructions, which has typically difficult and non-documented geometries, unknown and highly variable materials, not visible damage states, and non-well defined boundaries and diaphragm conditions. Particularly, this paper presents the results of geometrical and structural surveys that are being carried out in the church 'San Juan Bautista de Huaro' in Cusco, Perú, as part of an ongoing research aiming at assessing its seismic vulnerability. The church dates back to the 17th Century and represents a typical Andean adobe church. Regarding to geometry, novel techniques such as laser scanning and photogrammetry from drones were successfully integrated to generate an accurate 3D reconstruction, and a numerical model of the building for seismic analysis. This numerical model was preliminary calibrated considering experimental results from operational modal analysis tests. The calibration process showed the importance of considering the connection elements in the numerical model, as well as allowed a preliminary assessment of material properties.

1 INTRODUCTION

Perú has a great legacy of ancient adobe buildings, which are part of cultural identity and an important economic source for the communities due to the tourism. Moreover, given the high seismicity and fragility of traditional adobe as construction system, architectural heritage and its occupants are at constant risk.

A structural assessment of historical buildings considers experimental diagnosis and numerical analysis, which are necessary to propose further rehabilitation and restoration activities. According to Sánchez-Aparicio et al. (2014), the following considerations are required to perform a proper analysis: a) obtaining a complete and accurate geometry of the structure, b) determination of mechanical properties of materials, c) characterization of loads; and d) development of numerical models for reproducing the structural behavior and performing predictive analysis.

This paper presents the preliminary study for the structural assessment of the 'San Juan Bautista de Huaro' church by using modern techniques to obtain a representative and reliable model of the structure. The paper will first address the process of geometrical 3D reconstruction and then the generation of the solid model under the concept of reverse engineering. The considerations for the development of the Finite Element FE model of the church and a sensitivity analysis that was performed to understand the variables that influence its dynamic behavior are then presented and, finally, the paper highlights the main conclusions of the work.

2 THE CASE STUDY

The church of is located at the main square of the village of Huaro, which is located about 41 km to the south-east of the city of Cusco, Perú. Due to its architectural characteristics, its construction probably dates back to the XVI century and was built by Spanish Jesuits. The church was declared as a Peruvian historical monument in 1972 (World Monument Fund, 2015).

As shown in Figure 1a, the church comprises an enlarged nave, a presbytery, a baptistery, a bell tower, a sacristy and an anti-sacristy, and two side chapels. The main nave is connected to the bell tower, choir loft, arcade, baptistery and the two lateral chapels. In the presbytery sector, there are located the triumphal arch, the sacristy and the anti-sacristy. Interior views are presented in Figure 1b.

The structural system is composed by adobe walls, with an average thickness and height of 1.6m and 11m, respectively. The foundations are of stone masonry walls and the roofing system is of an A shape timber truss known as ‘par y nudillo’. The lateral walls are restrained by pairs of timber tie-beams, which are distributed along the nave. Additionally, the door frame and the bell tower are made of stone masonry.

(a)

(b)

Figure 1. Church of ‘San Juan Bautista’ of Huaro: (a) exterior view; (b) interior view (Ruta Del Barroco Andino 2015).

In the past, several conservation works have been done in the church. However, the majority of interventions focused only on aesthetic aspects. No official documentation of these interventions was found so far.

3 3D RECONSTRUCTION

3D modelling was conducted using photogrammetry and Terrestrial Laser Scanner (TLS). Aerial photogrammetry was used to collect information of the upper exterior of the church. For the lower areas, terrestrial photogrammetry was carried out due to the presence of a perimeter wall that did not allow the use of unmanned Aerial Vehicle (UAV). The interior geometrical data was collected with the TLS.

The aerial photographs were taken using an UAV. A total of 24 aerial photographs from outside of the temple were taken, considering an average distance of 30 m between the camera and the surface. Terrestrial photogrammetry was conducted using a digital camera Sony Nex 7 of 23 MP. Around 300 terrestrial photographs were taken focusing in the corners between nave and chapels, as well as on the back wall of the church. In Figure 2 shows the positions where terrestrial and aerial photographs were taken (blue rectangles). This figure also shows the flight route followed by the UAVs.

Figure 2. Image acquisition for photogrammetric 3D reconstruction of the church of ‘San Juan Bautista de Huaro’

Laser scanning was conducted using a Leica ScanStation C10. The reconstruction was performed in six individual sessions considering scanning distances around 5-10m between each other. One session was conducted in front of the frontal façade, whereas the remaining sessions were carried out in strategic locations inside the church.

The process for the geometrical 3D reconstruction was composed of four stages: 1) photograph alignment and generation of the sparse point cloud; 2) generation of the dense point cloud from the sparse cloud; 3) triangular mesh generation based on the dense cloud; and 4) textured model generation considering photographs. Due to the particularities of the building, the model was built through processing of individual segments, which were then integrated into a single model. The characteristics of each step are summarized in Table 1. Figure 3 shows the results obtained from each stage of the process.

Table 1. Characteristics of the model generation of the church using photogrammetry.

Reconstruction stages	Characteristics	Figure
Sparse cloud	60,877 points	3a
Dense cloud	68,837,359 points	3b
Triangular mesh	4,783,138 vertex and 2,391,616 faces	3c
Texturized model	40,960 x 40,960 pixels	3d

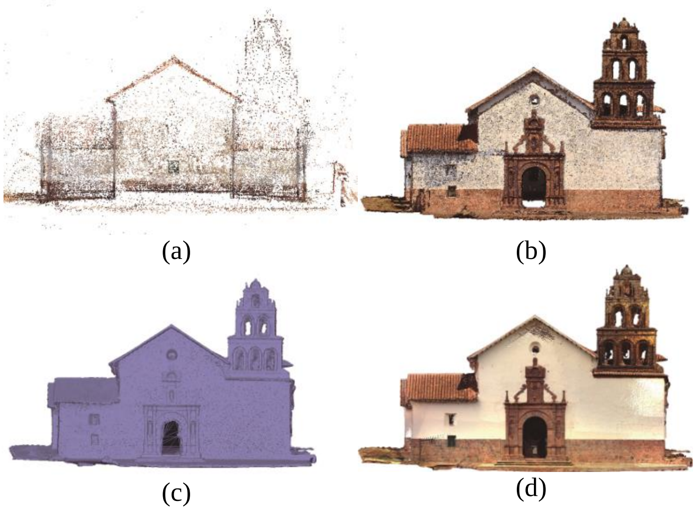

Figure 3. Photogrammetry process for model generation of the church of 'San Juan Bautista' of Huaro: (a) sparse cloud; (b) dense cloud; (c) triangular mesh; and (d) texturized model

For the reconstruction with TLS, the data of the scanning sessions was processed using the software Cyclone Leica® (Leica Geosystems, 2015). The resulting point cloud had a total of 23,683,162 points. The next step involved the manual cleanup of the undesired points acquired by the scanner. Later, the triangular mesh generation was conducted using the Poisson Surface Reconstruction algorithm (Ahmadabadian et al., 2013) implemented on the software MeshLab. The results obtained from this process are shown in Figures 4a and Figure 4b. In Figure 4c, the final model is presented, which was generated combining exterior and interior data obtained from photogrammetry and TLS, respectively.

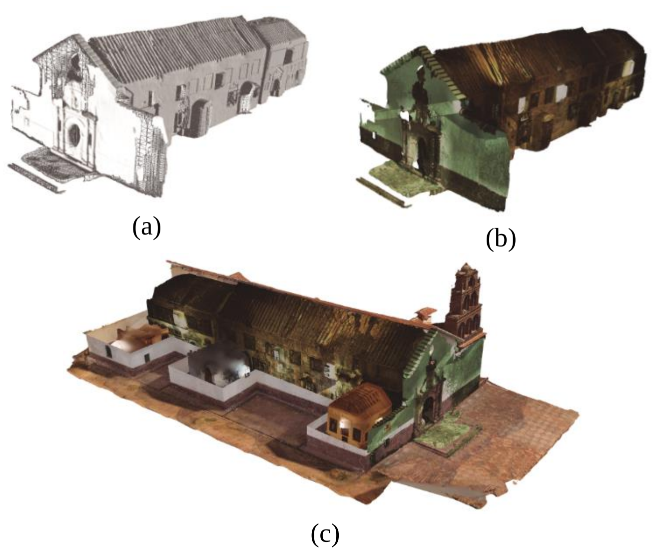

Figure 4. Model generation using laser scanner data of from the church of 'San Juan Bautista' of Huaro: (a) uncolored triangular mesh and (b) texturized model, (c) combined model using photogrammetry and TLS

4 FINITE ELEMENT MODEL GENERATION

The generation of the FE model was performed by first building a solid model using Geomagic Design X® (3D Systems, 2015) using the principle of reverse engineering.
The construction of volumes needed the previous definition of boundaries of sections which was carried out by drawing lines, arcs and polylines using the point cloud as reference. Figures 5a and 5b show the defined contour of the facade and its extrusion volume, respectively. A perfect coincidence among generated volumes is necessary to omit the creation of problematic volumes, which would difficult the generation of the finite element mesh. Figure 5c shows the boundary generation of the stone doorway, considering as reference the contours of the adjacent volumes. Finally, all volumes that represented structural elements with same materials were merged. The final solid model, which is shown in Figure 5d, was composed of only four volumes: bell tower, church body, tie-beams as well as the foundation with the doorway.

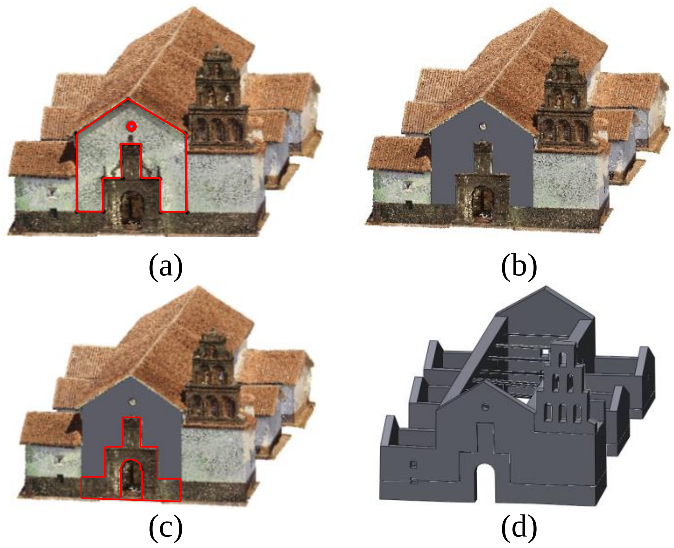

Figure 5. Modeling process of Huaro Church: first step (a) contour definition of frontal façade (b) extrusion of the façade contour (c) contour generation of stone doorway based on previous volumes; second step (d) final merged model

The FE model of the church was subsequently built in DIANA TNO® (TNO DIANA, 2015). Adobe walls, wooden tie-beams, stone foundation and bell tower were modelled using tetrahedral elements. Due to section variations in the solid model, detailed mesh were required in certain areas (i.e., connections between beams and lateral walls). The roof was not modelled due to the complexity of simulating the rotational and sliding connections following the suggestions of Fonseca & D' Ayala (2012). However, the weight of the roofing system was represented by distributed masses located on top of the walls. In Figure 6, a general view of the developed FEM is presented.

Figure 6. Finite element model of the church

5 DYNAMIC IDENTIFICATION

Operational Modal Analysis (OMA) tests were carried out in the church and its results were taken as reference for later calibration of the numerical model. OMA is an innovative tool applied to characterize the dynamic properties of structures and is considered as a powerful tool to understand the structural behavior of historical buildings (Lourenço et al., 2012). In these tests, the structures are excited with environmental noise, such as traffic or human-induced vibrations.

The OMA tests consisted on the measurement of twenty degrees of freedom in the building, as shown in Figure 7a. The transducers were piezoelectric accelerometers with a sensitivity of 10V/g and a dynamic range of +/-0.5g, as well as an acquisition system of 24-bit of resolution. The acquisition considered sampling rates and sampling times of 200 Hz and 10 minutes, respectively.

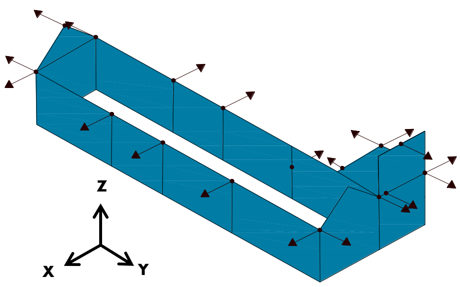

Figure 7. (a) Schematic view of the operational modal analysis test setup

The data processing carried out using the Stochastic Subspace Identification Technique (SSI) method implemented in ARTeMIS® (SVS, 2015) provided the possibility of identifying the first five modal shape of the building (Figure 8(a-f)). As shown, the movement of first mode is concentrated on the bell tower, while the following three modes are translational vibration of the nave. The fifth mode shows an out-of-plane movement on the timpani of the two façades and the bell tower.

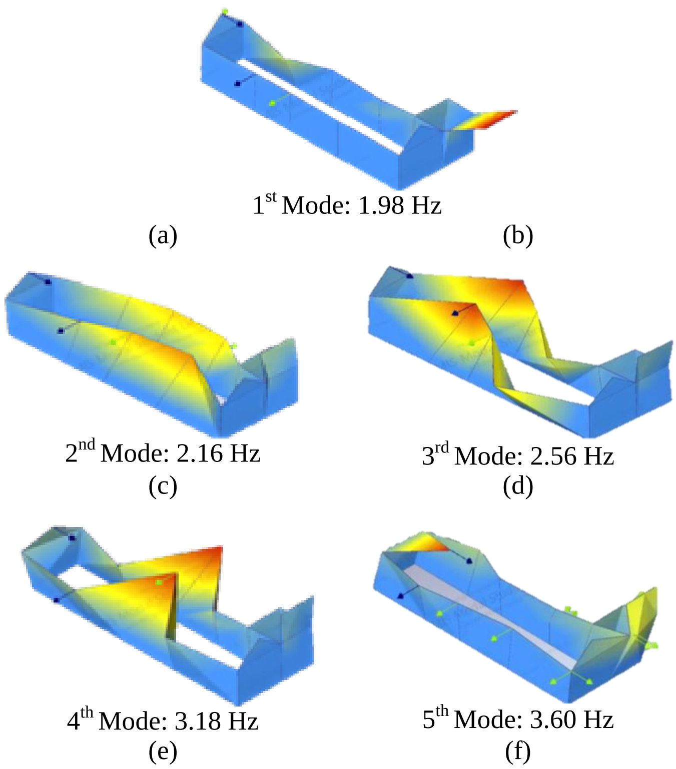

Figure 8. Modal identification tests in the church: (a) first, (b) second, (c) third, (d) fourth and (e) fifth modal shapes

6 FINITE ELEMENT MODEL PRELIMINARY CALIBRATION

After the dynamic identification, a sensitivity analysis was subsequently carried out considering variations in the boundary and connectivity conditions, as well as the mechanical properties, i.e. Young's modulus. Poisson ratios and densities values were kept fixed and were taken from literature.

The first model (M1) is the representation of the church that considered all its structural elements perfectly connected. For assessing the contribution of the wooden tie-beams, an additional model (M2) without them was developed. The third model (M3) was generated without the bell tower, aiming at determining its influence on the dynamic behavior of the church. Finally, a fourth model (M4) was built considering transition elements between the frontal façade and the bell tower. The transition material was defined considering a lower elastic modulus for the adobe masonry (10%E_{adobe}), representing a weak connection between both structural elements. In all the models, a perfect embedment condition at the base of the church was considered as well as homogeneous materials for the adobe masonry, stone foundations and wooden elements. The summary of manually tuned material properties are shown in Table 2. Note that these values were considered similar to those obtained by previous studies on a historical adobe churches (Ivancic et al., 2014).

Table 2. Final values for the elastic materials' properties

Material	Specific weight (kN/m^3)	Modulus of elasticity (MPa)	Poisson's Ratio
Adobe	15.1	350	0.25
Stone	19.0	800	0.20
Wood	4.7	10000	0.20

The global changes in the dynamic behavior of each model were measured considering the differences of frequencies and modal shapes (computed with the Modal Assurance Criterion - MAC) taking as reference the experimental results. For having a graphical comparison, frequency vs MAC (FMAC) plots were calculated for each case.

Figure 8 presents FMAC graphics for each model, comparing the results of the first five experimental and analytical modes. The results from the complete model with wooden tie beams (M1) evidenced a good correlation in terms of frequencies and MAC values for the first four vibration modes. In this case, the comparison in the fifth vibration mode did not show a good correlation. In the second model (M2), analytical results and experimental measurements showed low agreement, demonstrating the importance of considering the tie-beams timber to connect the two parallel walls of the nave. For third model (M3), results showed high MAC values and low frequency correspondence. However, the fifth mode showed an evident improvement in both indicators when compared to model M1. In addition, the first experimental modal shape was not detected since this mode corresponded to a local vibration of the bell tower. The model M4 showed an improvement of MAC values for the fourth and fifth modes but a reduction in the frequency ratio of the first mode in comparison to the initial model M1.

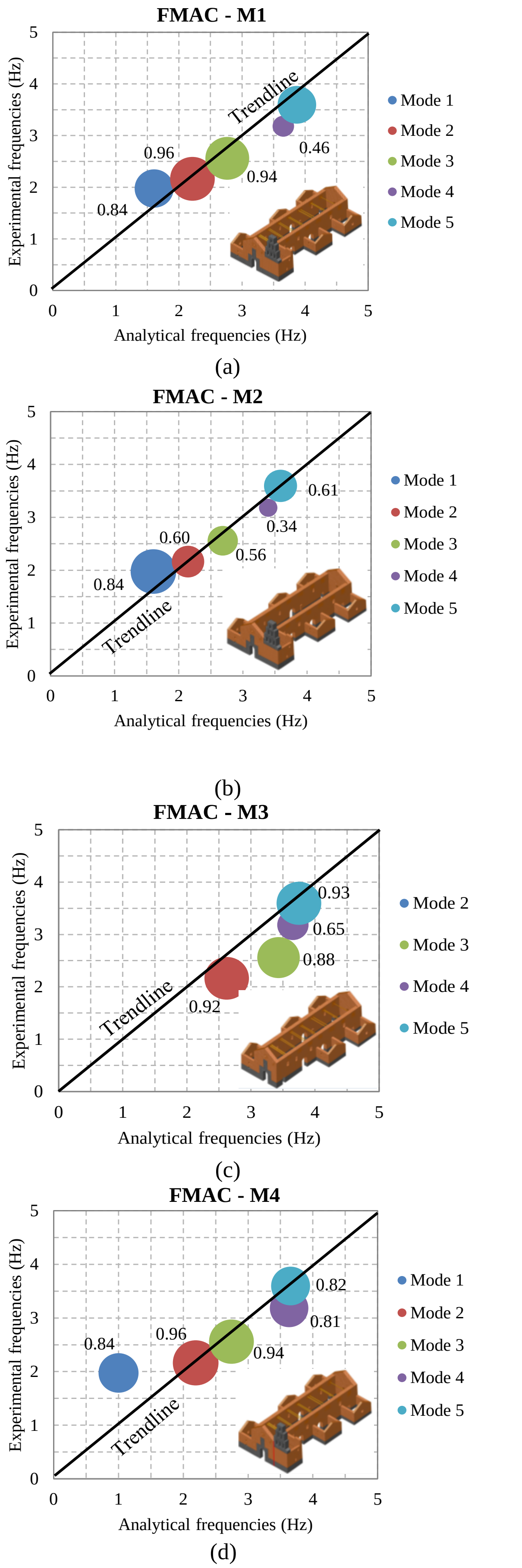

Figure 9. FMAC graphics corresponding to the church, when (a) wooden tie-beams were considered (Model M1); (b) without tie-beams (Model M2); (c) omitting belfry tower (Model M3) and (d) considering a transitional material (Model M4)

The previous numerical and experimental results evidenced that the first vibration mode is a local mode of the bell tower which is composed by a single material (stone masonry). Aiming at improving results of M4 model, a new value for the elasticity modulus of stone masonry belonging to bell tower was set to 1000 MPa. This consideration was included in an additional numerical model (M5). The resultant FMAC graphic of this last model is presented in Figure 10. As shown, improved results were obtained since the difference between the value of the first analytical and experimental frequency has been drastically reduced. This modification did not affect modal shapes and consequently MAC values in all the five identified frequencies.

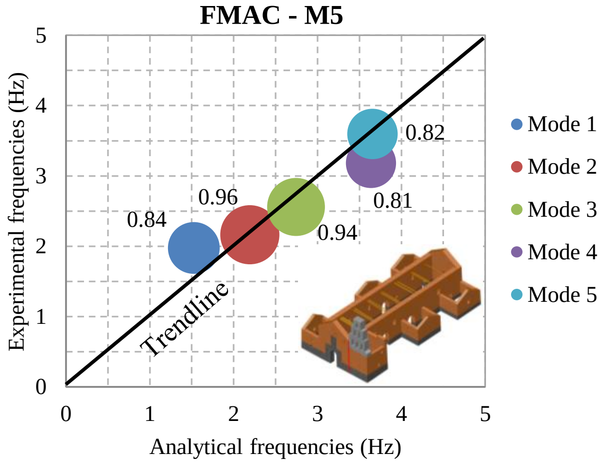

Figure 10. FMAC graphic corresponding to M5

The final verification of the accuracy of model M5 considered the use of the Coordinate Modal Assurance Criterion (COMAC) which allowed obtaining local information from measurement points and identify which points causes a low correlations between experimental and analytical modal shapes. In Figure 10a, COMAC values for the twenty degrees-of-freedom are plotted, whose positions are shown in the schematic plan of Figure 10b. The results showed low MAC values in the first eight measurement positions, which belongs to the bell tower. Results indicate that still a further and more detailed calibration is required to have a better match between experimental and numerical results.

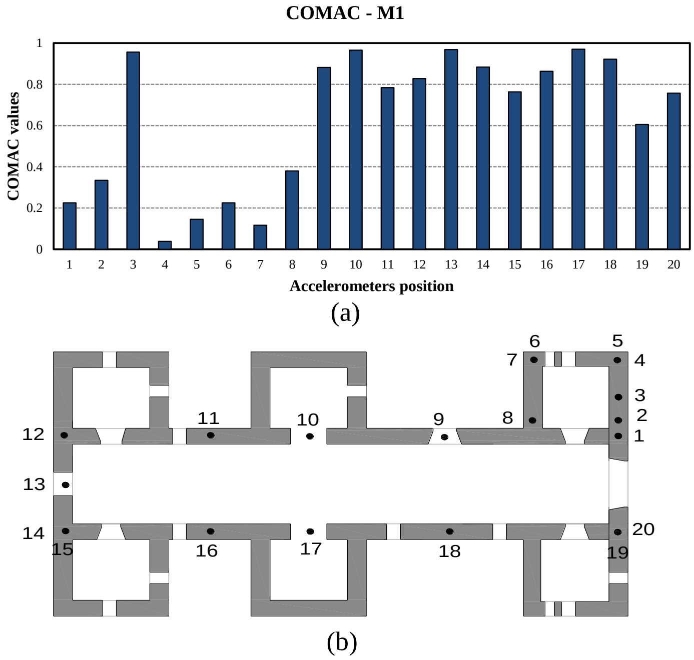

Figure 11. COMAC values for the 20 measuring points (a) COMAC graphic corresponding to M5 (b) scheme of arrangement of the accelerometers.

7 ACKNOLEGMENTS

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8 CONCLUSIONS

The church ‘San Juan Bautista de Huaro’ is a representative adobe building in the Peruvian Andean region. This paper focused on the development of a representative numerical model for future predictive analysis.

Aiming at determining an accurate geometry, a 3D reconstruction was carried out combining techniques of photogrammetry and laser scanner. The use of these two complimentary techniques showed to be very effective for fast data and reliable acquisition, as well as for covering areas that were not accessible with one or the other technique.

The numerical model of the church was implemented from a solid model built with the 3D reconstruction data. Several numerical models were built to assess the influence in the dynamic behavior of the connectivity among structural elements and the material properties. The results evidenced that the wooden tie beams effectively provide lateral constrain to the nave walls, and that there might be a poor connection between the bell tower and nave. These analyses allowed also a preliminary identification of the E-modulus of the stone and adobe masonry of the church. Future studies still need to be carried out to confirm these findings considering in the model the still missing internal elements of the tower and choir loft.

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