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APPLICATIONS OF MODERN TECHNOLOGIES FOR THE SEISMIC ASSESSMENT OF HERITAGE CONSTRUCTIONS IN PERU

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Abstract

Heritage conservation in earthquake prone areas involves the development of integrated multidisciplinary studies to understand the present state of a historical building or archaeological site, predict its structural behavior under future seismic loading, and if needed, propose appropriate intervention procedures or retrofit measures. These type of studies are challenging and require the use of innovative technologies for reliable structural assessment since historical constructions may be already affected by seismic or other types of damage, their construction records and drawings are often not readily available, sometimes the structure has been built in stages over a wide time frame, they may have unknown or difficult to define boundary conditions, the materials are not easy to characterize and sometimes units or layers are not visible, and in general their seismic analysis and evaluation often requires sophisticated nonlinear models.

This paper presents an overview of recent and ongoing studies that are being carried out by the Engineering & Heritage research group at PUCP. This multidisciplinary research group has been performing seismic assessment of multiple archaeological and historical sites in Peru using a wide variety of cutting-edge tools, such as 3D reconstruction using image collection and processing, NDT material characterization, and detailed structural analysis and seismic assessment. The paper will provide an overview of the application of these technologies to two emblematic case studies of Peruvian earthen heritage buildings: i) the archaeological complex of ‘Chokepukio’ in Cusco, and ii) the church ‘San Pedro Apostol de Andahuaylillas’ in the same city. The first case will present work carried out involving geometrical surveys with unmanned aerial vehicles and in-situ dynamic testing. In the second case, the same techniques are complemented with IR thermography. The results of these tests were integrated in both cases in numerical models that allowed predicting the seismic behavior of the studied monuments.

Keywords: Heritage buildings; Seismic assessment; Nondestructive testing, Numerical modelling

1. Introduction

The conservation of historical structures is of high importance for cultural and economic reasons. These constructions are part of the world cultural heritage and at the same time represent a major source of income from cultural tourism. In the specific case of Peru, ancient cultures left behind a magnificent legacy which is particularly expressed in their constructions. Peru is unfortunately located in one of the zones with higher seismic hazard due to the subduction of two tectonic plates which provoke constant danger to its built heritage.

Traditional conservation techniques are mainly based on empiric experience. Contrarily, as presented in [1], modern scientific approaches for the intervention in heritage buildings requires the organization of phased studies that are similar to those used in medicine. As shown in Fig.1, after defining the necessity of structural evaluation and the hazard source and level, these studies may require the application of comprehensive diagnosis methodologies which include detailed inspection, in-situ non-destructive testing, traditional laboratory experiments for material characterization, in depth numerical analysis and the verification of the effectiveness of the intervention solutions through long-term monitoring processes.

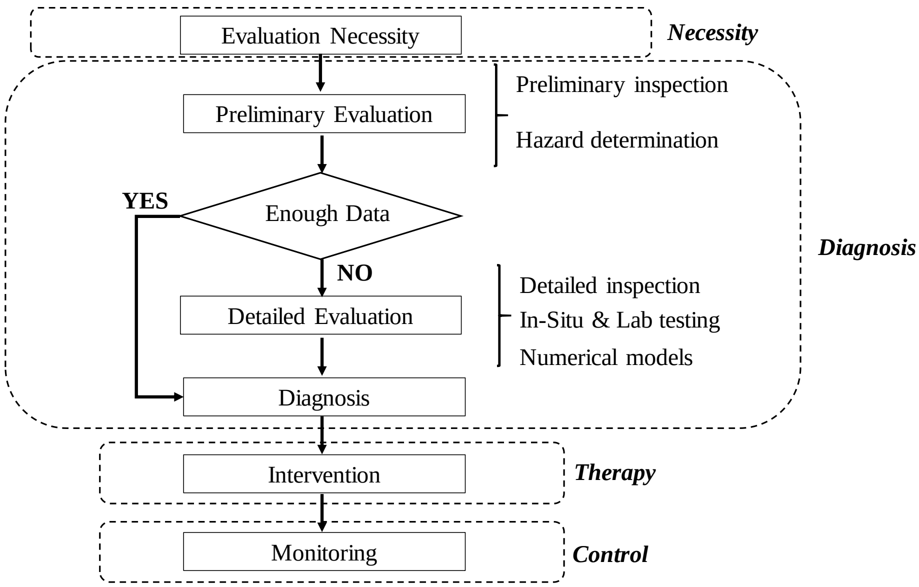


Fig. 1– Schematic view of a structural intervention in heritage buildings (adapted from [1])

The present paper presents two case studies where new technologies were applied in a framework of seismic behavior assessment. In both cases, aerial photogrammetry is combined with in-situ Operational Modal Analysis (OMA) and IR thermography to produce geometry, material, and state-of-damage information that is later integrated in numerical models where seismic assessment is carried out through equivalent static nonlinear analyses.

2. Case Study 1: Seismic Assessment of Archaeological Heritage Using Modern Technologies

2.1 Description of the case of study

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, as shown in Fig.2, presents a special architecture with walls forming enclosures around open spaces. The perimeter walls were of around 12 m high and had trapezoidal and rectangular niches at different heights. The masonry found in Chokepukio was made of semi rounded stones with irregular joints of mud and straw mortar that range between 25 and 100 mm [2]. Unfortunately, this complex is severely damaged due to past earthquakes 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.

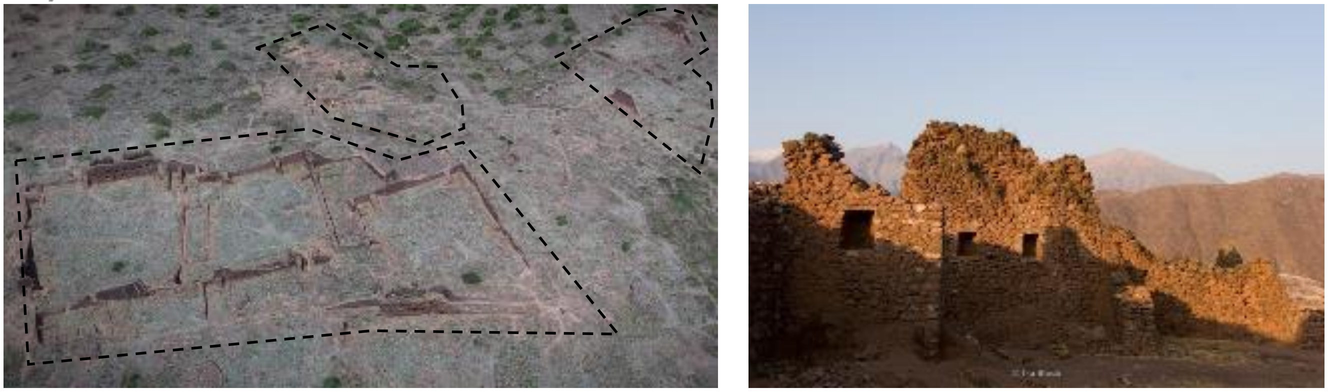
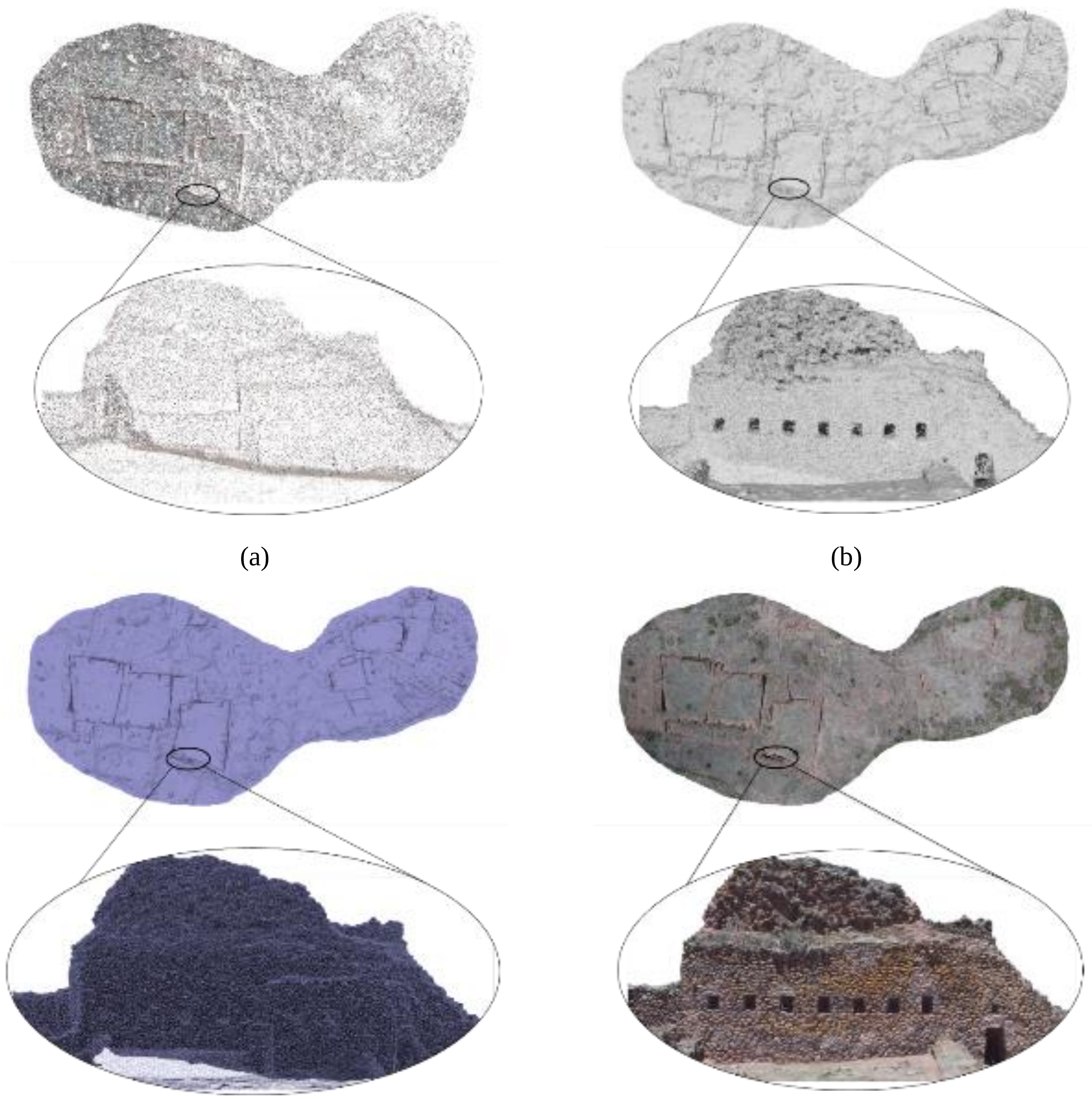


Fig. 2– Aerial photography and architectural details of the archaeological complex of Chokepukio

2.2 Geometrical survey using photogrammetry

The methodology used to generate the digital model of Chokepukio is known as photogrammetry. The photogrammetry is a modeling technique capable of generating 3D models from 2D images. During the last 20 years, intense investigations have taken place about the extraction of information from digital images which allowed a fast development of image processing algorithms [3]. The most used algorithms on photogrammetry are Structure from Motion and Dense Multi View Reconstruction [4]. These algorithms allow digitalizing high quality 3D models from a collection of organized and overlapped digital images [5] that describe an object or structure from different angles [6]. These algorithms incorporate also the alignment process of all the images to generate a point cloud that represents the geometric surface of the digitalized object [7]. Photogrammetry is commonly used for digitalization of 3D models on various applications due to its fast data collection process and the low prices of the devices involved [7,8].

There are different options for the acquisition of digital images: Unmanned Aerial vehicles (UAV_s) for aerial photography and terrestrial cameras for ground-level photos. For the present investigation, the 3D reconstruction was carried out using only aerial photography. The device used was a DJI Quadcopter Model Inspire 1 (www.dji.com/). This aerial vehicle has an integrated 12 megapixel camera and a 20 mm lens. Data processing was carried out using the software Agisoft Photoscan [9]. A total of 103 aerial photographs were captured on the archaeological complex. The inclination angle of the camera was -90°. The average distance between the camera and the surface was 72m, and the average distance between each photo was 25m. The generation of the 3D model was then performed by first, the image alignment and then the generation of a spread point cloud, conformed by all the common points identified among each picture (Fig.3a). By using the spread point cloud as a reference, a dense cloud was generated with the geometric information of the surface of the complex (Fig.3b). Later, a triangular meshing procedure of the entire digitalized complex was generated through the process of point triangulation (Fig.3c). Finally, the result obtained is a 3D texturized digital model based on the information from the acquired aerial photographs (Fig.3d).



(a) (b) (c) (d)

Fig. 3–Process of 3D model generation: a) image alignment and spread point cloud generation; b) generation of dense cloud; c) generation of triangular mesh; and d) generation of the texturized model

2.3 Operational modal analysis and numerical modelling

The aim of this study was to assess the structural behavior of a wall located on a well preserved sector. The studied structure consists of a stone masonry wall with an irregular geometry with more than 20m of length, 9m of high and a variable thickness of 1.20m – 1.80m at the base and 0.60m – 0.80m at the upper part. The base is composed by a masonry system with big stones units and thin mud mortars while the upper part is composed by smaller stone units and thicker mortars.

As shown in Fig 4, OMA tests were carried out through the instrumentation of the wall with high sensitivity (10 V/g) accelerometers and high resolution (24 bits) data acquisition equipment. The experimental program allowed the determination of the first seven natural frequencies and vibration modes that ranged among 1.9 Hz and 9.2 Hz (see more details in [10]).

Fig. 4–Studied area and experimental setup during the Operational Modal Analysis tests

A Finite Element (FE) model was next implemented using solid elements with homogeneous properties considering two different materials, one for the lower part and one for the upper part of the wall (coinciding with the change of section). An optimization and calibration process was then carried out using the Douglas Reid method [11] aiming at matching the numerical and experimental results of the first four natural frequencies and modal shapes. The selection of appropriate calibration variables was made through a sensibility analysis which showed that the most important parameters to consider were the elasticity modulus (affected the results of the natural frequencies), and the geometry and specific weight of the material (affected the modal shapes). As shown on Fig. 5, the calibration process allowed obtaining a model that adequately represented what was registered on the field. As shown on Table 2, the final values obtained for the mechanical properties of the material show a clear difference on the quality on the lower and upper masonry of the wall (verifying what was observed on the field).

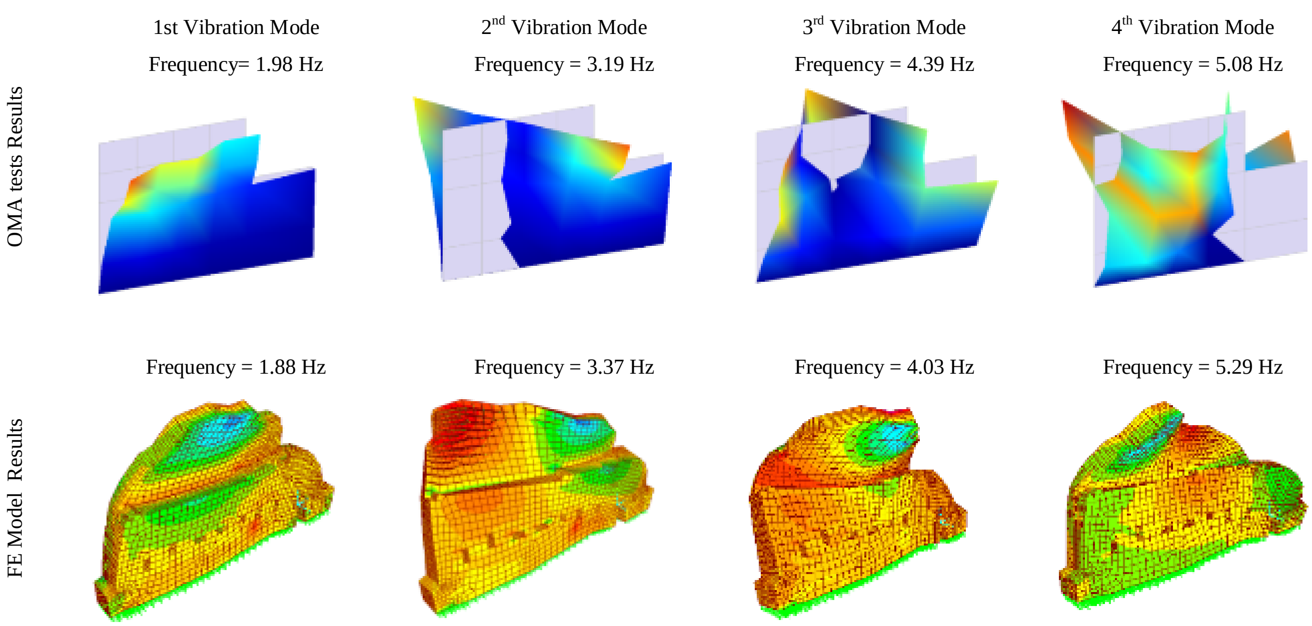


Fig. 5–Final Results of the calibration process of the numeric model (adapted from [10])

Table 1 –Initial and final values for the materials mechanical properties obtained on the process of calibration of the FE model in Chokepukio

Calibration Parameters	$E_{\text{lower part of the wall}}$ [MPa]	$E_{\text{upper part of the wall}}$ [MPa]	$\gamma_{\text{Lower part of the wall}}$ [N/mm^3]	γ upper part of the wall [N/mm^3]
Initial Values	800	800	269E^{-3}	269E^{-3}
Final Values	644	427	343E^{-3}	317E^{-3}

2.4 Seismic capacity assessment

Static non-linear analysis is a simplified method to evaluate the seismic response of buildings through the simulation of a unidirectional lateral static increasing load that acts on the structure [12]. In this work, this analysis was performed to identify the critical sections and possible collapse mechanisms of the studied wall. As shown in [10], the non-linear behavior of the stone masonry was determined from empiric relations with the elastic properties determined through the calibration process of FE model and OMA tests. The analysis considered a constant gravity load and a lateral load pattern proportional to the mass. Fig. 6 presents the evolution of the mechanism of the wall when it is submitted to a lateral load. As shown, the cracking associated to tensile stresses in bending develops simultaneously at the base of the wall and the upper section (where the thickness transition exists). On the next phase, the crack propagates on altitude but a concentration of fissures propagates to the interior of the section at the base. On the next phase it is observed that liberation of stresses take place on the upper section and that the development of a global balancing mechanism initiates. Finally, the mechanism evolves with the total damage that corresponds to a complete overturning with the propagation of the cracking pattern inside the wall at the base.

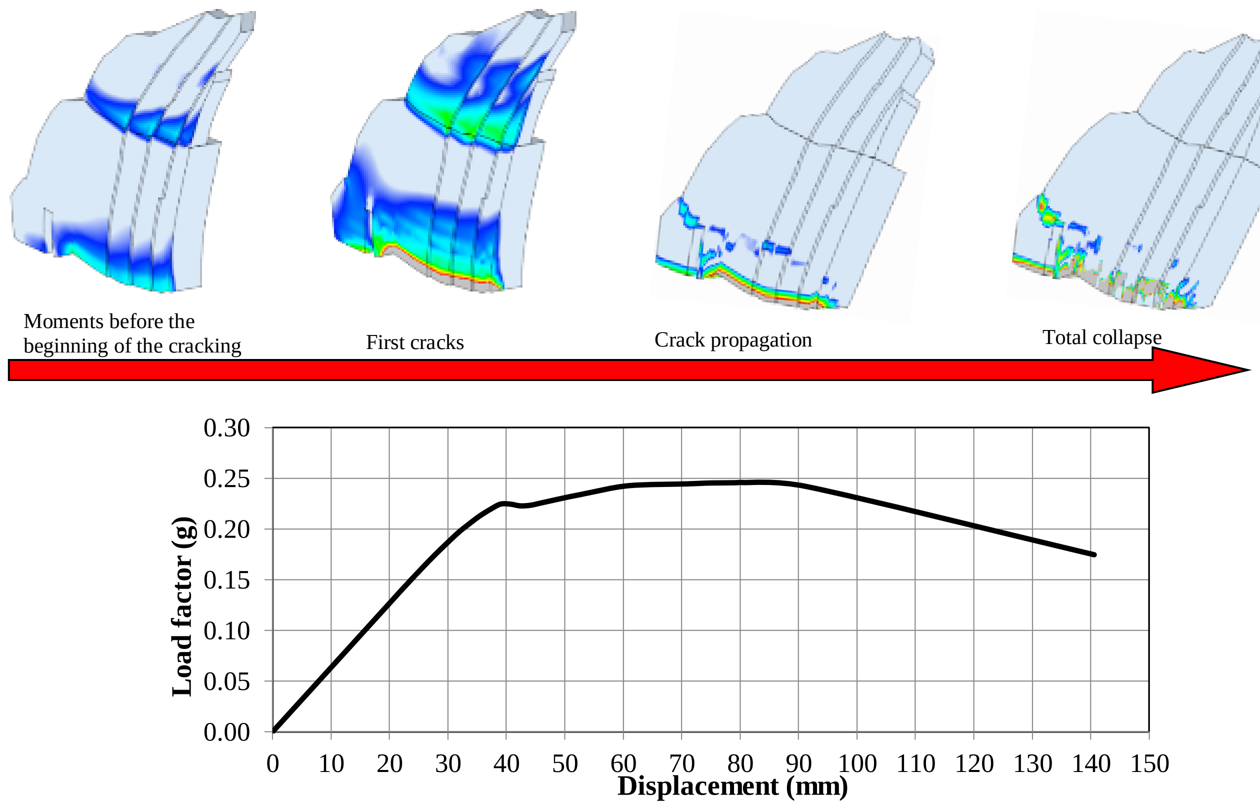


Fig. 6–Evolution of the collapse mechanism and capacity curve of the studied all at Chokepukio (adapted from [10])

3. Case Study 2: Seismic Assessment of Historical Heritage Using Modern Technologies

3.1 Description of the case study

Andahuaylillas is a small town located 40 km from Cusco that shows a typical outline of colonial beginnings; narrow stone streets and adobe houses of one and two floors. The 'San Pedro Apostol de Andahuaylillas' church was built approximately on 1610 and is located on the main square of this town. The architecture presents renaissance characteristics with mannerist style influence, mainly on the mural decoration [13]. The church has a main nave consisting of a rectangular plant of 10m x 55m and 13m of high, one bell tower of 5 m x 5 m in plant and 18 m of high, and seven lateral chapels. The structural system of the main nave and bell tower are adobe walls ranging from 1.5 m to 2 m of thickness. The foundation is made of stone masonry with mud mortar with a depth of 0.50 m. The roof is a particular A-shape truss timber structure with a decorated ceiling underneath.

3.2 Geometrical survey using photogrammetry and laser scanner

A total of 162 aerial photos were taken in Andahuaylillas church. The inclination angle of the camera used was -45^{O}. For more general images, it was used an average distance from the camera to the surface of the church of 20 m and the distance between photographs of 15 m. For detailed images, the average distance from the camera to the surface of the church was 10 m and the distance between photographs was 5 m. The flight plan consisted on surveying the church at different heights and focusing on the corners of the side chapels because they were hampered by trees. Laser scanner survey was also executed by means of 49 separate sessions with scanning distances of 5 m – 10 m between each other. The scan sessions were conducted inside and outside the church to capture all the possible details of the structure. Each scan session took an average time of 15 minutes, which resulted in a total of 16 hours of data acquisition. Fig. 7 shows the complete 3D model generated combining the exterior model obtained with aerial photogrammetry and the interior model obtained with laser scanner.

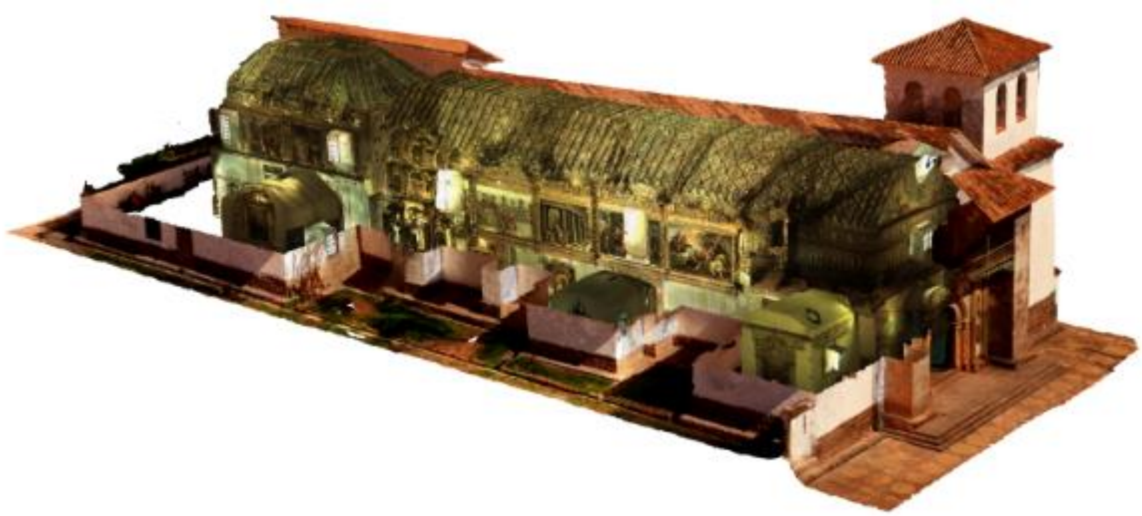
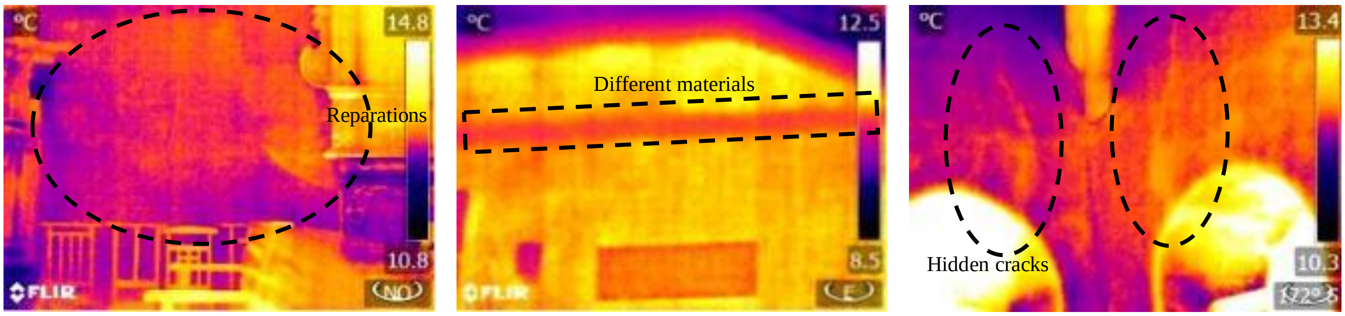


Fig. 7–3D reconstruction of the Andahuaylillas church

3.3 Thermography for the structural diagnosis

The church had undergone repetitive interventions, especially in the last 50 years. Unfortunately, most of them were aesthetic and their effect was only to hide the structural damage of the church [14]. In a detailed visual inspection on 2012, some major anomalies were found: large cracks in the triumphal arch, severe cracking patterns in some walls of the presbytery, cracks in the Baptistery's lintel and on the main façade, deflection and deterioration in some structural timber elements (especially in the tie rods that connect the lateral walls in the nave and the supporting system of the choir and exterior balcony).

To complement the initial visual survey, Infrared (IR) Thermal Imaging was carried out aiming at identifying hidden reparations, change of materials, hidden cracks, and presence of humidity. The technique of IR thermography allows the identification of differences in surface temperature caused by changes in heat flow [15], which could indicate anomalies in the structure. Passive IR thermography approach was considered for the experimental program carried out in July, 2015. All the tests were carried out while the exterior temperature was around 8°C higher than the interior temperature of the church. For the tests, a FLIR Infrared Thermal Imaging Camera model T440 [16] was used. IR thermography allowed the identification of reparations, insertions of different elements, changes in materials, and cracks that were hidden with recently renewed plaster. Embedded timber beams were detected in the transitions of walls and tympani in the lateral chapels. Cracks were identified on the walls near the connections of timber beams and roofing system. Several cracks with a scattered distribution were also identified on the back façade wall. Diagonal cracks near openings (windows and doors) were also found. Fig. 8 shows three types of the more common structural anomalies found in the field survey.



(a) (b) (c)

Fig. 8– Results of the experimental program with IR thermography (adapted from [17]): (a) evidences of reparations in walls; (b) evidences of different materials in the walls of the chapels; and (c) evidences of cracks in the bell tower

The visual inspection and experimental program with IR thermography allowed the identification of the most damaged areas in the church. Fig. 9 summarizes these results showing that the damaged areas are located in the bell tower, triumphal arch, front façade, choir, and connections of timber tie rods and adobe walls in the main nave. Vulnerable mechanisms were also identified as possible out-of-plane failure of the tympani of the front and back façades.

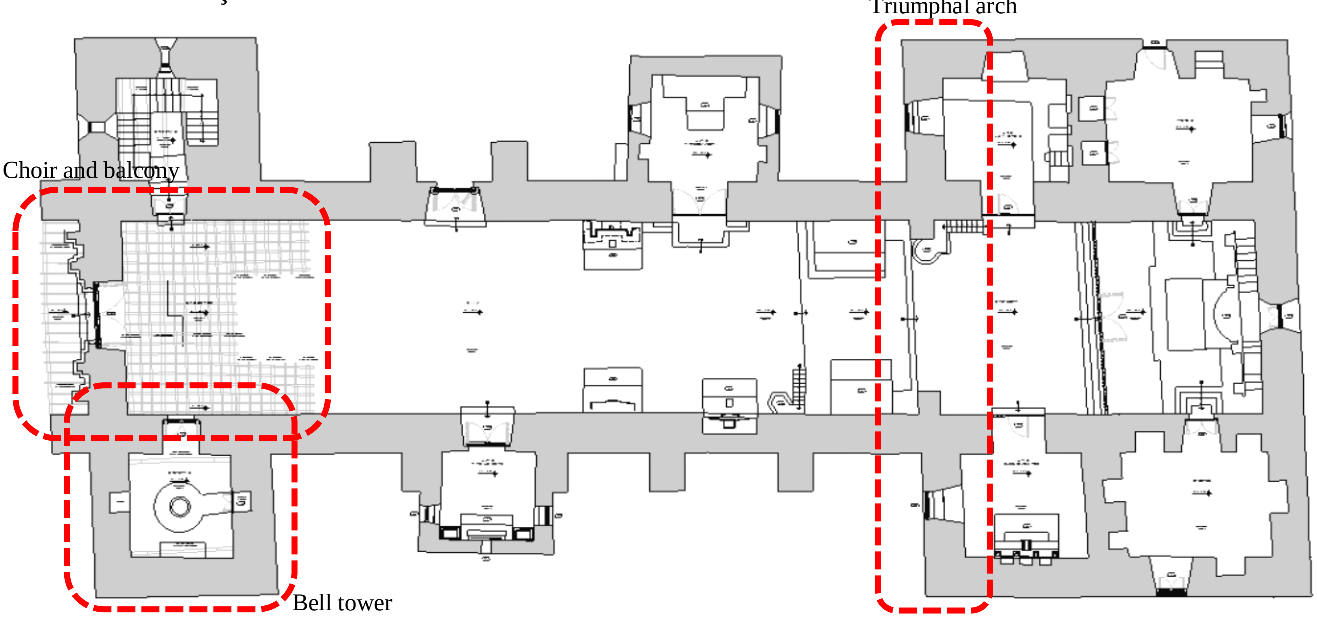
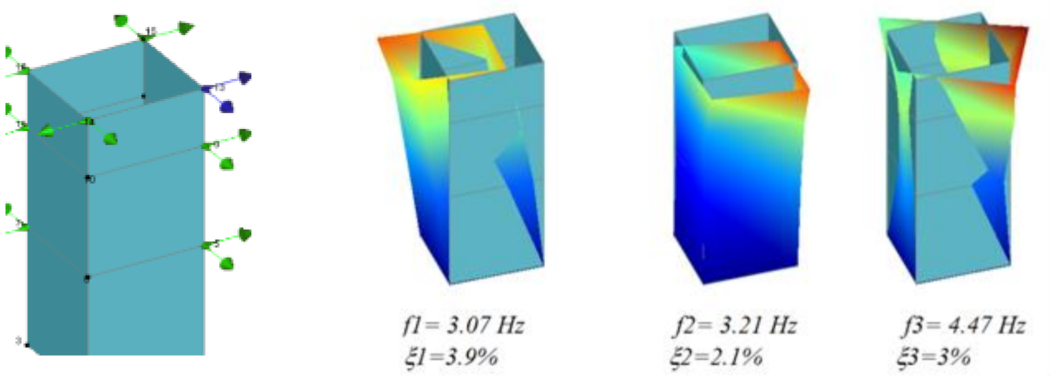


Fig. 9–Results of most damaged areas in the church after visual inspection and IR thermography

3.4 Operational modal analysis

As part of a preliminary study carried out on 2013, OMA tests were performed in the bell tower of the church to estimate its dynamic properties. Eight measuring points according to a biaxial configuration were established in seven setups, considering two fixed and two rowing sensors. The transducers used were four piezoelectric accelerometers with a sensitivity of 10 V/g and a dynamic range of ± 0.5 g together with an USB-powered 24 bits resolution data acquisition module. The data processing was carried out using the stochastic subspace identification method (SSI) implemented in the Artemis Software [18]. The results in terms of the identified first three mode shapes are displayed in Fig. 10 (more details can be found in [19]).



(a) (b)

Fig. 10–Modal identification tests in the bell tower: (a) general test setup and (b) first three mode shapes (adapted from [19])

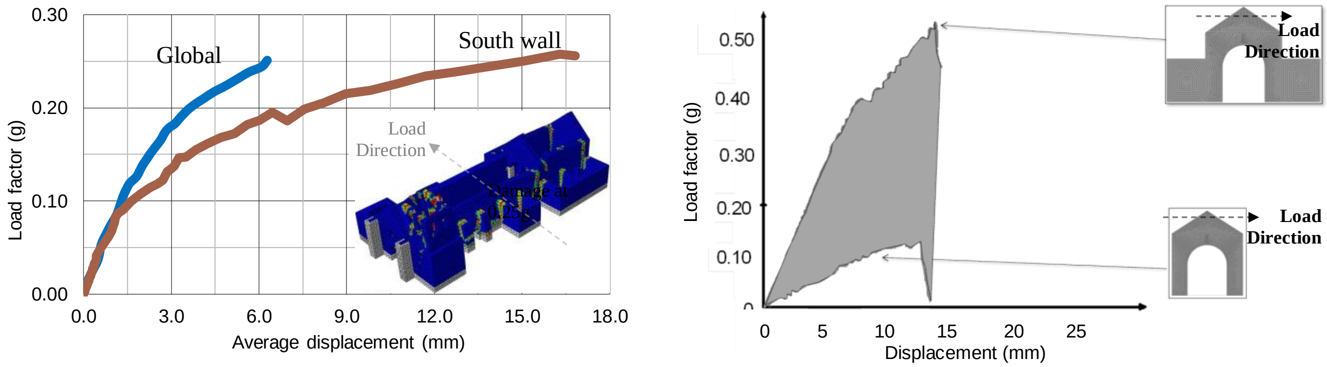
A FE model was then implemented considering the adobe masonry as a homogeneous material. With the results of an Eigenvalue analysis, the model calibration was carried out comparing the modal response measured in the field and the numerical model. At the end of the calibration process, a high correlation was observed between the numerical model and experimental results. The first three modes shapes have Modal Assurance Criterion - MAC [20] values of 0.95, 0.97 and 0.75, respectively. The final material properties resulting from the calibration process are presented in Table 2.

Table 2 – Material properties obtained for the church after the calibration process

Material	Specific weight, ɣ (KN/m3)	E-modulus (MPa)
Adobe masonry (walls)	15.1	350
Rubble stone masonry (foundation)	24.0	800
Timber elements (roofing system)	4.7	10,000

3.5 Seismic capacity assessment

As in the previous case study, a pushover procedure was carried out to assess the seismic capacity of the entire church and a particular substructure. The constitutive laws of the materials in compression and tension were also defined based on empirical relationships from the linear elastic properties defined in the previous section (more details can be found in [21]). As shown in Fig. 11a, the global analysis of the church was carried out in only one direction and the results show that the maximum lateral capacity of the building may be around 0.25 g. Ongoing studies are being carried out to assess the capacity in the four perpendicular directions which will also allow identifying out of plane mechanisms. For the analysis of vulnerable substructures, the triumphal arch was selected due to the clear evidence of severe damage. A parametric study was carried out in this case considering different geometrical considerations such as the non-existence of lateral buttresses (formed by the walls of the chapel), lateral windows, and the tympanum. As shown in Fig. 11b, the result of this analysis is an envelope of a capacity curve defined by the extreme conditions. This analysis show that the lateral capacity can have large variation and that the maximum resistance can be from around 0.15 g to 0.50 g depending on the structure configuration.



(a) (b)

Fig. 11–Lateral force capacity curves for: (a) entire church; and (b) triumphal arch

4. Conclusions

The combination of modern technologies such as UAV_s, in-situ non-destructive testing and advanced numerical modelling are a powerful tool for the study of historical and archaeological heritage. In the specific case studies shown in the present article, it is clearly reported the advantages of rapid geometrical survey with UAVs, in-situ experimental testing with Operational Modal Analysis, structural diagnosis with IR thermography, finite element modelling and static non-liner analysis all integrated in a global tool for seismic capacity assessment. The application of broad scale analyses can be time consuming but they are of particular importance for the application of modern conservation criteria in heritage buildings. The results in both case studies allowed for instance understanding failure patterns which can be translated in future less intrusive interventions. The results also evidence that when dealing with heritage buildings there is the necessity of combining global studies with the analysis of sub-structures/sub-elements that can motivate vulnerable mechanisms or local failures.

5. Acknowledgements

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