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SEISMIC ASSESSMENT OF THE ST. PETER APOSTLE CHURCH OF ANDAHUAYLILLAS IN CUSCO, PERU

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Abstract. *The Saint Peter Apostle church of Andahuaylillas, in Cusco, is an emblematic example of a large number of early colonial adobe churches in Peru. The church is comprised of a main nave, six chapels and a bell tower, and features a typical 'par y nudillo' roof system. Although this monument is considered to be one of the most important churches due to its historical, architectural and artistic features, the investigation of its seismic behavior has received almost no attention even though the church is located in a high seismicity zone. This paper presents a study on the structural modeling and the seismic assessment of the Andahuaylillas church. The research is based on in-situ operational modal analysis (OMA) tests and subsequent numerical modeling. Finite element (FE) models of the church developed in DIANA and Abaqus/CAE, were calibrated through a sensitivity analysis, to approximate experimental frequencies and mode shapes. A damage plasticity model of adobe masonry was adopted for the non-linear FE analysis in Abaqus/CAE to evaluate the overall response of the church due to non-linear static (pushover) and dynamic (base motion ground acceleration) loading conditions. The pushover tests confirm the weakness in tension of the wall connections, and the concomitant onset of separation and independent behavior of structural parts of the church. In addition, the dynamic tests indicate the vulnerability in tension of the bell tower, the triumphal arch and the wall connections to continued ground motions.*

1 INTRODUCTION

Construction with adobe is a traditional feature of Peruvian architecture, mostly associated with archaeological remains of pre-Hispanic monuments, the 'huacas', as well as with traditional adobe housing in mountainous regions. However, adobe was also a preferential material for the construction of churches across colonial Peru, and particularly in the Andean region during the baroque period. The church of St. Peter Apostle in Andahuaylillas is one of the masterpieces of Andean adobe architecture (Figure 1). This monument is part of the Andean Baroque Route, a cultural itinerary which includes several churches of great cultural and artistic value belonging to the baroque artistic movement. These churches feature a complex architecture, and are particularly popular because of their magnificent paintings. The Andean Baroque Route is of great importance for the tourism in Peru.

Historic masonry buildings have been studied since the 1990's in Italy and Portugal. These studies and the experience of subsequent interventions on masonry constructions have markedly expanded the knowledge of masonry building materials and construction processes [1]. The decisions concerning the rehabilitation and restoration works aiming at preserving these constructions require a diagnosis of the current state of the structure. This step is fundamental prior to any intervention, because the effects of the intervention itself are difficult to predict and could negatively impact the structure.

The engineering modeling and analysis of masonry buildings are very complex tasks, since hypothesis of homogeneity, elastic behavior, and isotropy, which are commonly assumed for materials like steel or reinforced concrete, are not acceptable for masonry [2]. Masonry presents a highly nonlinear behavior which requires the definition of complex constitutive laws. Furthermore, the current condition of an existing masonry construction is itself a source of nonlinearity, thus requiring information about the geometry, crack patterns, foundation settlements, and other anomalies. Knowledge of the materials and corresponding mechanical properties is important for a proper structural evaluation. In order to obtain such information, it is necessary to apply a scientific method, which includes qualitative as well as quantitative approaches. In general, this involves the collection of historical information, inductive investigation, experimental tests, and structural analysis.

This paper presents a series of investigations to evaluate the seismic behavior of St. Peter Apostle Church of Andahuaylillas. First the church is briefly described in its historical, architectural, and structural aspects. Next, details of dynamic tests carried out on the bell tower are reported and the process for finite element (FE) model calibration is discussed. Finally the results of FE pushover and base motion (ground acceleration) analyses are presented.

2 ST. PETER APOSTLE CHURCH OF ANDAHUAYLILLAS

St. Peter Apostle Church, shown in Figure 1(a) dominates the main square of the village of Andahuaylillas, located about 41 km southeast of the city of Cusco. The church is of great significance for the preservation of the local culture in Andahuaylillas [3]. According to Castillo et al. [4] the construction of the church dates from the late 16th or early 17th century, an assumption that is accepted based on the style of the paintings in the church interior. The church covers an area of 27 m x 61 m, including the nave and the presbitery, the bell tower and several side chapels. The main nave connects to the baptistery, the bell tower, the choir loft, and two chapels. The presbitery is separated from the nave by the triumphal arch and opens on four side rooms. The second level of the church consists of the choir loft and an open chapel.

The structure of the Andahuaylillas church is composed mainly of adobe walls with an average thickness of 2 m. The walls corresponding to the nave body present an average height of 10 m while those in the presbitery are about 12 m high. Wooden tie-beams and (un-tensioned) steel tie-roads connect the longitudinal (north and south) walls. The adobe walls have a stone masonry basement 1 m high. The church has buttresses located in the front facade and side walls. The buttresses in the front present an adobe core covered with stone masonry ashlars, while the side ones are entirely in adobe. Similarly to other churches in the Cusco area, the adobe bricks are supposed to be set in an English bond pattern, with alternating courses of header and stretcher bricks [5]. The roof structure of the church is composed by two wood framing sub-systems: 'par y nudillo' and 'sobre par'. Both systems consist of a triangular arrangement of wooden elements, spanning approximately 12 m across the walls of the nave. The 'par y nudillo' framing covers the nave internally and is composed by trusses formed by two rafters joined with a collar tie, positioned at one-third of the truss height.

The church has undergone conservation works, especially in the last 50 years, which have negatively affected the monitoring of structural behavior by hiding the deeper damage of the church [6]. Deep cracks in walls of the presbitery and the chapels, and in the triumphal arch have been identified. A map with the major damage occurrences in the church is presented in Figure 2. For example, a large opening is observed in the south wall next to the triumphal arc and diagonal deep cracks are identified in the tympanum above the triumphal arch, possibly due to delayed effects associated to self-weight load.

(a)

(b)

Figure 1: St. Peter Apostle Church of Andahuaylillas: (a) front view and (b) interior panorama.

3 OPERATIONAL MODAL ANALYSIS

Ambient modal identification, also known as Operational Modal Analysis (OMA) [7], offers a useful approach to study earthen historical constructions, since it allows for the identification of structural conditions, such as local damage [7]-[8]. In this study, OMA tests were carried out in the bell tower of the Andahuaylillas church, in order to estimate the dynamic characteristics of the entire structure. The tests were performed in the tower in order to capture a higher amplitude of the modal response. These measurements were then used to calibrate the accuracy of the FE models developed for the structural evaluation of the church and for its seismic assessment.

The OMA tests in the bell tower were carried out by using the ambient noise as the excitation source. Eight measuring points according to a biaxial configuration were established in seven setups considering two fixed and two rouing sensors, as shown in Figure 3(d). The transducers 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 (Figure 3(a)-3(c)). In each setup, the sampling rate and sampling time were set to 200 Hz and 10 min respectively. The data processing was carried out using the stochastic subspace identification method (SSI) implemented in the Artemis Software. The first three mode shapes identified in the tests are shown in Figure 3(e).

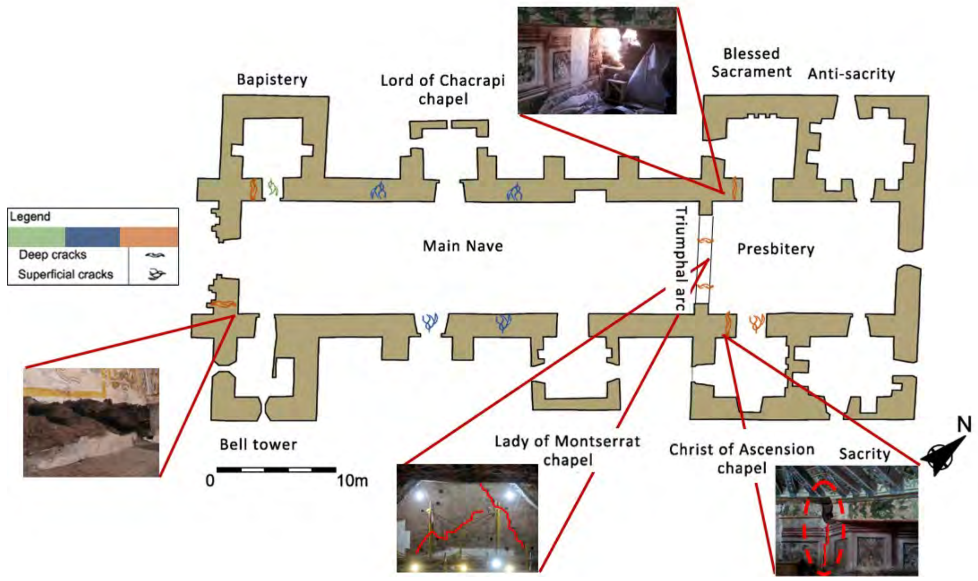


Figure 2: Mapping of the major pathologies observed in the church.

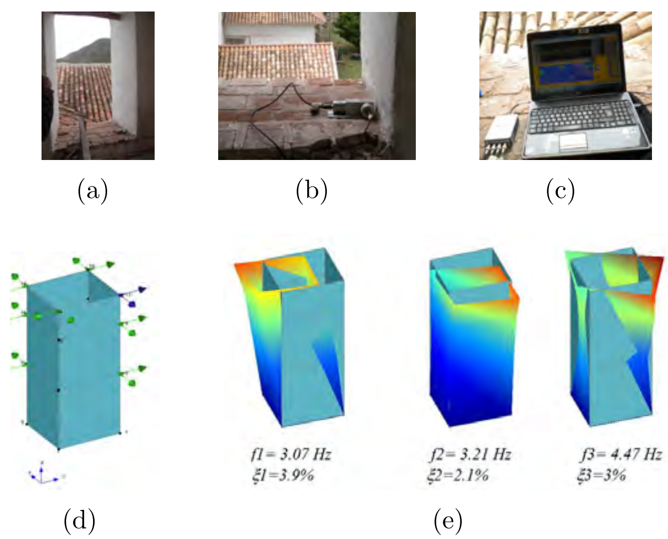


Figure 3: Modal identification tests in the bell tower: (a) view of the instrumented zone, (b) detail of sensors arrangement, (c) acquisition station, (d) general test setup and (e) first three mode shapes.

4 NUMERICAL MODELS AND CALIBRATION

The reliability of numerical models in simulating the structural response of buildings is determined by several factors, such as material properties and boundary conditions, which need to be calibrated. For the church, the model calibration is based on a modal analysis approach, for which the structural response is considered to remain in the elastic range. Since the composition of adobe bricks and mud mortar are similar, the adobe masonry is assumed to be a homogeneous material [9], amenable to a continuum finite element (FE) approach. The elastic properties of materials are assumed on the basis of the recommendations given in [9] - [10], according to the values presented in Table 1. Taking into account its significantly deep foundations, the church is considered to be fully constrained at the bottom face of the stone masonry basement.

Table 1: Elastic properties of materials.

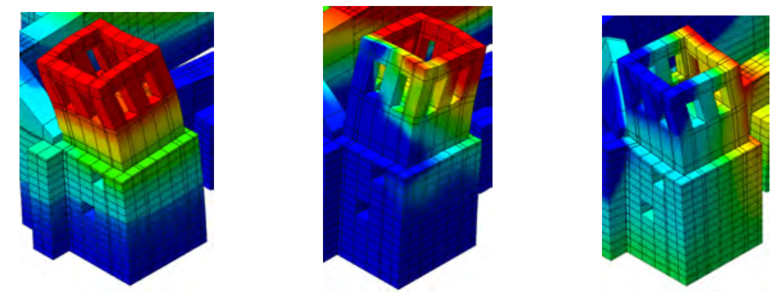
Material	Specific weight, w (kN/m3)	Elastic modulus, E (MPa)	Poisson ratio, ν
Adobe masonry	15.1	350	0.25
Rubble stone masonry	24.0	800	0.20
Wooden elements	4.7	10000	0.20

In order to establish a comparative approach, finite element models of the church were developed in DIANA [11] and Abaqus/CAE [12] softwares. In DIANA, the adobe walls as well as the stone masonry basement were modeled using approximately 74,000 eight-node isoparametric brick elements of type HX24L. In Abaqus/CAE, the complete model of the church was comprised of approximately 72,000 ten-node modified quadratic tetrahedral elements of type C3D10M. The roof was not modeled due to the complexity of simulating the relative rotation and the sliding in the wood connections [9]. The complete models of the church have a mass of about 8,550 tonnes each.

The models were calibrated via a sensitivity analysis of the material properties and the boundary conditions, by comparing the results of FE modal eigenvalue analysis to those of the OMA experimental tests. To compare the experimental and numerical mode shapes and frequencies, the Modal Assurance Criterion, MAC [13] and Frequency scales with MAC representation, FMAC [14] were used. The MAC allows for the establishment of a relation between the experimental and numerical modal vectors (MAC values range from 0 to 1, with 1 indicating a perfect match), while the FMAC is used to compare experimental against numerical frequencies and MAC values in a single graphical representation.

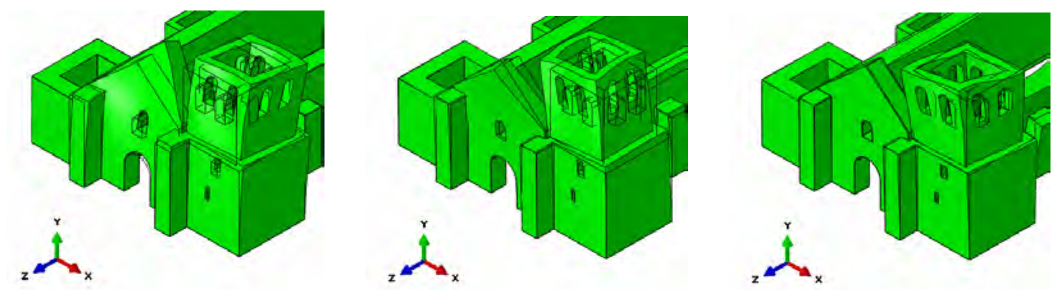
The calibration process for the DIANA model is presented first. The mode shape and frequency results in Figure 4 show that high correlation is seen between the numerical model and experimental results. The first two modes shapes have MAC values of 0.95 and 0.97 respectively. The third modal shape, which is mostly associated with torsional deformations of the bell tower, presents a moderated approximation to the corresponding experimental mode (MAC = 0.75). The prediction is acceptable on the basis that the church presents a complex structure and unknown features, particularly the existence of deep damage and the effectiveness of connections between structural elements. Thus, the numerical model developed in DIANA is considered representative of the church when responding in elastic range.

The results of the modal analysis with the equivalent Abaqus/CAE model are similar to those obtained using the DIANA model. Figure 5 shows the three modes shapes of the tower which are all within 3% of their corresponding experimental modes in terms of frequency. The first two bell tower modes have MAC values of 0.97 and 0.96 respectively while the third bell tower mode MAC value is 0.76. These three MAC values and the bell tower frequencies demonstrate the equivalence of the DIANA and Abaqus/CAE models. A comparison of the FMAC plots from the DIANA and Abaqus analyses is shown in Figure 6. Hereafter the Abaqus model is adopted for the seismic nonlinear analyses.



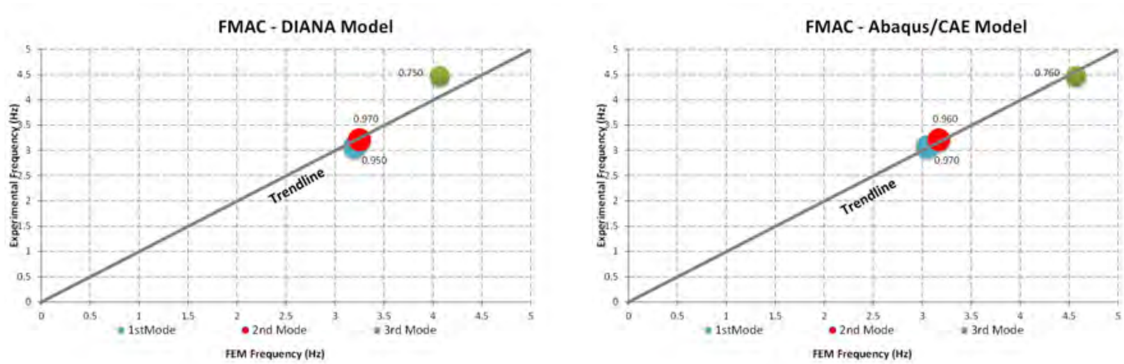
(a) 1^{st} Mode: 3.20 Hz (b) 2^{nd} Mode: 3.25 Hz (c) 3^{rd} Mode: 4.07 Hz

Figure 4: Modal analysis results of the church: (a-c) first three mode shapes.



(a) 1^{st} Mode: 3.05 Hz (b) 2^{nd} 3.17 Hz. (c) 3^{rd} 4.57 Hz.

Figure 5: Modal analysis results of the church using Abaqus/CAE.



(a) FMAC DIANA (b) FMAC Abaqus

Figure 6: Comparison of FMAC plots determined from the DIANA and Abaqus analyses.

5 PUSHOVER ANALYSIS

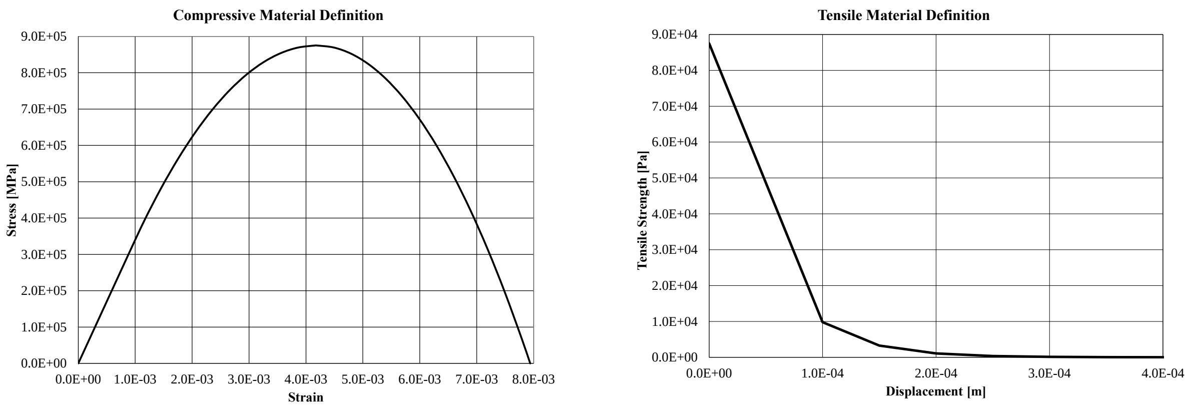
The church is at risk since it is located in a high seismicity region - consider for example the 1950 Cusco earthquake - but until now the structural aspects of the building have received little attention, particularly regarding seismic events. The building is inherently vulnerable since it presents a structure without box behavior (i.e. with poor structural connections and no horizontal diaphragms) [14]. In addition, it is subjected to deterioration which causes weakening and even loss of connection between structural elements.

A pushover analysis, usually performed to capture the global response of a structure, has been developed as an acceptable approach for assessing the damage sequence. The analysis is helpful to identify critical zones in order to proceed with local implicit safety verifications, e.g. through kinematic limit analysis [14], and to support seismic retrofitting. In addition to pushover analysis, the seismic assessment of an existing structure requires a multiple-view analysis approach, using different methods to cross-validate one method against the others, for example by comparing FE results with those of macro-element models [15]. For the Andahuaylillas church, pushover analysis was performed using an explicit formulation and adopting the concrete damage plasticity model available in Abaqus/CAE.

Using published results ([16], [17], [18]) the material strength properties were estimated as follows. The compressive strength was taken as $f_m = E/400$, where E is the Young's modulus (calculated as 350 MPa in the previous section), and the tensile strength is $f_t = f_m/10$. Thus $f_m = 0.875$ MPa and $f_t = 0.0875$ MPa. Considering the ductility factor of 1.6 mm [17], the compressive fracture energy was estimated as $G_m = 1.6 \times f_m \approx 1.4$ Nmm^{-1}. Finally, extrapolating from the experimental results in [16]-[17], the tensile fracture energy is assumed to be $G_f = 0.004$ Nmm^{-1}. The material laws in compression and tension are assumed respectively to follow parabolic and exponential curves [17], as shown in Figure 7. The static analysis, performed in Abaqus explicit is comprised of two dynamic explicit steps: gravity (1g) is applied first, followed by a horizontal force distribution proportional to the mass up to 0.25g (2.45 m/s^2) that is applied perpendicular to the nave in the northern direction (negative x direction).

The contour plot in Figure 8(a) maps the tensile cracking in terms of a damage parameter, where 0 means that no damage has developed while 1 indicates that the material is completely damaged. The displacement in the south side of the church inevitably causes tensile damage to develop in the wall connections between the side rooms and the nave and presbitery walls. The buttresses are also separating from the wall. In contrast, the buttresses and room walls located on the northern side restrain the displacement of the nave wall. In addition, three other areas develop tensile damage: the northwest corner of the bell tower, the west and east ends of the southern nave wall and the northeast corner of the presbitery. The triumphal arch which separates the nave and the presbitery presents low damage throughout the pushover analysis.

An additional pushover analysis was performed on a reduced model of the church in which the side rooms and nave buttressing were removed in an effort to determine how the structural response changes when these lateral stiffening mechanisms are not present. As expected, Figure 8(b) shows that this model develops tensile damage earlier in the pushover loading process when compared to the full model of the church. The damage on the northern nave wall is consistent with an overturning mechanism as separation is occurring between the adobe wall and the stone base. The triumphal arch is showing tensile damage at the crown of the arch. Additionally, the north presbitery wall is damaged near the triumphal arch and the back wall of the church. A comparison of the results in Figure 8, shows that the buttressing and sides rooms attached to the nave and presbitery play a critical role in stiffening laterally the main structure of the church. While the separation of the side rooms from their respective walls in Figure 8(a) does not seem to produce catastrophic damage to the church, the overturning mechanism seen in Figure 8(b) could potentially cause the structural collapse of the building.



(a) (b)

Figure 7: Material law for adobe masonry in tension and compression.

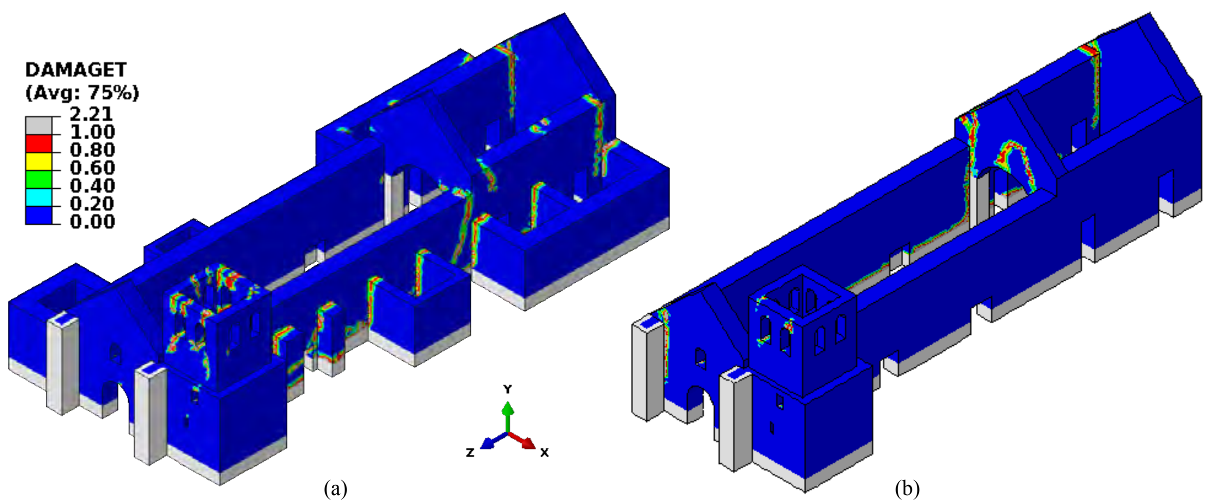
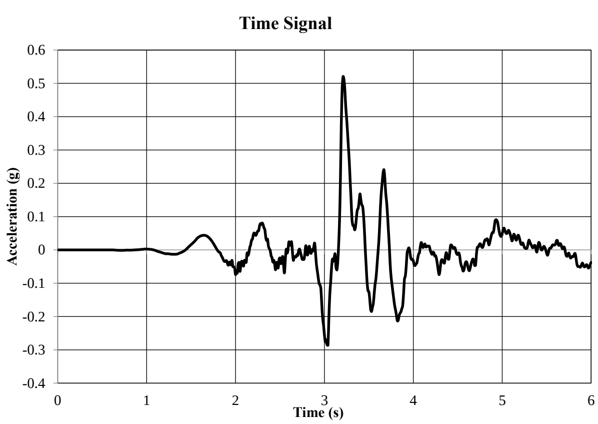


Figure 8: (a) Tensile damage development in the full model at 0.25g. (b) Tensile damage development in the reduced model at 0.14g.

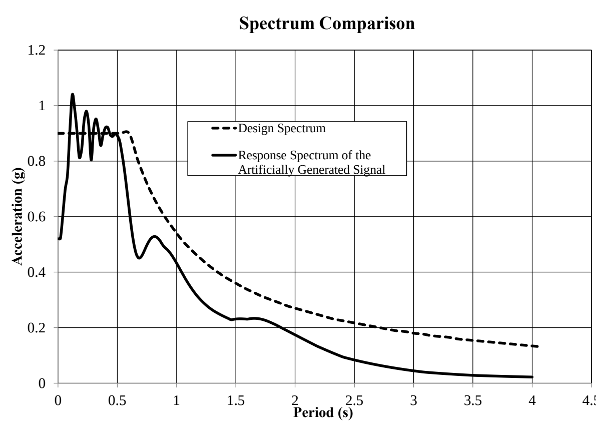
6 DYNAMIC ANALYSIS

In addition to the pushover analysis, a time history analysis was performed to capture the global response of the structure due to ground accelerations simulating an earthquake similar to what is specified in the Peruvian seismic code [20]. As previously stated, the seismic evaluation of a structure requires a multiple-view analysis approach and therefore, the dynamic base motion test further helps in identifying the onset of possible critical damage zones. As shown in Figure 9, an artificial accelogram was generated. Only the first 6 seconds of ground motion data - Figure 9(a) - were used in order to reduce the computational cost of the analysis. Figure 9(b) shows the correlation of the data to the design spectrum for the region in which the church is located. As with the pushover analysis, the ground motion data was only applied in the x-direction (north-south) so that a comparison of the damage could be made with the results of the pushover analyses. Due to the development of tensile damage in the structure during the dynamic loading, the results presented below were produced by applying a load with approximately 1/10th the amplitude specified by the design spectrum. In particular, the bell tower showed typical seismic tensile fracture patterns at all four top corners which continued to propagate during the entire loading of the structure. Additionally, the rooms located on both the north and south side of the church develop tensile fractures at their connections to the nave and presbitery walls (see Figure 10(a)).

As with the pushover test, the dynamic analysis was also performed on the reduced model of the church. In this case, tensile damage developed in several areas of the church including the triumphal arch, bell tower and rear wall - Figures 10(b). This high level of structural damage at approximately 3.8 seconds into the simulation caused numerical instabilities which prevented the full 6 seconds of loading from being applied. Figure 11 shows the average x-displacement of the top surface of each of the nave walls vs time in the full and reduced models. This figure indicates that the displacement of the nave walls in the reduced model was larger than the displacement of the same walls in the full model leading to earlier development of tensile fractures. Overall, the reduced model performed as expected in that the tensile damage developed more quickly throughout the structure in response to the applied ground motion. This provides additional confirmation that the side rooms and nave buttressing act as effective stiffening mechanisms during seismic loading conditions.



(a)



(b)

Figure 9: (a) First 6 seconds of the ground motion acceleration data. Approximately 1/10th the magnitude of this data was used in the dynamic analysis. (b) Response spectrum of the ground motion acceleration data.

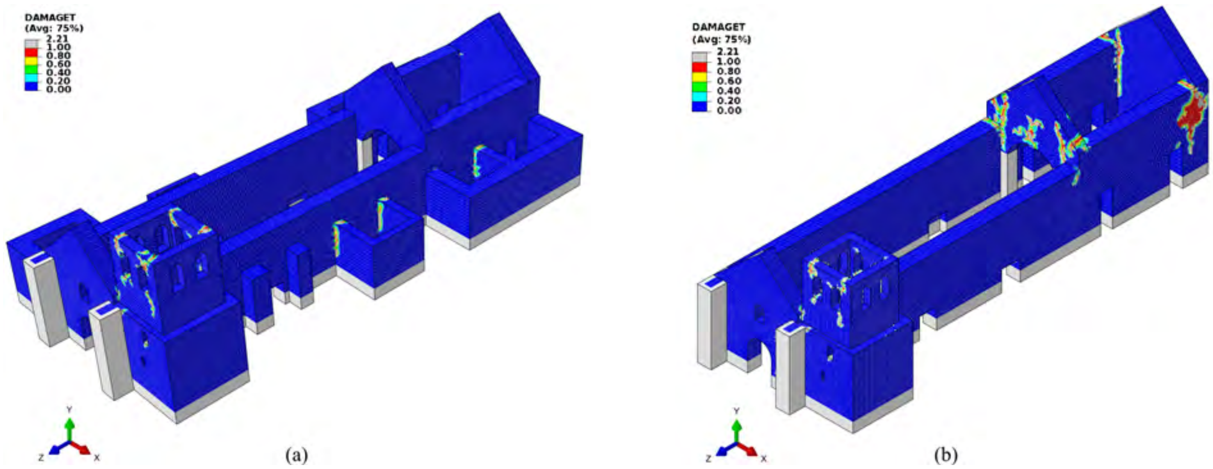


Figure 10: (a) Full model tensile damage at 6 seconds of the seismic loading. (b) Reduced model tensile damage at 3.83 seconds of the seismic loading.

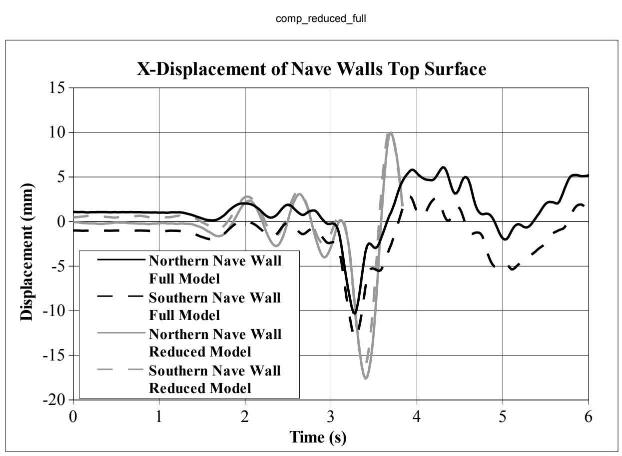


Figure 11: Comparison of the average nodal displacement in the x-direction of the top surface of each of the nave walls in the full and reduced models.

7 CONCLUSION

St. Peter Apostle Church of Andahuaylillas is a representative structure of early colonial Peruvian earthen temples, but also an example of the artistic movement and sociocultural action in the Cusco region. The structural study of this church is particularly challenging, not only for the fact of being built in adobe, but also because the church interior is almost completely covered with paintings, which hinder the inspection of the load bearing structure. This paper presents the results of investigations regarding the seismic assessment of the church, including damage survey, in-situ dynamic tests and initial numerical analyses.

Operational modal analysis tests were carried out in the bell tower, in order to extrapolate the modal response of the entire church through calibration of FE models. The models of the entire church in DIANA and Abaqus/CAE were verified by comparing the numerical frequencies and modes shapes of the bell tower to the experimental results.

Pushover and dynamic analysis provided distinct insights into the degree of propagation of the tensile fractures in both the full and reduced models of the church. The pushover analysis confirmed the weakness in tension of the wall connections, and the concomitant onset of separation and independent behavior of structural parts of the church. The time history analysis at 1/10th the amplitude demonstrated the vulnerability in tension of the bell tower, the triumphal arch and the wall connections to continued ground motions. The development of these kinematic conditions suggests the importance of applying a kinematic method to assess local failures, which must be preceded by a survey of the deep damages present in the structure and must include potential failure mechanisms revealed by the pushover and dynamic analyses. Taken together, the tests presented here confirm that, whenever possible, pushover and dynamic methods for evaluating structures should be used in conjunction with kinematic approaches which will be the objective of future work. Considering the high seismicity of the Cusco region (maximum spectral acceleration of 0.9g - see Figure 9(b)) the church in its actual state presents high vulnerability, and thus urgent structural interventions are needed.

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