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Implementation of a seismic retrofitting solution for the San Pedro de Atacama church in Chile

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Abstract

The vulnerability of earthen buildings in seismic areas may require special attention to avoid injury or loss of life and to also make a future seismic retrofitting possible. The considered reinforcements must comply with fundamental concerns of heritage conservation, as well as minimum intervention for authenticity, compatibility with the original materials to avoid damages, and reversibility to allow applying better solutions appearing in the future. This paper presents a case study of a seismic retrofitting project of the historical adobe church of San Pedro de Atacama in Chile. A parametric modal analysis was carried out to identify and analyze vulnerable areas, and to understand the dynamic behavior and the necessity of strengthening to control displacements in the walls and the main structural elements. The paper describes finally in detail the retrofitting process carried out in the church which convert it as one of the few cases in the world where an actual seismic retrofitting solution compatible to earthen buildings and seismic prone regions was implemented.

Keywords: Seismic retrofitting, numerical modelling, synthetic ropes, heritage preservation, earthen buildings

1. Introduction

In the world's driest desert, located at 2430 m above sea level, with a dry and hostile climate with ephemeral winter rains and high seismic activity, arises the San Pedro de Atacama oasis. With lush vegetation, agricultural and livestock development, it is positioned as one of the most emblematic cultural landscapes in the Atacama Desert. The appearance of the first sedentary people in these lands dates between 3000 and 500 BC, with the first signs of pre-Hispanic Atacameño art and probably one of the first religious cults. Afterwards, agriculture, handicrafts, farming and metallurgy were consolidated, thus beginning to form the San Pedro culture, also called Likanantai. After the cultural contact with Tiwanaku and Inca civilizations, San Pedro became part of Hispanic history with the arrival of Diego de Almagro in 1536 [1]. In these conditions, as shown in Fig. 1, a united and active community attached to its faith decided to erect the San Pedro de Atacama church.

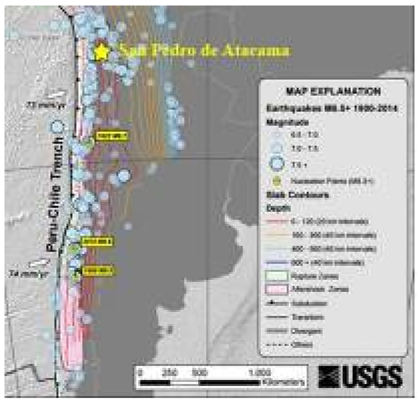


Fig. 1. Tectonic and seismic activity map with the location of San Pedro de Atacama. U.S. Geological Survey.

2. General description

The church, a mid-18th-century historical monument shown in Fig. 2, is a remarkable construction, a result of the ecology, seismicity and materiality of the desert. The style is defined by [2] as Andean baroque. The church has a Latin-cross plan, with 43 m by 7 m central nave, braced by a transept, two side chapels and structural buttresses as shown in Fig. 3 and Fig. 4. On the west side of the church there is an exempt bell tower and an attached solid volume (an 8 m by 3 m low buttress).

The structural system of the monument has 1.20 m thick adobe walls. The sloped roof is supported by a "par y nudillo" chañar wooden structure (Geoffroea decorticans) with cactus sheathing (Pachycereus pringlei) on which rests an earth-based finish. The compression tests performed on the adobe bricks of the church, with 600x400x10 mm dimensions, indicated low strength capacity.

Fig. 2. San Pedro de Atacama church, 1950.

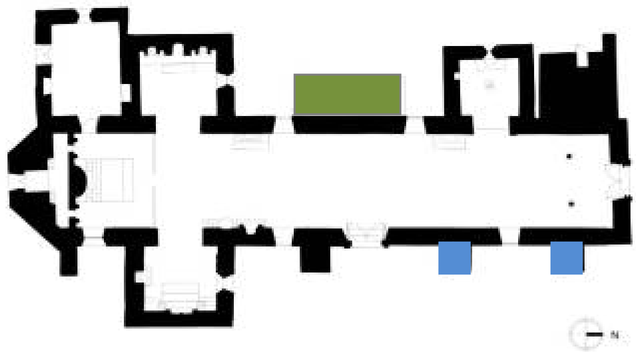


Fig. 3. Floor plan of the church with two new buttresses included (light blue). Green buttress is a widening of the west central wall (1.2 m height aprox.).

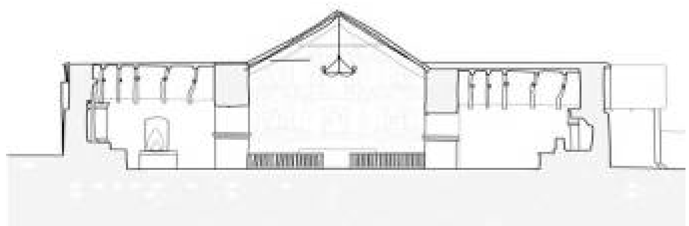


Fig. 4. Section of the central nave of the church with two aisles.

The traditional practice to repair the roof after every rain period applying a new earth layer has generated increased loads and stresses in the structural system. The church has undergone successive fires; the most destructive occurred in 1839 leaving the church in ruins (the local community needed 5 years to rebuild it). In addition, the church has suffered damages by other natural causes such as flooding or recurrent earthquakes (the most damaging, in 1950, caused the collapse of the eastern wall of the nave). These all tragedies and the lack of maintenance configure a very serious vulnerability condition to the building.

From the structural point of view, the two longitudinal walls of the church have a slenderness ratio (height to thickness) of less than five, suggesting a good seismic performance by having more resistant wall area and better stability against overturning. In addition, walls of transverse naves act as buttresses working along with real buttresses, which are of two types: i) widening the base of the west wall up to four times the thickness of the longitudinal walls, and ii) buttresses with basis three times longer than the thickness of the longitudinal wall. On the other hand, in the east wall, there is a long stretch with some openings that reveals a less stable condition. The west wall is better braced than the east wall. The front wall is slightly thinner than the longitudinal walls and it has greater height and slenderness, although the choir loft acts as a horizontal bracing. The front wall is very stable because of its shape and thickness.

3. MODELING AND ANALISYS

3.1 Strengthening philosophy in earthen buildings

The observed behavior in past earthquakes allowed understanding the high vulnerability of earthen churches to earthquakes. The fundamental reason for their weakness is due to the low tensile strength of the earth as a building material. Earthen constructions without reinforcements have a very high seismic risk. Earthquake cracks walls which finally collapse, often with also the ceilings.

In the field of heritage conservation in seismic areas, the reinforcement decision can be understood as general strengthening incompatible with the authenticity and integrity of the cultural buildings. However, given the necessity to obtain durability to the earthen buildings, the balance between these two concepts must be found. The reinforcement will have to comply with certain conditions, such as minimum intervention, the compatibility between the original masonry and reinforcement, the reversibility of solutions and the possibility of reinforcing again the original building with different and better solutions than the originally conceived [3]. Recent researches to find better reinforcements have improved the quality of confinement and reduced the aggressiveness that represents the presence of a strange material. Research carried out by the Pontificia Universidad Católica del Perú (PUCP) in the last 40 years and the Getty Seismic Adobe Project 90's project, had as main objective the search for materials with tensile strength capacity to confine and to grant ductility. After practical experience in reinforcement in Andean churches in northern Chile [4], the reinforcement used in the church of San Pedro belongs to the fourth generation of solutions tested in the laboratory of PUCP, exhibiting improved dynamic behavior because of the use of the mesh of ropes involving each wall [5]. Based in the acquired knowledge, the Peruvian government printed out a manual aiming at setting guidelines for the retrofitting of adobe buildings [6].

3.2 Structural Design Criteria

There are three criteria for structural design:

1. The criterion based on the strength consists of the use of thicker walls, as many walls as possible or small openings, so that the amount of material per unitary area of construction increases.

2. The criterion based on stability consists of avoiding overturning the walls (the key elements in the construction of earth) which is achieved with trapezoidal walls sections with lower center of gravity or the use of buttresses.

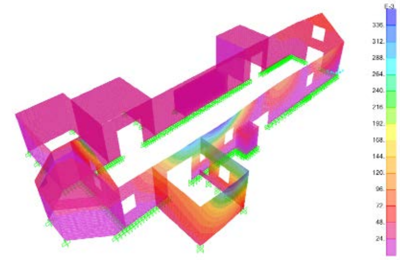
3. Finally, the design criterion based on the seismic behavior consists of giving displacement control to the construction with the use of reinforcements of tensile resistant materials.

The first two criteria used since pre-Columbian times have proven not to be enough to avoid the collapse of the earthen walls, with the consequent loss of life and strong damage. The third criterion is the only one that prevents earthquakes collapse, because earthquakes are recurrent disasters and produce accumulation of damage until the collapse of the earthen structures.

3.3 Eigen-value analysis to assess the influence of buttressing

The influence of the buttress in the dynamic behavior of the church was analyzed by finite element models implemented in the program SAP2000. All the walls were modeled with shell elements considering shell thin elements which not consider perpendicular shear to its plane. The material was represented as a homogeneous system with 0.65 MPa for modulus of elasticity and 17.65 kN/m^3 as density.

A first model was studied which considered the central west low buttress and one in the east wall close to the altar as shown in Fig. 5. These buttresses existed since the time of the original construction, as proved during the fieldworks. As expected, the buttresses controlled the displacements of the lateral walls. The vulnerable areas were identified as the central east wall and the gables. By the shape of the church, with an elongated nave, the major concern is also the out of plane behavior of the longitudinal walls.



Participative mass: 13.3 %
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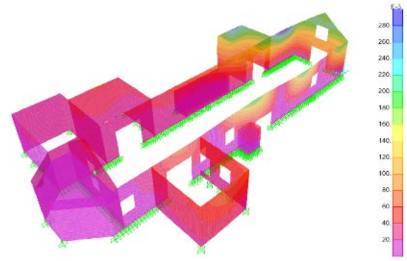

Participative mass: 12.2 %
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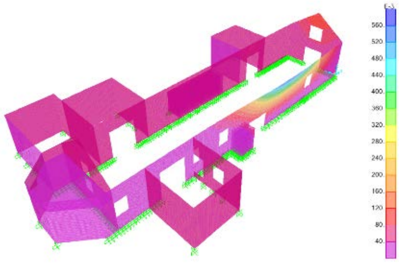

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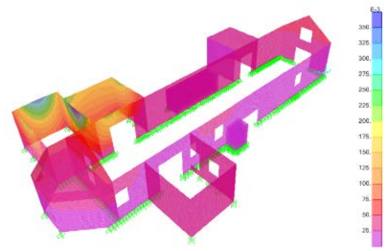

Participative mass: 6.7 %
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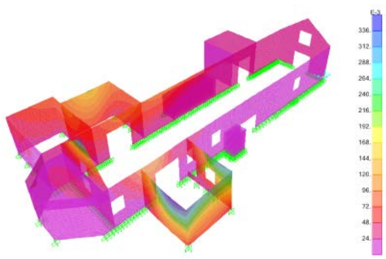

Participative mass: 5.6 %
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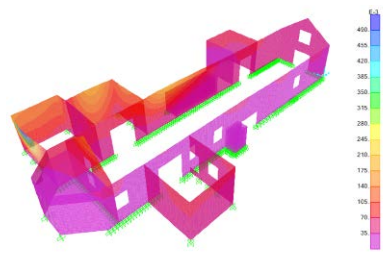
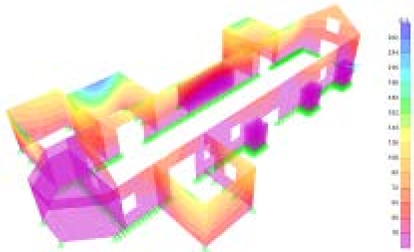


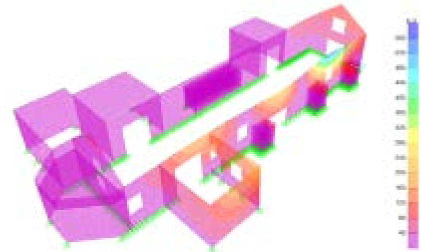
Participative mass: 4.1 %
Period: 0.12 sec

Fig. 5. Six modes with major participative mass in transverse direction (Y).
Model with only original buttresses. Colours indicate modal deformation.

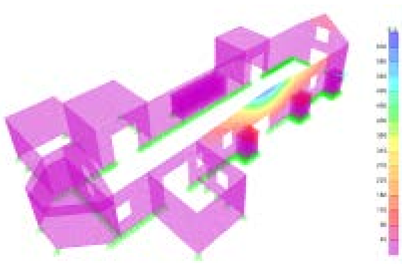
A second model was implemented considering the inclusion of all the buttresses as shown in Fig. 6. The natural period for 'Y' direction increased for the most relevant modes and the modal deformation of the east wall has less magnitude in the first mode shape. The presented six modes for each model allow understanding better the seismic behavior of the church with the two new buttresses. However, these few number of modes are not representing a high effective mass participation. In order to represent an effective mass close to 90% will be necessary to show more than 400 modes.



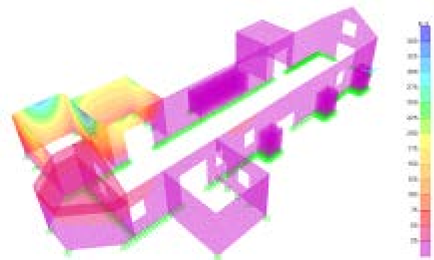
Participative mass: 15.1 %
Period: 0.13 sec.



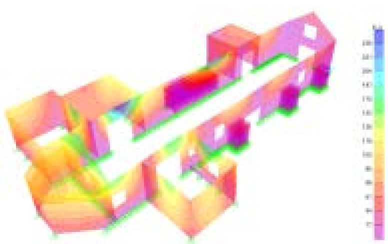
Participative mass: 12.3 %
Period: 0.14 sec.



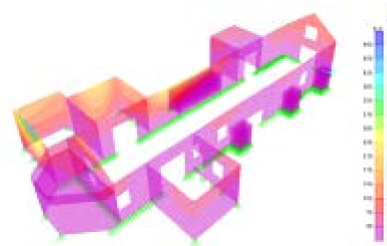
Participative mass: 6.6 %
Period: 0.18 sec.



Participative mass: 6.3 %
Period: 0.12 sec.



Participative mass: 5.1 %
Period: 0.10 sec.



Participative mass: 4.2 %
Period: 0.12 sec

Fig. 6. Six modes with major participative mass in transverse direction (Y). Model with all buttresses. Colours indicate modal deformation.

3.4 Seismic Analysis

The seismic assessment of the church was carried out using a spectral linear analysis with the two previous described models. In Fig. 7 it is possible to compare the displacements of the two models as a result of a linear relationship behavior in the central part of the east wall using the Chilean Standard NCh433 [7] spectral acceleration. The results evidences that the displacements after installing new buttresses are close to half the original displacements.

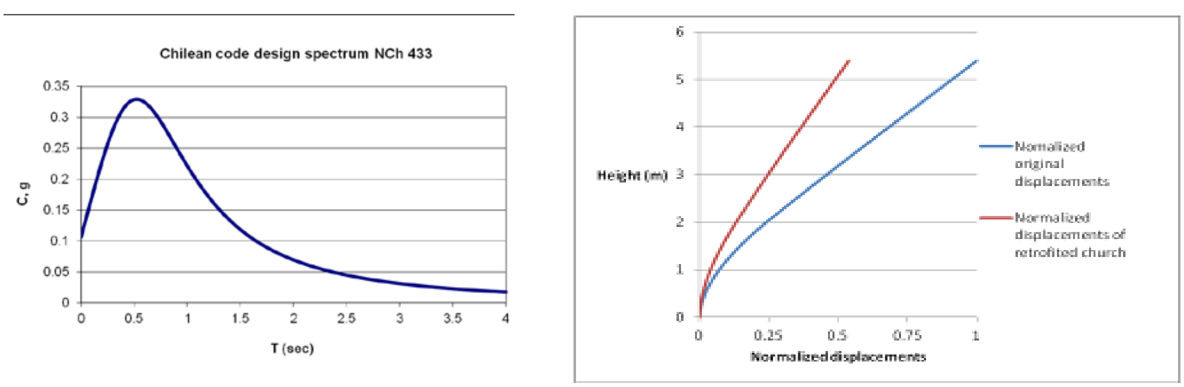


Fig. 7. Lateral deformation comparison in the top part of the middle east wall.

4. REINFORCEMENT WORKS

4.1 Structural consolidation of adobe walls

During the comprehensive restoration of the temple conducted in 2015 by "Fundacion Altiplano" all the walls and roof were restored, intended to retrofit the whole structure. After removing mud plasters from interior and exterior face of walls, real damages were verified to assess their condition and stabilization action. Consolidation involved the repair of cracks with mud injection, new bricks and mud plaster consolidation.

4.2 Structural consolidation of the roof

The damaged beams (the ones evidencing loss of material, cracks and infesting moths), were replaced by new pieces of local wood. In total, 20 beams were replaced. All joints were reinforced with 12 mm diameter bolts and tied with cowhide as it has been traditionally done. The damaged boards of the cactus ceiling (atacamensis echinopsis) were replaced, which corresponds to 15% of it. The total area of the cover is 745 m^2.

Only the coronation of the walls of the central nave had a support beam for roof structure. The measure of this piece is variable between 63 mm and 152 mm. In the case of the side chapels and sacristy this beam does not exist and the beams rest directly on the adobe walls. The new design considered a wood ring beam that was installed in the top of the walls (see Fig. 8). This double wooden bond beam, reinforced with crossbars, was installed around the perimeter of the temple during the consolidation of the roof, including side chapels and sacristy. Timber was 100 by 100 mm and crossbars were spaced 1 m. This solution was implemented in order to provide a better distribution of loads of the roof to the walls and act as an anchor for the eaves of the church. Fig. 9 shows the process of intervention.

Fig. 8. Wood collar beam in the top of the walls.

Fig. 9. Support platform to work the wooden roof.

4.3 Buttresses reintegration

Two new buttresses are reintegrated into the 22 m long and 1.20 m thick east wall of the temple. The buttresses have a stepped typology and rise on a foundation of 0.80 m deep, built with stone boulders and lime mortar. Masonry rises with 0.60 x 0.40 x 0.10 m adobe bricks which are hooked to the wall of the temple every 3 rows at a depth of 0.30 m.

4.4 Structural reinforcement of the walls

Structural reinforcement of the walls is made using synthetic netting ropes. The reinforcement includes the walls of the main nave, new and existing buttresses, bell tower and side chapels. The basis of this method is to confine the adobe walls by tensioning ropes and improve their behavior in case of any seismic loads. Part of this system consists of connecting the bond beam with the mesh to the walls, thus allowing an overall behavior of the structure as shown in Fig. 10, Fig. 11 and Fig. 12.

Synthetic polypropylene ropes have a diameter of 12 mm and have a maximum tensile strength of 12.89 kN (1315 kgf) and an elongation of 35%. Ropes are distanced 0.60 m vertically and 0.30 m horizontally in the upper third of the wall and 0.40 m in the lower 2/3 of the wall (Fig. 12). Structural reinforcement of the bell tower is done by netting synthetic ropes in the second body of the construction. In this case polypropylene ropes have a diameter of 6 mm, are distanced 0.15 m vertically and horizontally and a have maximum tensile strength of 3.9 kN (398 kgf) and an elongation of 36%.

The adobe walls are perforated in section to fix the mesh on both sides of the wall with 6 mm diameter crossties, while in the bell tower crossties are 4 mm diameter. The crossties tie side by side the ropes of the mesh, the upper half of the wall is tied on every intersection of the ropes while the bottom half of the wall is just alternately tied (Fig. 13 and Fig. 14). The ropes are not at the level of the mud mortar joints, but in the middle of adobe bricks as a precaution. Ropes are knotted by double eight knots. Knots get an approximate initial tension of 392 N (40 kgf); two days after the knot suffers a loss of strength up to approximately 275 N (28 kgf), and the string tension is stabilized within two days.

Fig. 10. Beginning of the installation process of vertical and horizontal ropes.

Fig. 11. Ropes are connecting roof and walls through the collar beam.

Fig. 12. Structural reinforcement by tensioning synthetic ropes.

Fig. 13. Vertical and horizontal layout of the ropes.


Fig. 14. Crosstie ties the ropes at the intersection

5. Conclusions

The paper presented a case study of a recent application of the modern conservation philosophy for the structural rehabilitation of an adobe building located in a high seismic prone area. The process incorporated the experience gained in over 40 years working in the field of the preservation of earthen buildings. Numerical models were first implemented to evaluate the initial vulnerability condition and the effect of possible strengthening solutions. With these outcomes, a practical intervention procedure was designed considering the connection of the walls with a ring beam and the installation of synthetic ropes to assure stability in seismic events. The proposed procedure represents a practical implementation of what was suggested by the Principles for the Conservation of Earthen Heritage located in Seismic Areas adopted by ICOMOS Peru in 2012.

6. Copyrights

Figure 1 was taken from USGS web site.

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