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STUDY CASE: REPAIRING AN ADOBE COLONIAL BUILDING IN CUSCO, PERU

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Abstract

Many of the historical buildings located in seismic prone areas, like Cusco in Peru, are built out of adobe. Because adobe as a construction material has shown a poor behavior during earthquakes, it’s a great challenge for engineers to propose adequate methodologies to face this problem. This paper deals with the geotechnical and structural studies developed for the restoration and retrofitting of an adobe colonial mansion. It was built in the mid eighteenth century, constructed on pre Inca and Inca terraces and located close to the archaeological complex of Koricancha in the historical center of Cusco.

This construction suffered at least three severe earthquakes (1650, 1950 and 1986) which damaged his structure. The repairs following those events were in general inadequate. Many of the cracks were only covered with plaster and poor reinforcement was placed in some parts of the structure. Beside this, former tenants took even worse actions like carving walls to enlarge window openings and doors and the addition of poor quality water pipes caused leaking. All of those procedures increased the vulnerability of the construction introducing inadequate changes in its structural configuration as well as moisture in the adobe walls. This drastically decreased the strength of some of the walls leading the structure to an incipient state of collapse. The critical stage was reach when the facade walls started to fall apart.

As a first action, bracing was placed all around the structure prior to the implementation of engineering studies. The Ministry of Culture commissioned an archaeological site and architectural researches for restoration purposes. Studies of soil mechanics as well as structural analysis were performed to retrofit the building. A basic study to the dynamic behavior of the building was performed with the help of a 3D dynamic FEM-program. Reinforcement alternatives were developed and analyzed based upon effectiveness, cost and applicability; the most effective ones were chosen.

The selected alternatives were thereupon combined and detailed. Wood rigid diaphragms, wood collar beams and steel tensors were used as reinforcement. Due to the historical value of the building, other alternatives such as adding walls, vertical reinforcement as well as mesh, were ruled out. Because of its multidisciplinary approach, the case presented in this study can be considered representative for future studies on historical buildings located in seismic prone areas.

Keywords: Adobe; historical buildings; restoration; retrofitting; repairing; Cusco.

1. Introduction.

Peru is located at the west coast of South America on the Peru-Chile trench, also known as the Atacama trench. This tectonic feature causes Peru to be subject to many earthquakes [1]. The city of Cusco, located in the southern part of Peru, among other cities has endured the consequences of earthquakes, which have destroyed many heritage buildings.

Many historical buildings throughout the andean region, like Cusco in Peru, are built mainly with adobes bonded with mud mortar and straw. However this traditional construction material has little resistance to earthquake-induced forces. During the earthquakes of the years 1650, 1950 and 1986, Cusco City recorded the collapse of important historical monuments including various colonial houses.

Most of the common buildings located in the historic center of Cusco are the product of a complex construction processes. They include many stages of occupation such as pre-Inca, Inca, colonial and republican. The Casanova-Lastarria Mansion that is studied in this article is an example of that convoluted process. It was built in the mid-eighteenth century and is located in the area of influence of the archaeological complex of Koricancha in the historic center of Cusco City. (Fig. 1) This historical building was constructed upon Inca and pre-Inca basis and some of the remaining walls of the structure in the first floor show Inca construction features.

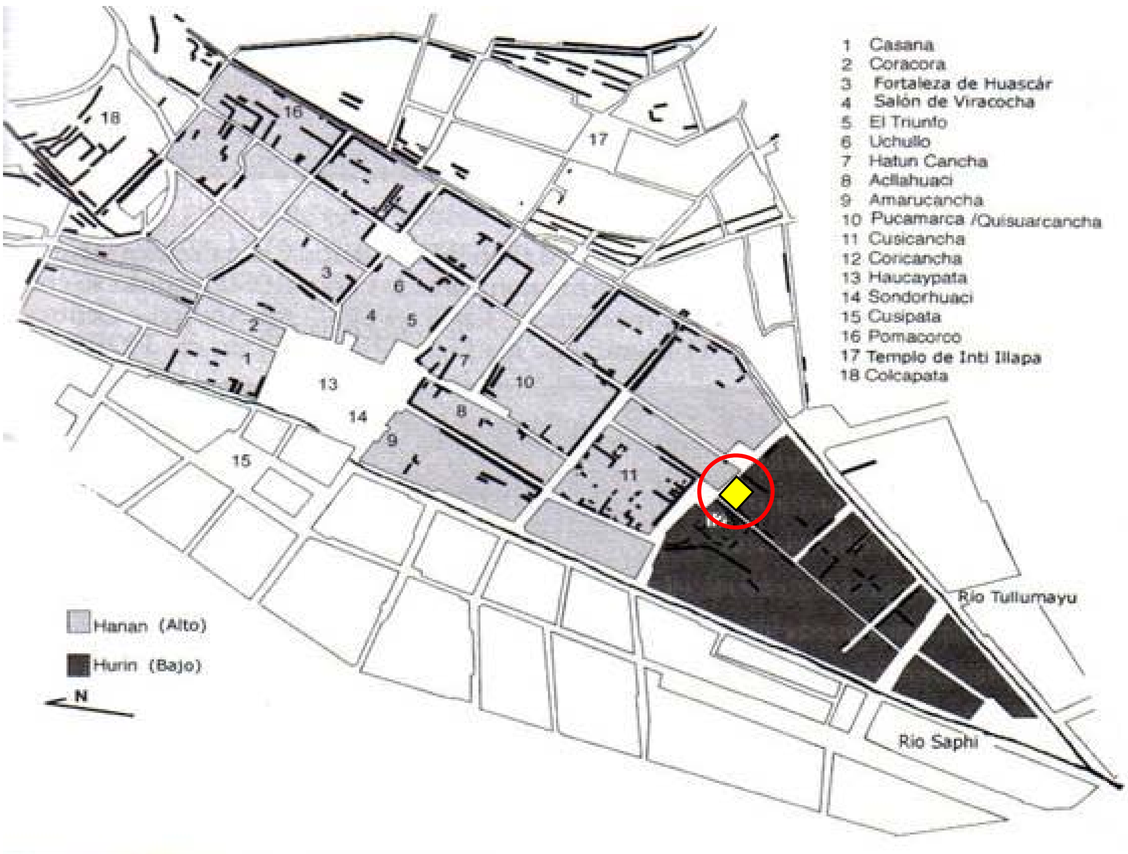


Fig.1- Location of the studied mansion in the old Inca settlement (Koricancha). Adapted from [2]

2. Methodology.

The study for preservation and repair of this historical mansion has required a multidisciplinary approach. As a first stage, archaeological exploration and architectural studies were carried out. Using the emerging results, geotechnical studies as well as structural modeling and analytical approaches were developed in the second stage. To conclude the multidisciplinary approach, studies on retrofit alternatives for foundations and structures were carried out as a last stage. This paper however deals only with the engineering aspects developed in the last two stages of the process.

It is important to note that prior to the implementation of the studies mentioned above, bracing was placed for security purposes, throughout all the structure. (Figs. 2 and 3)

Fig. 2 - Provisional bracing (facade)

Fig. 3 - Sustainable bracing (arches-patio)

3. Preliminary structural evaluation.

Extensive and detailed structural inspections of the various sectors of the mansion were carried out. These technical observations covered: foundations, adobe walls, stairs, floors, roofs, arches, ceilings and lintels, among other structural systems.

The conclusions of this preliminary structural evaluation are:

(1) The inadequate constructive intervention, without any technical orientation, in the south-east area of the building, is likely to induce structural destabilization of more than half of the building, enforcing emergency bracings at the facade of the property.

(2) The leaking of indoor water facilities could induce a decrease in the resistance of the adobe walls.

(3) The reduced thickness of the wall could reduce lateral rigidity of the construction in various sectors of the property.

(4) The aging of the construction and the impact of past earthquakes, expressed in cracking and settlement of the walls, gradually lessen the damping and stiffness properties of the structure.

(5) The change of the mansion use, from residential to commercial, altered the structural configuration in both plan and elevation. It required new wall openings, removal or inclusion of walls, wall thickness reduction and new facilities, among others.

(6) A lack of earthquake resistant criteria was taken into account at the time the mansion was build, or latest repaired after seismic events.

4. Geotechnical and Structural Studies

The structural intervention of an historical building demands advanced knowledge of the soil, foundations and the adobe walls behavior in general. As part of the geotechnical approach, the subsoil needs to be explored, the foundation requires a specific evaluation and the mechanical properties of adobe walls need to be taken into account. On the other hand, structural applications including modeling, seismic analysis, retrofitting, detailing and repairing work sequences, will need to be appointed.

4.1 Soil and foundation exploration

The geotechnical exploration took place after the archaeological excavations were completed. These were carried out at places without cultural remains as do not interfere with them. In Fig. 4 the location of pits for soil exploration, foundations and steamwall observation ditch and groundwater levels are shown.

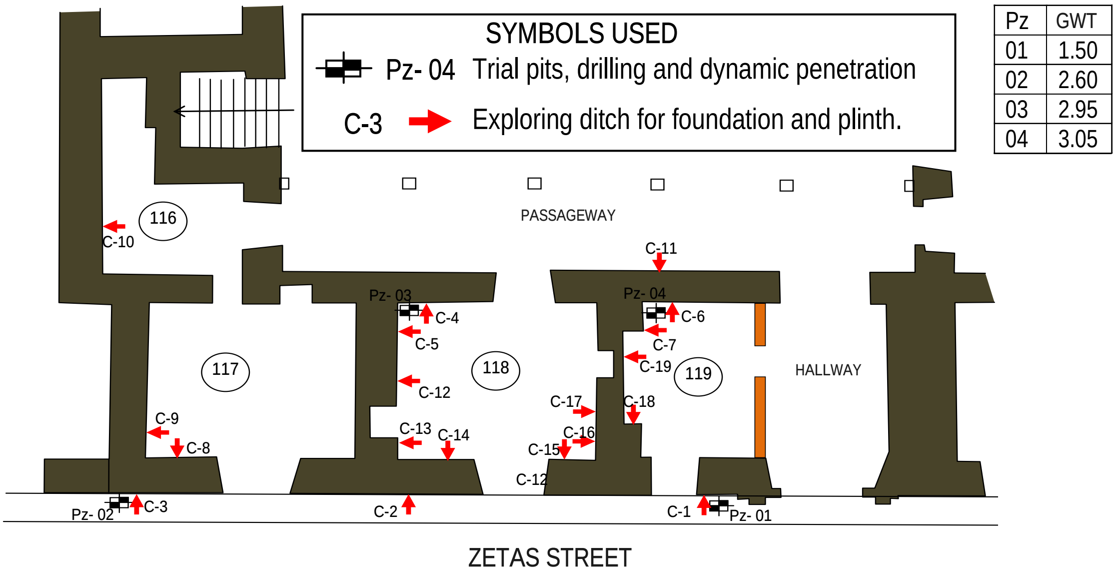


Fig. 4 - Schematic floor of the building.

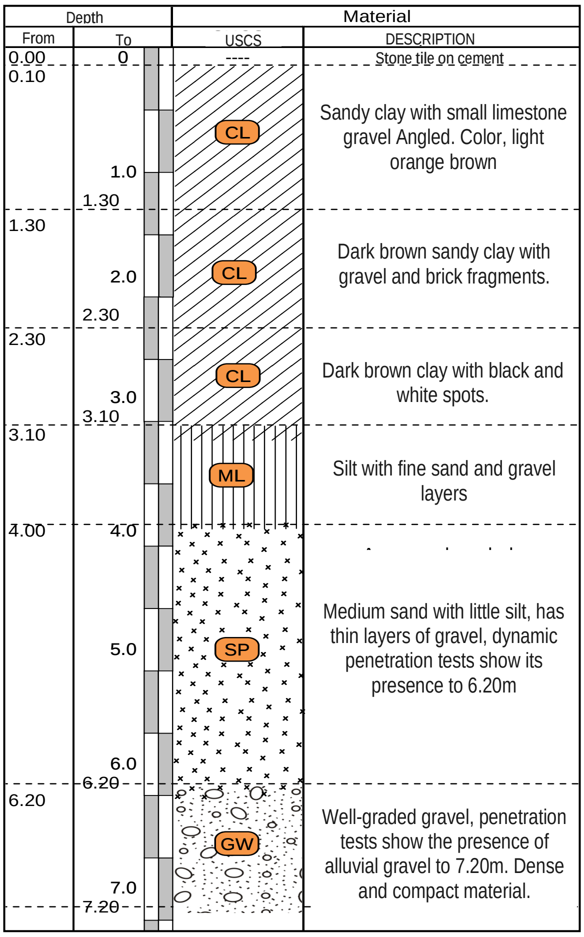
4.1.1 Stratigraphy

The soils have a chaotic distribution. Materials found are: From ground level to 1.80 m depth, darker soils with gravel and black coal points; between 1.80 to 4.00 m compact and dense fine sand and silt; between 4.00 to 5.50 m layers of clay, sand and gravel lenses; from 5.50 m to great depth, fluvio alluvial deposit of sandy gravels with midsize stones (Fig. 5)

4.1.2 Evaluation of the Foundation

It is common for colonial buildings in Cusco that their adobe walls were constructed above Inca stone walls, which in turn are founded on pre-Inca foundations. The facade wall that collapsed partially was supported only on the outer face by a narrow stone foundation (Fig. 6a). In the area without collapse, exploration shows a more stable foundation (Fig. 6b). The foundation of the inner wall which leads parallel to the street is more stable. It has a depth of 1.50 m, and a 0.25 m stone and mud plinth. The foundation of the perpendicular walls is 1.00m deep and has similar plinth. Both foundations remain the same width of the wall.

The bearing capacity [3] of the soil for strip foundations of 1.00 to 1.45 m depth and 1.00 m width varies between 88 to 91 kN/m^2. The consolidation settlement of 19.2 mm, was calculated using the following parameters of mechanical behavior: void ratio of 0.645, pre-consolidation pressure of 84.3 kN/m^2, compressibility index and index of recompression of 0.21 and 0.024



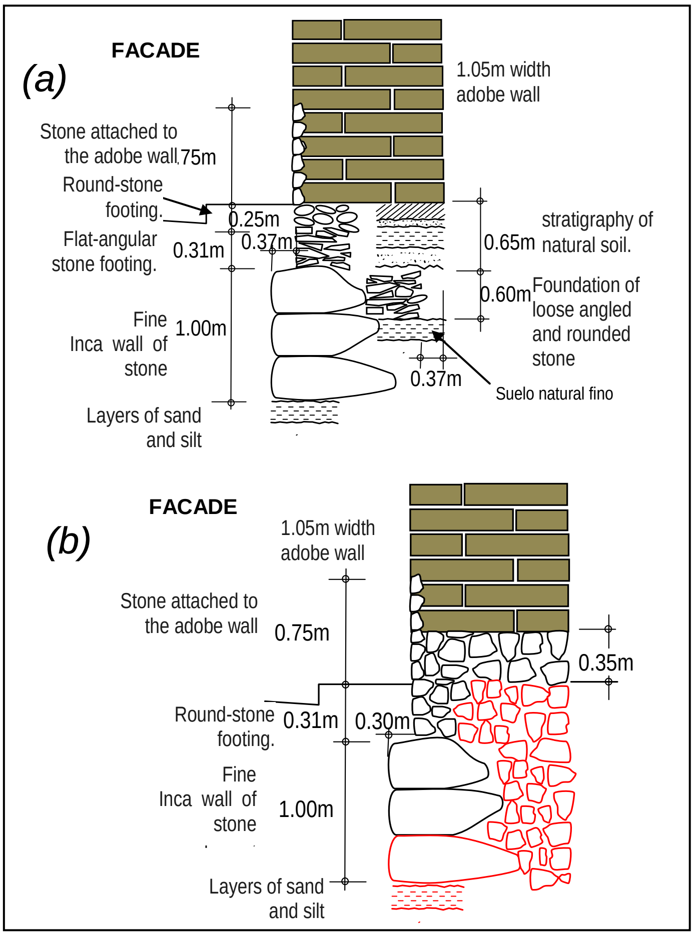


Fig. 5 - Stratigraphic profile of the sector.

Fig. 6 - Foundation a) collapsed zone. b) Not collapsed

4.1.3 Study of mechanical behavior of adobe.

To evaluate the structural behavior of the building, unconfined compression tests were performed on specimens of adobe taken out of the existing walls (Fig. 7 and 8). It´s average side dimensions were 11.3 cm and 13.3 cm high [3]. The results of adobe strength varied from a minimum of 112 kN/m^2 to a maximum of 659 kN/m^2. The average resistance of the adobes of the first floor is 224 kN/m^2 and of the second floor 303 kN/m^2. The average modulus of elasticity of adobe is 7523 kNg/m^2 for the first floor and 8403 kN/m^2 for the second floor.

Fig. 7 - Compression

Fig. 8 - Adobe specimens for testing mechanical behavior.

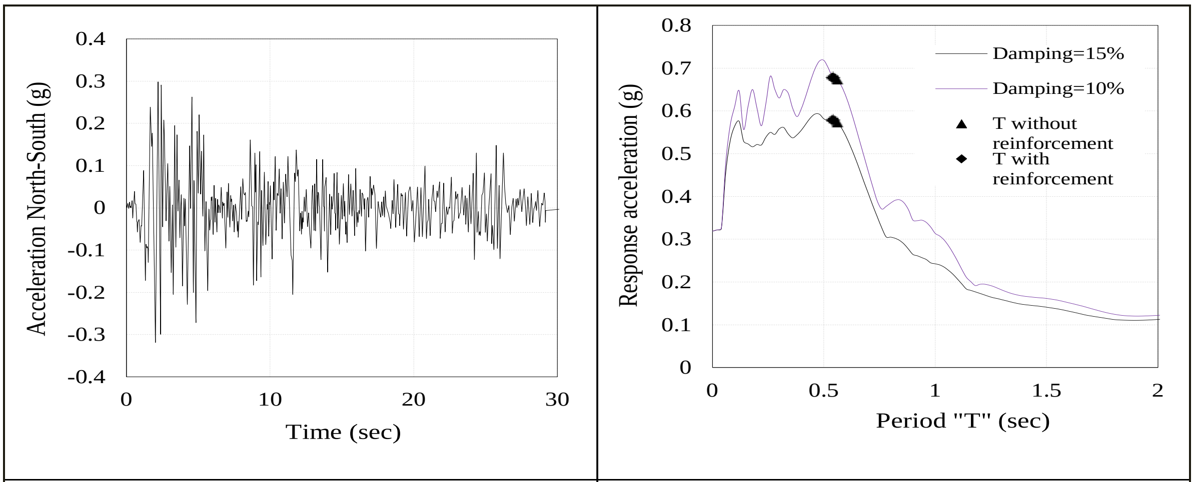
The structural restoration considers the replacement of the walls of the collapsed area using new adobes. Samples of new adobes tested showed resistances ranging from 205 kN/m^2 to 409 kN/m^2 with an average of 317 kN/m^2. The average modulus of elasticity of adobe is 10024 kN/m^2.

4.2 Structural modeling [5]

To calculate the stresses and/or displacements in an adobe house, one must make a model. We need to keep in mind that a model never represents the reality 100% and always contains simplifications. Thus it is important to verify whether the simplifications are allowable. This remark will explain what assumptions and simplifications were used in the models in order to get reliable and thus usable information. The main reason to choose SAP2000 for the modeling was its capability to analyze structures in a dynamic and three dimensional way and his relatively user–friendly interface. These features can also be used to acquire knowledge and test alternatives for retrofitting purposes. Adobe can be modeled as an isotropic material; it strength varies widely. The properties of the adobe used in this report are based on information obtained from the section 4.1.3 of this paper. The calculations in SAP were carried out assuming a linear elastic behavior of adobe.

Linear elastic analysis is indeed limited compared with non linear analysis. Nevertheless the reinforcement target is the cracking control at initial stages of the behavior, mainly linear elastics. It is important to take into account that the occurring tension usually is caused by flexion of walls and therefore has a different value than the normal maximum tension stress.

In regard to the geometry, the connection between the ground, foundation and the rest of the structure will be assumed to be restrained by means of hinges. The walls will be modeled as a continuum, without distinction between the adobe blocks and the mortar joints. In the unreinforced model, it is assumed that the roof does not create any rigidity; which means that the walls do not interact with the roof. The floor will be modeled as timber beams that are supported by the walls and contain no rigidity. The floor beams will be attached to the wall by restraints that can only transmit vertical and axial forces; no bending moments can be transmitted by the restraints. If no reinforcement would be set to the beams, they are modeled in such a way that occurring horizontal forces will be transmitted to both attached walls. However the beams cannot pass on axial forces from wall to wall; the walls can move independently from each other. In this way, horizontal forces caused by an earthquake will load both walls but the beams will not connect the two walls creating artificial rigidity. For modeling permanent and temporary gravity loads, the values of the current Peruvian Loads Code E-020 was used. Because there are no records available of the past earthquakes in Cusco, the El Centro ground accelerogram and the correspondent response spectra for the earthquake in 1940 was used as a seismic input (Fig. 10a and 10b).



(a) (b)

Figure 10. El Centro earthquake (a) Time History for North-South Component (b) response acceleration versus period.

It is assumed that the soil and the foundation will move as one rigid body together. Therefore, all displacements at the base of the construction will have the same displacements. Because all displacements are assumed the same, the models will not rotate at the base. The period of adobe houses is about 0.5 seconds, likewise a ten to fifteen percent damping is used in the models. In the reinforced model, the interaction between the adobe and reinforcements will be modeled as fixed connections. This means that the reinforcement will be attached to the house at all times. To satisfy the trait the model must be well designed and all details implemented.

4.2.1 Analysis

The analysis of the model is elastic and will not include tearing or cracking of the walls. Neither does the analysis include the modeling of a total collapse. The maximum allowable stress is influenced by the occurrence of stresses in other directions. This phenomenon makes it difficult to determine whether cracks will occur and if the house will eventually collapse. Therefore, it is impossible to determine whether a structure will fail or only suffer from cracks.

By analyzing the structure, the influence of reinforcement will be investigated. As a result, the decrease of stresses after implementing reinforcement can be evaluated. Peak stresses before reinforcing will be compared to peak stresses after reinforcing whereupon the effectiveness of the proposed reinforcement can be assessed. Non-linear behavior will not be considered.

4.2.2 Retrofitting alternatives for existing adobe buildings [5, 6]

This section is based mainly on the reference [5], which studied and developed the characteristics of more than one alternative to retrofit existing adobe buildings. Six alternative reinforcements were studied; diaphragm, collar beam, vertical tension bars, additional interior wall, mesh and vertical diagonal stiffeners. The evaluation of the different alternatives is based on three main criteria: effectiveness, applicability and cost. To determine the effectiveness, the used method consists of comparing the number of elements that exceed certain maximum stresses for the unreinforced as well as the reinforced models. From the quantitative comparison of the different alternatives, it can be concluded that the diaphragm is the most effective alternative. The collar beam does not give any significant reduction of stress; nevertheless, considering the applicability, in order to let the diaphragm function properly a collar beam is necessary.

The total cost of each alternative is depending heavily on the costs of the details. If the cost of the details can be reduced by introducing cheaper alternatives, the total cost reduces significantly. As a reference, the total cost of construction materials of the diaphragm could be 1.8 times respect to the mesh and 3 times in regard to additional interior walls. A comparison of the stress reduction due to the presence of a diaphragm, which is used as reinforcement [5], is shown in Fig. 9

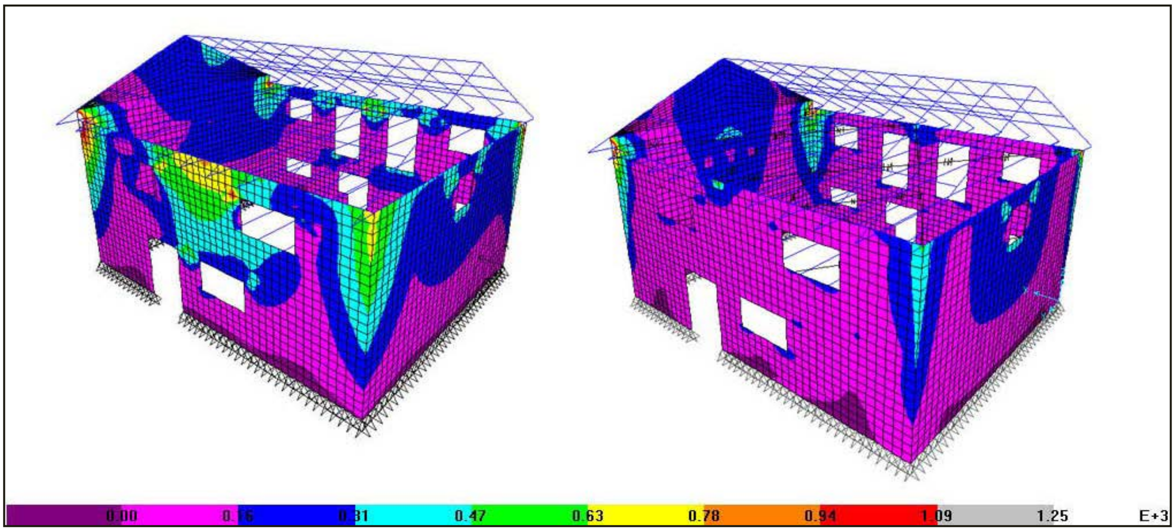


Fig. 9 - Reduction of horizontal tension stresses with diaphragm, left unreinforced, right reinforced, in kN/m^2

The horizontal bending stresses in the walls are reduced considerably compared to the model with no reinforcements and no connections between beams and walls. In the figure, the models with and without reinforcements are compared. As illustrated, the horizontal tension forces in the middle and at the corners of the longest wall have been reduced significantly. The compression strengths mainly caused by bending are reduced in 36 %; if the compression strengths are caused by pure compression this reduction is 27 %; for shear strengths the reduction reached around 32 %.

4.2.3 Results of the retrofitting process at the Casanova-Lastarria mansion

Based on the previous considerations, a combination of rigid diaphragm and collar beam was select as a basic structural retrofitting system for the Casanova-Lastarria mansion. The system was not only used for the walls but also at the roof. The analysis was done by using SAP to establish the stresses with the implemented reinforcement. The effectiveness of the reinforcement was determined by comparing the stresses in the mansion with and without reinforcement.

A general view of the model and 3D shear stresses with rigid diaphragm and without diaphragm are slow in Figs. 10 and 11. The maximum stress from dynamic analysis in the facade, comparing unreinforced and reinforced alternatives is show in Table 1. The horizontal bending stress at the middle of the wall is reduced due to the presence of the reinforcement. This stress reduction reaches 30 % in the case of vertical compression at the base of the wall; however at the middle of the wall the stresses for the reinforced model suffer even an increment of 2.4%. Further investigations are necessary.

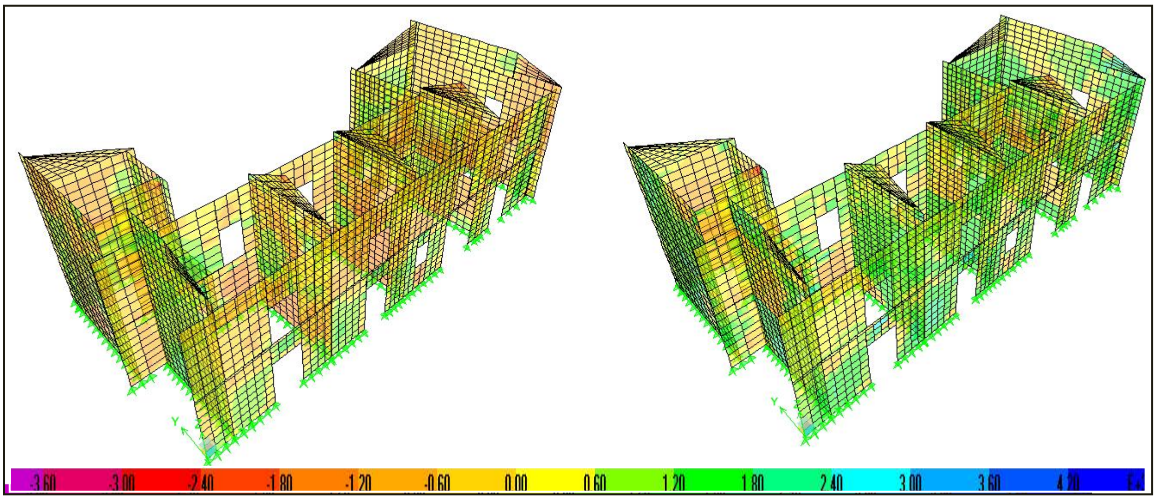


Fig. 10 - General view of the SAP models. Casanova - Lastarria mansion.

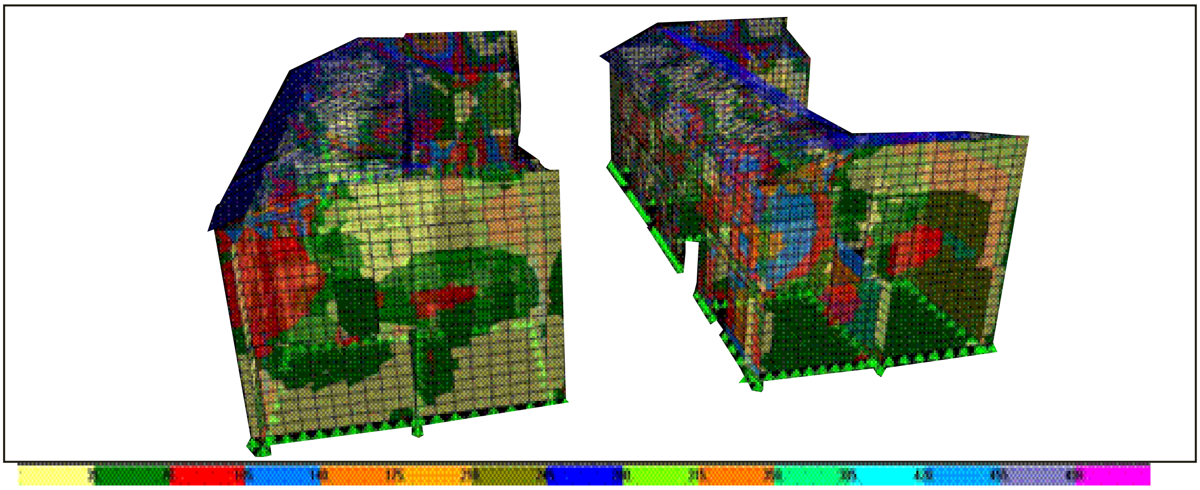


Fig. 11 - 3D Shear stresses. With rigid diafragm (left). Without diafragm (right) in kN/m^2

Table 1 - Maximum stresses from dynamic analysis in the facade

Shell ID	Type of stress*	Stress (kN/m2)				Description
		Unreinforced		Reinforced		
		negative	positive	negative	positive	
w458	S11	2450	2462	2064	2133	Horizontal bending – Middle of the wall
w523	S11	2145	1692	2110	1949	Horizontal bending – Top of the wall
w760	S22	2809	2806	1952	1941	Vertical compression – Base of the wall
w796	S22	1927	1541	1974	1870	Vertical compression – Middle of the wall
w720	S12	434	462	458	369	Shear – Close to the door – First floor
w263	S12	771	754	735	692	Shear – Close to the window– Second floor

* S11 Bending stress; S22 Compression stress; S12 Shear stress

As an example of the many calculations, Fig. 12 shows the dynamic behavior in the facade wall using the SAP2000 program. The fundamental period in the middle top of the longitudinal wall of the facade, in the out of plane direction, is slightly smaller in the reinforced model than in the unreinforced one.

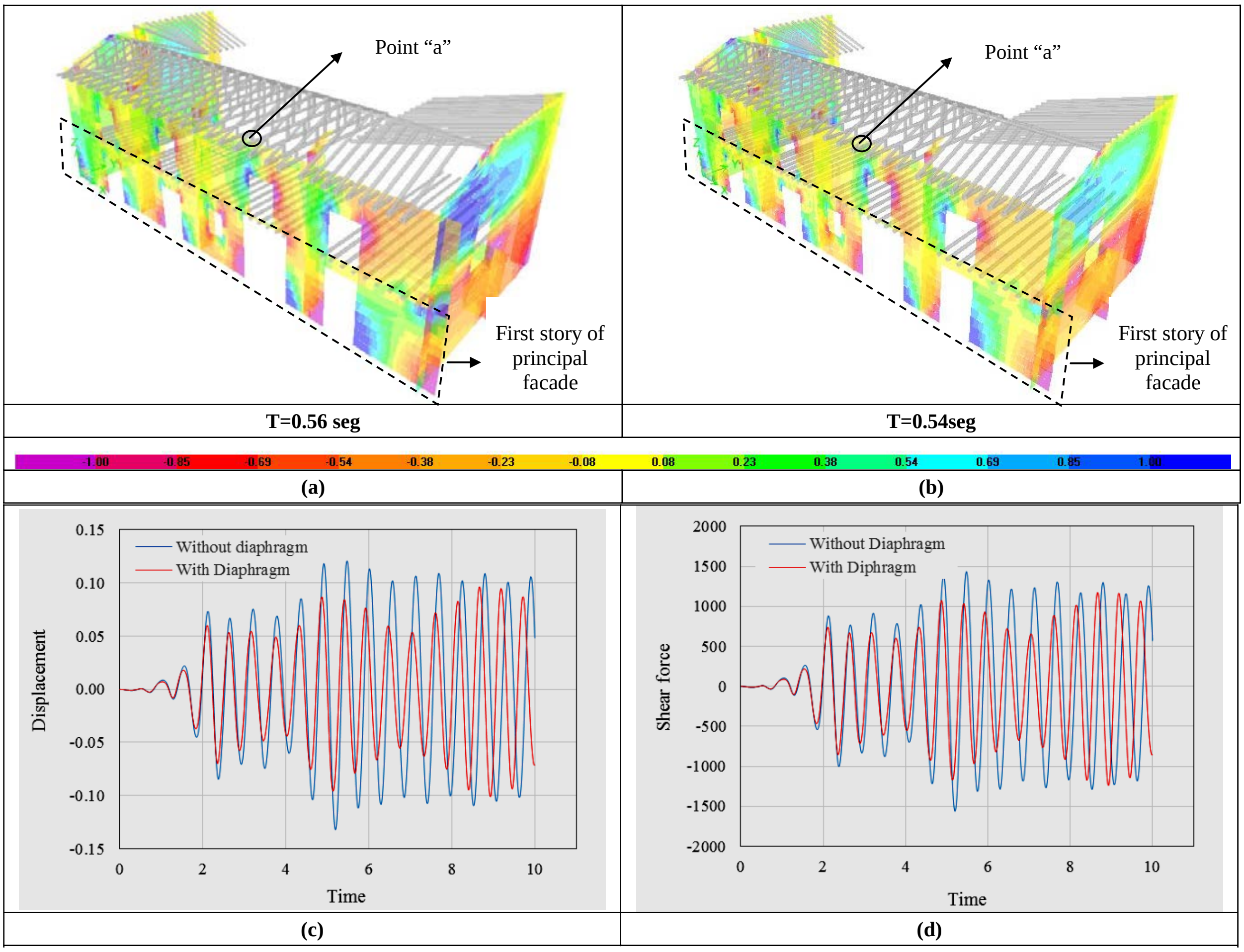


Fig. 12 - 3D model of dynamic behavior: (a) Without diaphragm (b) With diaphragm influence
(c) Out of plane displacement without and with diaphragm (d) Shear forces without and with diaphragm.

On the other hand, for the earthquake input used at this model, the out of plane displacements are clearly bigger in the unreinforced model regarding the reinforced model (Fig. 12c). The presence of a rigid diaphragm also reduces the shear forces in this part of the structure. These facts reveal the greater rigidity of the structure by the presence of the reinforcement systems suggested in this study, which in turn reduces stresses and strains in the system.

4.2.4 Detailing

The process of rebuilding and strengthening the facade of the mansion is shown in Fig.13.

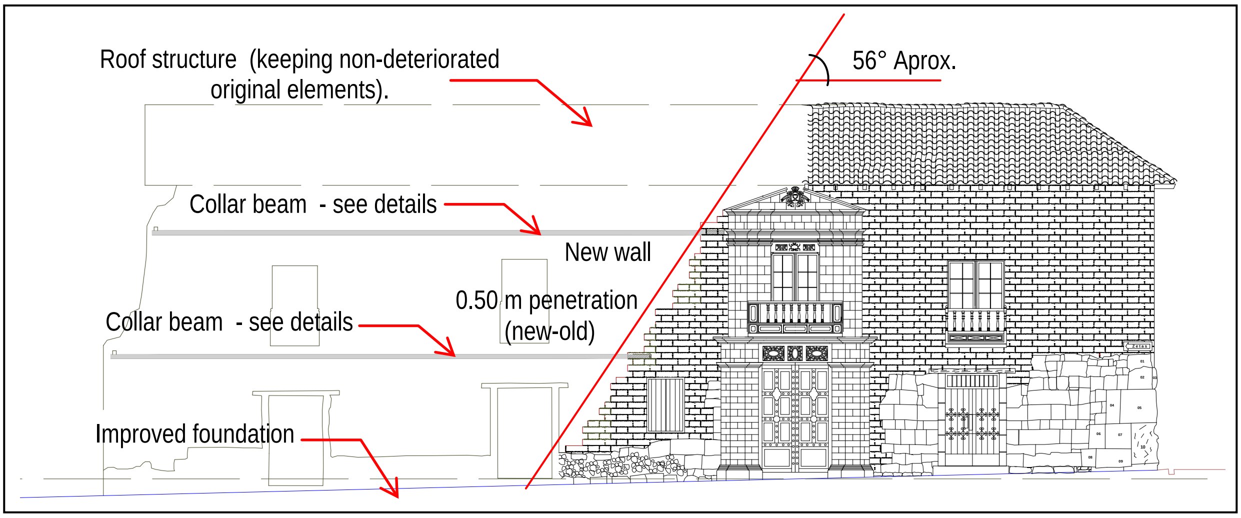


Fig. 13 - Intervention of the facade.

The combined alternatives of retrofitting using rigid diaphragms and collar beams must be completed with details. Only some of such details are shown next.

A wood collar beam was placed on the walls of the restored sector of the mansion (Fig. 14). Detail A shows the connection of the collar beam at the corner.

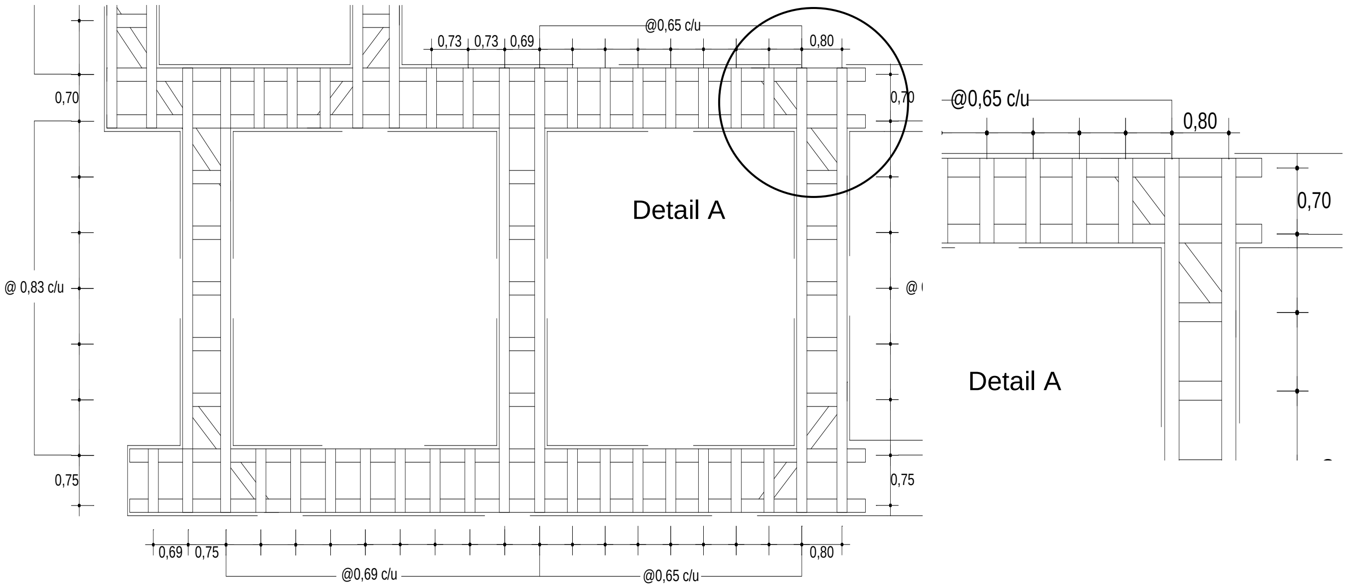


Fig. 14: Collar beam (plan view)

A rigid diaphragm made of a wooden grid, whose main function is to uniform and restrain displacements of the walls, was designed on the floors (Fig. 15).

- Detail A shows a transverse stiffening system using post tensioned wood pieces. Thus the diaphragm becomes more rigid.
- Detail B shows the connection of the beams of the diaphragm with the outer walls through steel rods. This alternative consists of a steel plate on the outside of the wall with two parallel holes in it. At the end of the bar, screw thread is created. A nut will be fastened to the screw thread to attach the steel bar to the wall.

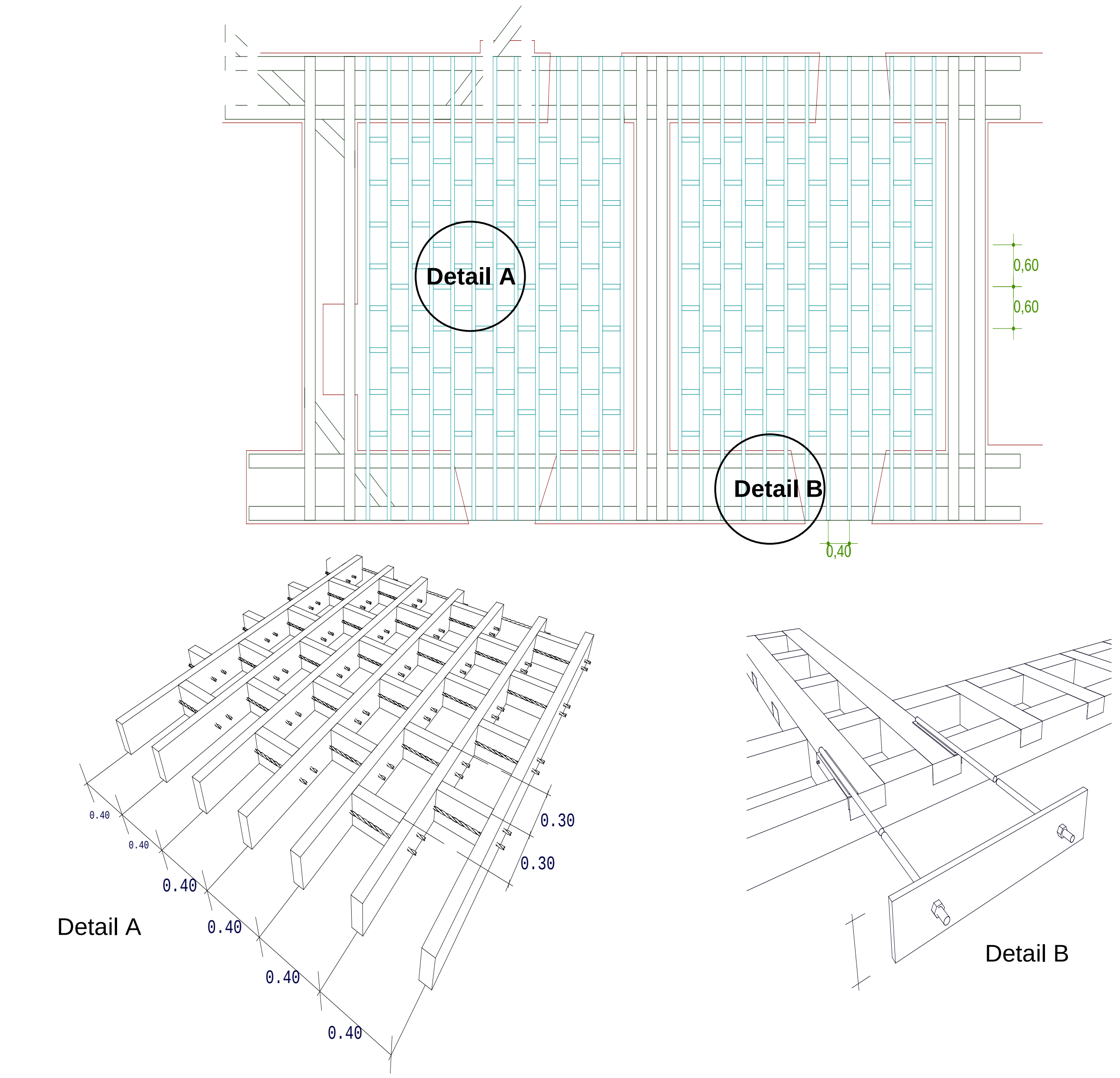


Fig. 15 - Diaphragm (plan view and details)

5. Conclusions

5.1 To understand the whole behavior of any historical building, is important the careful auscultation of the foundation. The explored soils are sandy and clayey with a bearing capacity of 88 to 91 kN/m^2 and a settlement of 19.2 mm. The foundation in many parts is insufficient requiring substantial improvement. The adobe strength varied from a minimum of 112 kN/m^2 to a maximum of 659 kN/m^2. The average modulus of elasticity of adobe for the first floor is 7523 kNg/m^2 and for the second floor 8403 kN/m^2.

5.2 Analytical studies based on models allow a proper choice of reinforcement systems. The horizontal bending stress at the middle of the wall is reduced due to the presence of the reinforcement. This stress reduction reaches 30 % in the case of vertical compression at the base of the wall; however at the middle of the wall the stresses for the reinforced model suffer an increase of 2.4%.

5.3 The study case presented here could be considered representative for future studies in the historic center of Cusco because of its multidisciplinary approach.

6. Acknowledgements

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