Seismic Assessment and Retrofitting of Peruvian Earthen Churches by Means of Numerical Modelling

C. Fonseca Ferreira & D. D'Ayala
University of Bath, United Kingdom

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SUMMARY:
Religious buildings erected throughout the Andean Cordillera in Peru during the Hispanic Viceroyalty of Peru, from 1534 to 1821, form a historic typology composed of several hundreds of buildings. These churches were built with a massive assemblage of thick adobe walls and buttresses with rubble stone base courses and a traditional timber pre-Hispanic roof structure. The longitudinal walls are restrained by timber tie-beams anchored to the walls. The present paper introduces the numerical modelling and structural analysis of the Church of Kuño Tambo, which is representative of the aforementioned typology. A finite element mezo-model is used to assess the global structural capacity of the building under lateral loading for different structural conditions.

Keywords: earthen construction, historic buildings, finite element mezo-model, structural capacity

1. INTRODUCTION

1.1. The SRP Project

The present research is part of the 'Earthen Architecture Initiative – Seismic Retrofitting Project in Peru' (SRP), a collaboration project of The Getty Conservation Institute, the University of Bath, the Pontificia Universidad Católica del Perú, and the Ministerio de Cultura del Perú. The project aims to research, design and validate seismic strengthening techniques for historic buildings built with earthen materials in Peru. The SRP identified four historic typologies of buildings erected during the Hispanic Viceroyalty of Peru and selected four prototype building, representative of each typology. These typologies were assumed as priorities for application of seismic strengthening techniques due to their high significance for the Peruvian culture and heritage and due to the potential high impact of the strengthening interventions in the local communities and also at a national and international level in seismic prone areas, especially in Latin America where similar historic typologies can be identified. A detailed description of the criterion followed for the selection of the prototype buildings can be found in Cancino *et al.* (2012).

1.2. Traditional earthen churches

Earthen construction is part of the history and culture of Peru. From the archaeological sites built by pre-Hispanic civilizations up to the adobe churches and traditional houses erected during the Hispanic Viceroyalty of Peru, historical buildings made of earthen materials play a significant role in the everyday life of the Peruvians. In particular, earthen churches erected throughout the Andean Cordillera in Peru, during the Hispanic Viceroyalty, a period spanning from 1534 to 1821, form a historic typology composed of more than 500 similar buildings that are centres of social and religious interaction of the villages.

Despite being more common in rural areas, for instance throughout the region of Cusco, similar religious structures were built in Lima from the end of the 16th century until mid of the 17th century, as suggested by San Cristobal (2003). However, according to the same author, a substantial number of temples was severely damaged by the 1687 and 1746 earthquakes and later rebuilt with different construction solutions.

The structural system of these churches is composed of thick walls made of sun-dried mud brick (adobe) masonry, stiffened by buttresses and isolated from the ground by a continuous rubble stone masonry base course. The roof's structure is a flexible system of trusses, known as the "par y nudillo" technique, which is supported by discontinuous wall plates sitting on the top of the walls. The longitudinal walls are restrained by wooden tie-beams which are fixed to the walls by timber anchors in some cases. These churches commonly have one tower, either adjacent to or meters apart from the building, also made of adobe masonry. In the former case, the tower's structure is usually independent from the rest of the building, according to Esquivel (2009).

1.3. Numerical modelling and seismic assessment of earthen buildings

In literature usually two approaches have been taken so far for the modelling of adobe structures: simplified limit state mechanism approaches or more sophisticated modelling by means of the discrete element method. Limit state mechanism approaches are suited to evaluating safety conditions of relatively simple structures and they require a reduced number of input parameters. Although limit analysis can be useful to verify the stability of portions of the buildings, separated from the rest of the structure by cracks, the location of which can be ascertained by finite element method approaches, its applicability to historic earthen structures, composed of thick walls, might be arguable. Experimental evidences from shaking table tests performed on historic adobe structures (e.g. Tolles *et al.*, 2002) indicate that, when cracking develops, the frequency of vibration decreases and the displacements substantially increase without the formation of a failure mechanism. Limit analysis entails that failure mechanisms form for small values of displacement, and thence it does not reproduce the real structural behaviour of historic adobe structures.

Discrete element approaches have been widely applied to the study of adobe structures. This method is able to simulate the discontinuous nature of the material and the large displacements that adobe masonry can undergo. However, discrete element approaches can only be applied to relatively small structures, with a limited number of elements due to the substantial amount of input parameters required, which increases the complexity of the analysis up to a level where the information required is hardly available for historical buildings and it is difficult to control the accuracy of the results.

At present, finite element software packages appear to be the most appropriate tools to study the global structural behaviour of large structures. To authors' knowledge, their use has not been deeply explored for seismic assessment of historic earthen structures by available literature; though the method has been successfully applied in the simulation of the nonlinear seismic response of adobe structures by, for example, Tarque (2011) and Islam and Watanabe (2004).

2. APPROACH FOR THE MODELLING OF EARTHEN HERITAGE BUILDINGS

Several uncertainties are present when modelling Peruvian earthen heritage buildings for the purpose of seismic assessment and strengthening. They are related to the level of knowledge on the building and the capability of the numerical approach to simulate the real physical problem. Hence, a general approach, able to assess the quality of the modelling process, is proposed (Fig. 1). Initially, information on geometry, construction details and material properties is collected and interpreted. Then, depending on the refinement and quality of the information, more data is collected or partial models of the structures are developed. Partial models are representative portions of the buildings that are used to ascertain the relevance and adequacy of different hypotheses related to geometry, structural interpretations, material models, finite elements' types, contact and boundary conditions. Decisions on the modelling of the global model are based on the results of the analyses performed with the partial models. The results of the analyses performed with the global model could be calibrated/validated by experimental testing, documentation, *in-situ* observation, and by comparing the results of the finite element analyses with the results of other approaches. Since the purpose of the modelling is to assess and improve the structural performance of the buildings under earthquake loading, strengthening techniques are then introduced into the global model with previous testing of different hypotheses with partial models. Hazard/performance requirements are used to check the structural capacity and ductility of the structures for a certain earthquake loading severity.

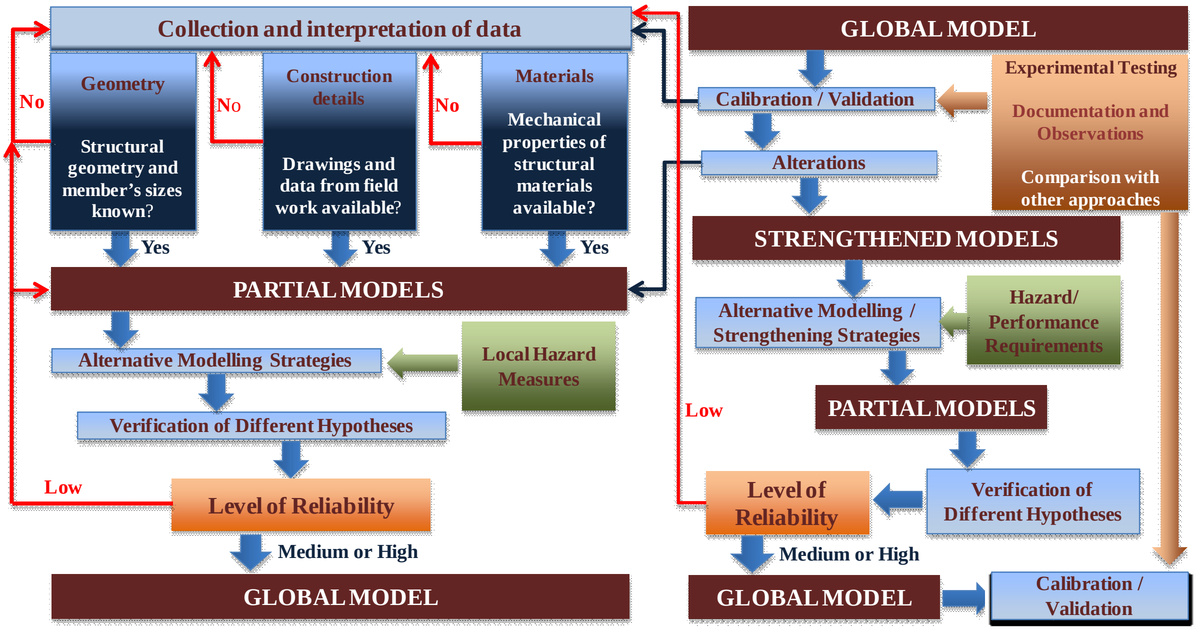

Figure 1. Outline of the general approach

The approach outlined in Fig. 1 includes the assessment of the level of reliability, or quality, of the modelling process. First, control variables of the modelling process are identified for a particular typology of heritage structures. These variables could be associated to geometry, structural details and mechanical properties of the buildings. Then, the quality of the modelling process is assessed by evaluating the level of knowledge, denoted by a knowledge index, and the influence of each control variable on the results of the numerical analyses. The latest factor is denoted by an influence index and it is used to identify the critical variables which have the most relevant effect on the outputs and, thus on the level of strengthening required for the structure achieving a certain performance level. The quality is assessed when different hypotheses are tested both with the unreinforced and the reinforced partial models, since different control variables emerge at different phases of the modelling process and also the knowledge level is not necessarily the same at all phases.

The work introduced in the present paper regards to the numerical analysis performed so far with the unreinforced and reinforced global model of the Church of Kuño Tambo. The complete modelling process of this church, as shown in Fig. 1, is not presented in this paper. The interested reader can find further details in other publications of the same authors, as indicated, for instance, in section 4.1.

3. THE STRUCTURAL SYSTEM OF THE CHURCH OF KUÑO TAMBO

The Church of Kuño Tambo is representative of the ecclesiastical earthen structures erected on the Andean Cordillera during the Hispanic Viceroyalty of Peru. An extensive campaign of condition survey, opening up and recording of essential construction components and connections was performed. Further details of the survey performed and the information collected can be found in Cancino *et al.* (2012) and Lardinois and Cancino (2012). The temple was erected in 1681 in Acomayo

(Cusco) and it is composed of a nave, baptistery and sacristy. The church's floor plan is shown in Fig. 2, where information regarding the thickness, *t*, of the walls and the existence or non-existence of effective connection between the various structural components is included. The height of the walls is not constant due to the fact that they follow the topography of the place. The height of the base course ranges from 1.20 to 1.50m and the height of the walls from 4.0 to 8.5, as measured from the top of the base course up to the top of the gables.

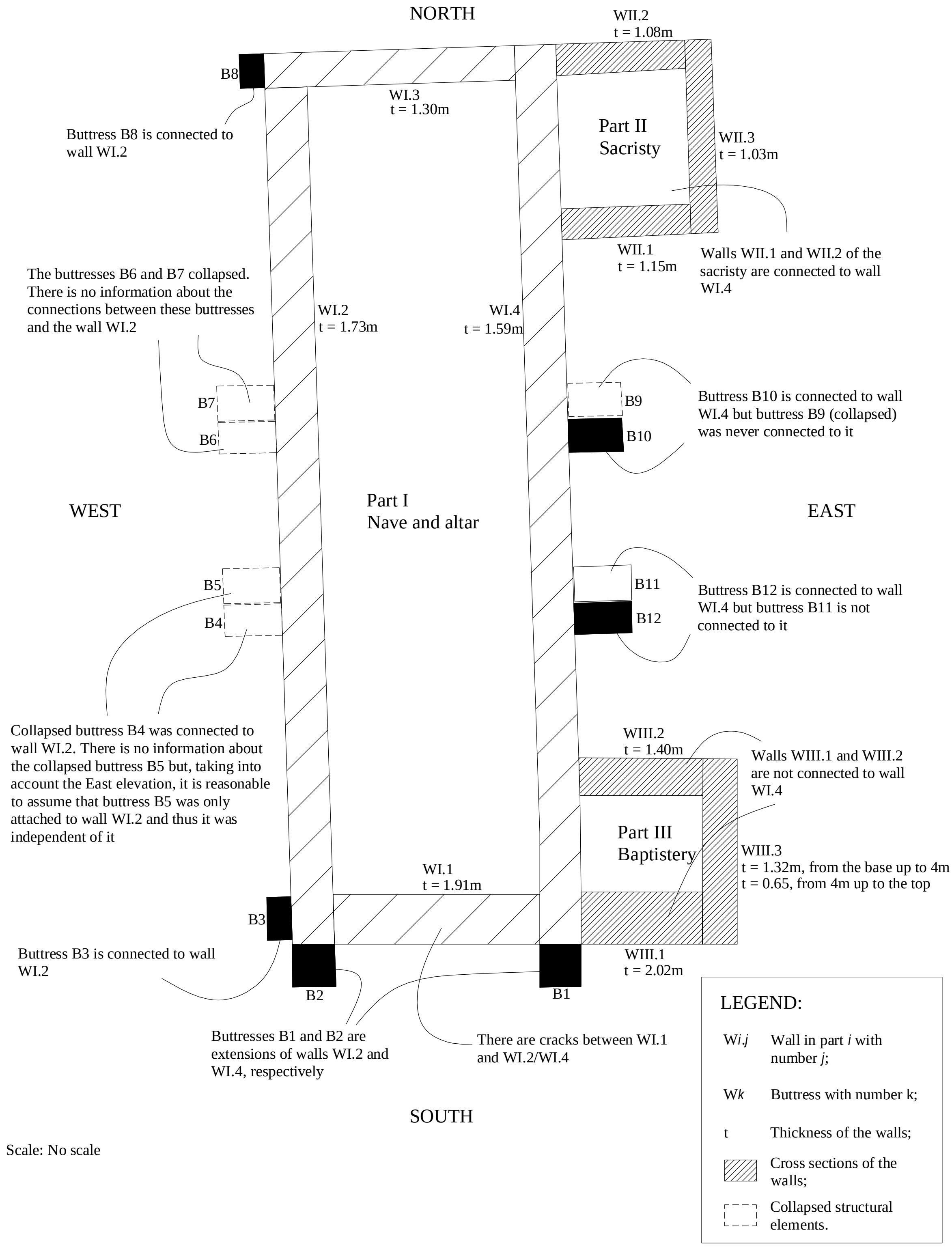

Figure 2. Church of Kuño Tambo's floor plan and structural details

Buttresses and walls are made of adobe masonry, with block of 700x350x200mm laid in mud mortar joint 15mm thick on average (Fig. 3). The base courses, of thickness similar to the thickness of the walls, are made of stones of variable dimensions also set in mud mortar, as depicted in Fig. 3c. In the cases where it is assumed that a physical connection exists between the walls and walls/buttresses it was observed during field work that there is intercalation of the adobe blocks of adjacent parts.

Figure 3. The Church of Kuño Tambo: a) frontal façade; b) baptistery; and c) sacristy

The church has a traditional roof's structure, known as 'par y nudillo' (rafter and collar beam), the construction system of which is based upon pre-Hispanic techniques. The nave's roof is composed of forty-seven roof-trusses, each one with two rafters and one collar beam (Fig. 4a). Wall plates rest on the top of the longitudinal adobe walls and they are composed of several discontinuous segments, each segment supporting four or five rafters. This configuration of the wall plates enables the load that comes from the roof weight of being distributed along the top of the adobe walls; however, it does not absorbs the roof thrust, especially because many collar beams are nowadays damaged and highly deteriorated.

Figure 4. Roof's structure and structural details: a) nave's trussed roof; b) wooden tie-beams; and c) timber anchors

The baptistery and sacristy's roof structure is composed of roof-trusses similar to those observed in the nave; however, the rafters rest directly onto the adobe walls due to the absence of wall-plates.

The rafters of the roof-trusses are connected together at the apex by means of scarf joints, leather straps and/or wrought iron nails. The collar beam is connected to the rafters by leather straps and/or wrought iron nails and it has also a scarf to further improve the connection.

Following pre-Hispanic techniques, small wooden elements, which connect the roof structure to the adobe walls by means of straps of vegetal fibres, working in tension, are, in some cases, used. Traditionally, these restraining elements are inserted during the construction of the walls, passing throughout the entire thickness of them, so that the rafter is tied to the wall both internally and externally.

The longitudinal walls of the nave and the lateral walls of the baptistery are restrained by means of wooden tie-beams (Fig. 4b) of approximately 0.20m diameter. Some of these tie-beams are fixed to the walls by means of timber anchors, as shown in Fig. 4c.

4. NUMERICAL MODELLING AND ANALYSIS OF THE CHURCH OF KUÑO TAMBO

4.1. Finite element model of the global structure

A mezo-modelling approach based on the finite element method is applied to the analysis of the Church of Kuño Tambo under lateral loading, using the software package ALGOR© (version 2011), since the purpose of the present work is the assessment of the global response of the building and, hence, phenomena occurring at a micro-level in the units, mortar and interfaces can be overlooked. Apart from the existence of straw in the adobe blocks, units and joint's compositions are usually similar, and, in some portions of the walls, the units and joints are hardly distinguishable due to the many centuries of weathering. Observation of the Kuño Tambo's walls indicates that the level of deterioration of the joint's mortar is usually either similar or lower, depending on the walls' orientation, than the level of deterioration of the units, despite the absence of straw in the mortar's composition. This observation could signify that, at some locations, the current mortar corresponds to a repointing material, which was applied during the lifetime of the building to compensate the loss of the original material. Due to the aforementioned observations, the assumption of adobe masonry as a continuous and homogeneous material appears to be acceptable for the objective of the modelling.

The walls of the church are thick, with a slenderness ratio (height/thickness) lower than 6, and hence, it is expected that the stresses do not remain constant through the thickness due to eccentricities of the vertical loads and bending and shear caused by lateral loading. This was further evidenced by the analyses performed with the unreinforced partial models. Volume finite elements are adequate to model these structures, as the through depth shear strain/stress, for instance, is properly simulated.

The roof's structure is not modelled since it is difficult to simulate the complex relative rotation and sliding that the typical connections of the roof undergo. Furthermore, the failure of these connections usually relates to localized damage of the roof's structure rather than failure of the walls.

The results of the analyses performed with partial models of the church can be found in D'Ayala and Fonseca Ferreira (2012). Different hypotheses were compared regarding choice of finite elements and material models and convenient simulation of boundary conditions. In summary, the modeling hypotheses selected for the global model are: *i*) use of volume elements rather than 2D finite elements; *ii*) use of a soil mechanics based material model, the Drucker-Prager model (Drucker-Prager, 1952), rather than a concrete theory based material model; and *iii*) use of elastic springs rather than rigid boundaries at the level of the foundations for the purpose of avoiding spurious stress concentrations.

4.2. Assessing different hypotheses for the purpose of improving the seismic response

The current structure of the Church of Kuño Tambo has suffered the collapse of some buttresses and material decay. Furthermore, there is evidence of the existence of timber anchors in only few tie-beams of the nave and in the baptistery. The rehabilitation and strengthening of the church has been studied by on-going research, taking into account the significant cultural value of the building, the seismic hazard of the area and the past seismic history of the structure. In the following, the preliminary conclusions of this research are presented. The response of the structure under lateral loading is investigated for different hypotheses, in which the collapsed buttresses and traditional strengthening techniques, as the introduction of wooden tie-beams anchored to the walls by means of timber anchors, are modelled. The hypotheses studied so far are the following: H_1) current structure without tie-beams; H_2) current structure with tie-beams; H_3) Rehabilitated structure without tie-beams; and H_4) Rehabilitated structure with tie-beams. Although H_2 is called "current structure", it corresponds, in reality, to a strengthened model of the church where all tie-beams are perfectly connected to the adobe walls by means of traditional timber anchors, and thence the global structure is able to work as a unity. Hypotheses 3 and 4 are called "rehabilitated" since the models assume the rebuilding of buttresses B4 and B6 (see Fig. 2). In reality, the structural response of the current structure of the church lies somewhere between the response of H_1 and H_2.

4.3. Eigenvalue analysis

Fig. 5 presents the modal shapes of the 1st mode of the hypotheses described above. The fundamental mode of H_1 corresponds to the movement of the West façade (detail 1 of Fig. 5), which is only restrained by buttresses B3 and B8 (see Fig. 2). If the tie-beams are included in the structure, hypothesis H_2, both West and East walls are mobilized (detail 2 of Fig. 5). The inclusion of the collapsed buttresses increases the participation of the frontal and back façades due to the assumption of continuity between all the structural components, walls and buttresses (detail 3 of Fig. 5).

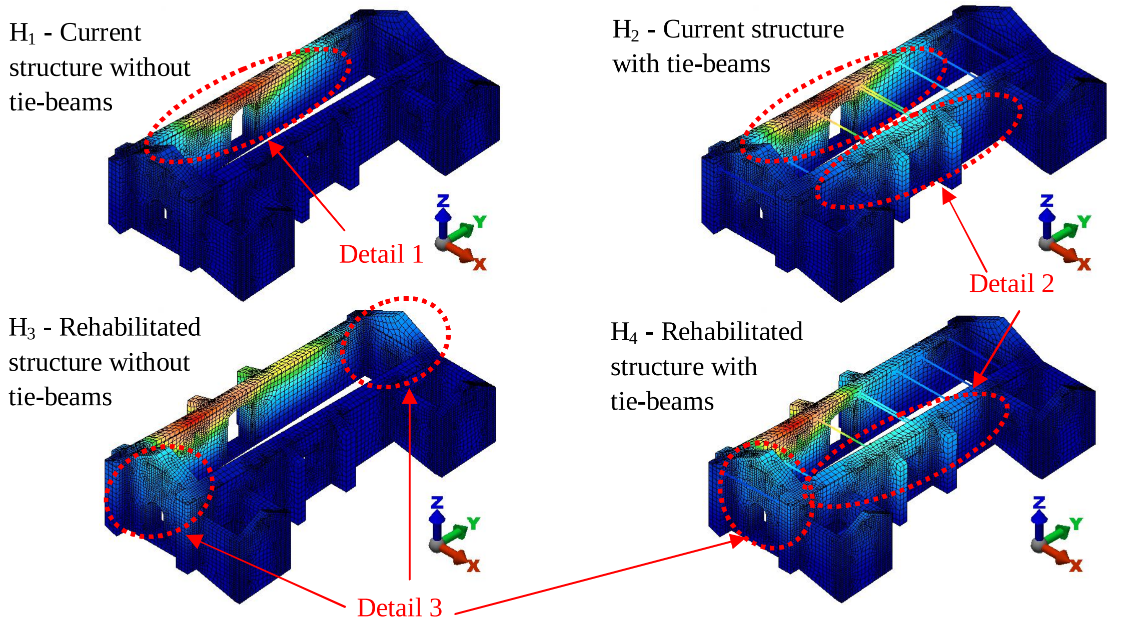

Figure 5. Eigenvalue analysis: fundamental modal shape of hypotheses $H_{i,\ i\,=\,1\text{-}4}$

Fig. 6 presents the natural periods of the first 40 modes for hypotheses $H_{i,\ i\,=\,1\text{-}4,}$ and the modal shapes of mode 2 up to mode 7. The cumulative modal effective masses in the X and Y direction are shown in Fig. 7. If 100 modes are calculated, the cumulative masses are approximately equal to 73.5% and 72.5%, in the X and Y direction, respectively. The dynamic response of the church is characterized by the existence of several local modes, in which different portions of the structure vibrate depending on the frequency, as shown in Fig. 6. This response is typical of unreinforced masonry structures.

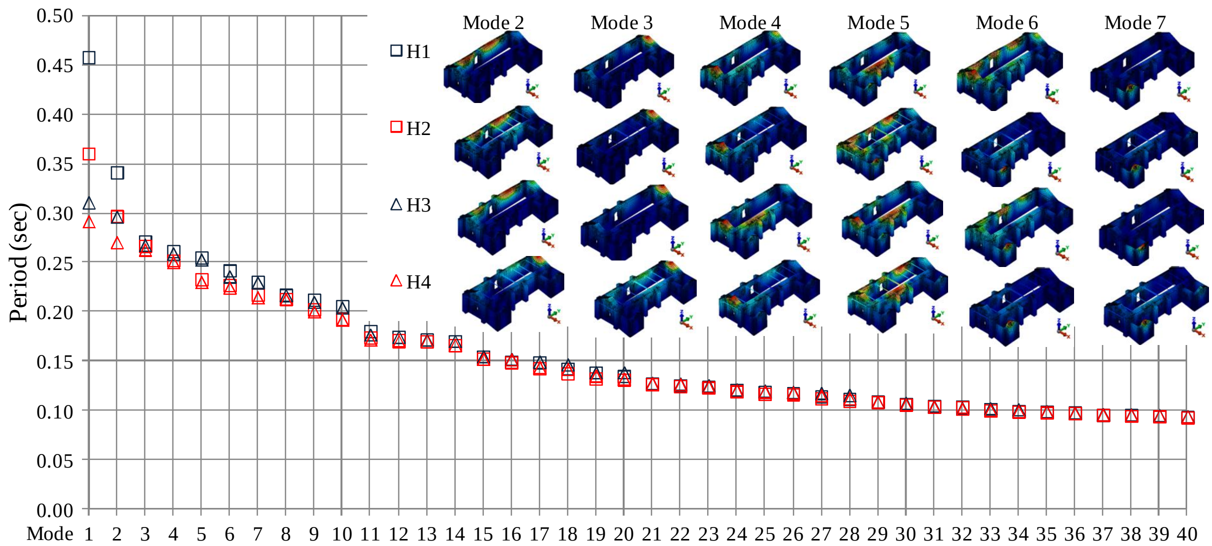

Figure 6. Eigenvalue analysis: natural periods of the first 40 modes

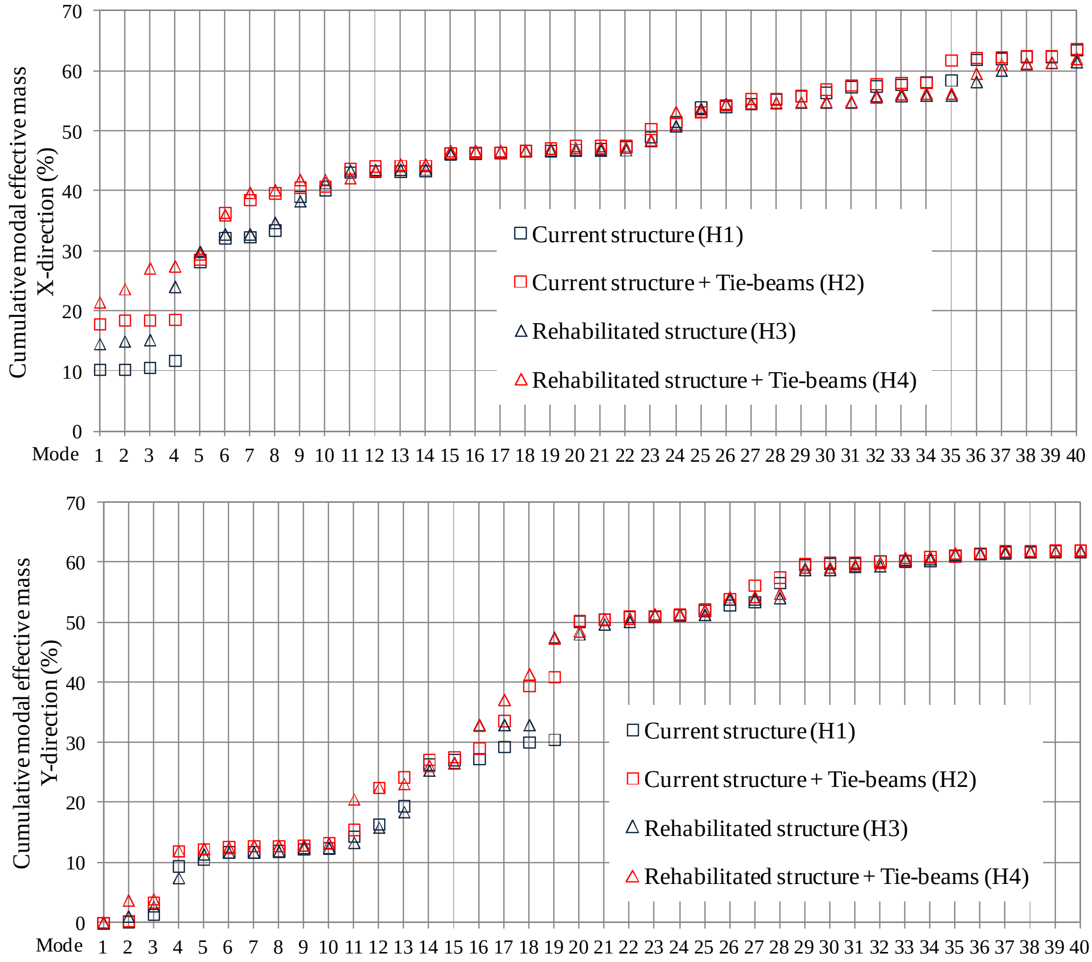

Figure 7. Eigenvalue analysis: cumulative modal effective mass (X and Y direction) of the first 40 modes

The most relevant differences on the natural periods between the different hypotheses occur at the first 10 modes, which are predominantly transversal modes (X-direction), as evidenced by Fig. 7, due to the fact that most of the tie-beams and the collapsed buttresses are effective in this direction. The tie-beams diminish the occurrence of local modes, favouring the global modes, as evidenced by mode 5 (see Fig. 6), implying the possible use of ridge purlins to connect the baptistery and sacristy's façade to the nave and, subsequently, to avoid local modes such as mode 7 (see Fig. 6).

4.4. Nonlinear analysis under simulated earthquake loading

Experimental work performed on adobe walls (e.g. Tolles *et al.*, 2002) shows that cracking occurs for low values of tensile stresses. As soon as cracking develops, degradation of stiffness occurs and nonlinear analysis should be performed to simulate adobe material failure. Nonlinear static (pushover) analyses are performed with the four models of the Church of Kuño Tambo. A uniform lateral load, corresponding to an equivalent static load for an acceleration equal to 0.15g in the global X-direction, is applied. The roof action is accounted for as vertical load on the top of the walls and as horizontal load which is produced by its horizontal thrust action. Table 4.1 presents the values used for material characterization of both adobe masonry and rubble stone masonry. The Drucker-Prager failure criterion is used to simulate the material failure of both types of masonry.

Table 4.1. Mechanical parameters for material characterization

	Specific weight, W (kN/m^3)	El. mod., E (GPa)	Poisson ratio, υ	Cohesion, c (kPa)	Friction angle, φ (rad)
Adobe masonry	1.90	0.20	0.15	30	0.47
Rubble stone masonry	1.90	0.80	0.20	100	0.37

Fig. 8 presents the maximum principal stresses distribution for the four hypotheses described above. It can be seen that the inclusion of tie-beams and collapsed buttresses substantially decreases the deformation of the West wall. However, important concentration of stresses occurs at the level of the top of the base course and at the intersection between the walls and walls/buttresses.

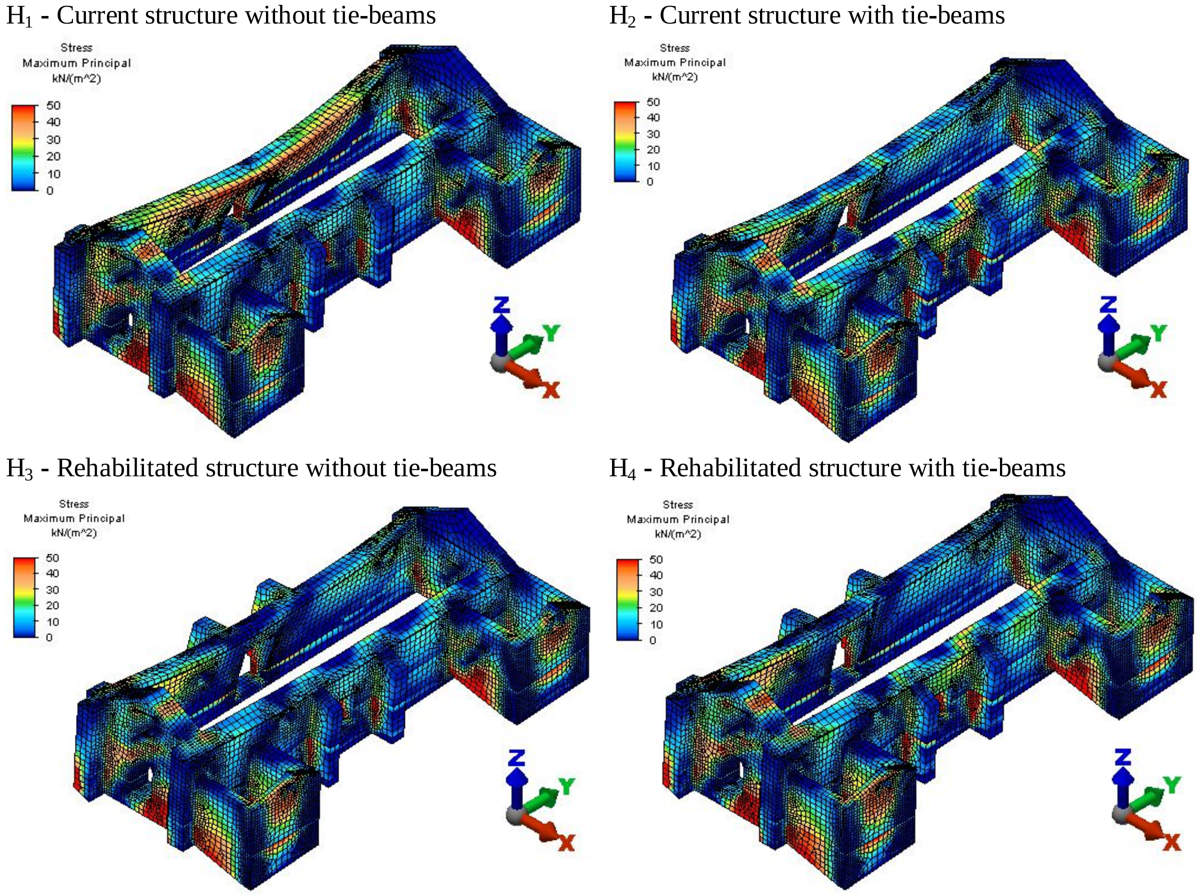

Figure 8. Nonlinear static analysis of the church of Kuño Tambo: maximum principal stresses distribution for hypotheses $H_{i,\ i\ =\ 1\text{-}4}$

The benefit of the tie-beams with anchors and collapsed buttresses is further evidenced by the capacity curves of Fig. 9, where the displacement at the top of the East and West façade is shown.

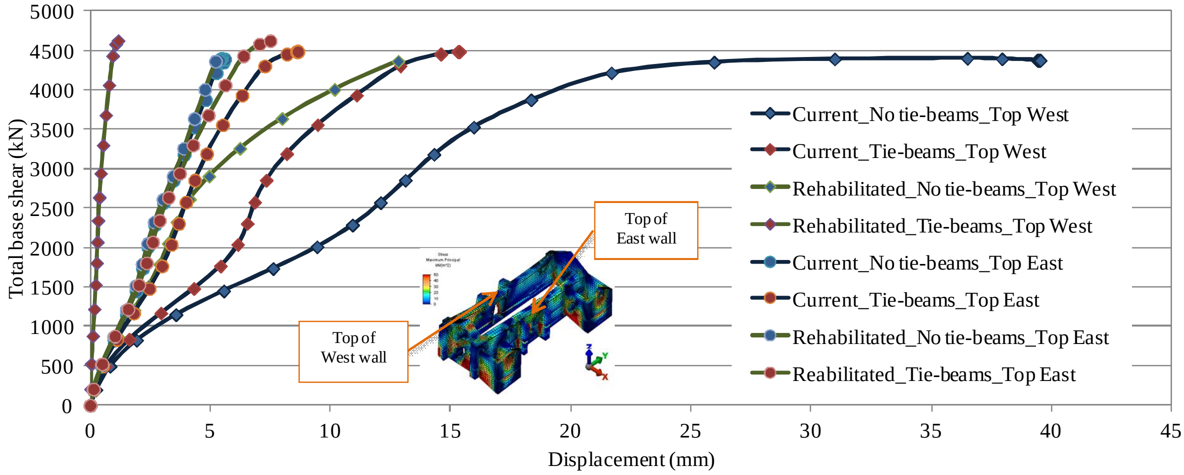

Figure 9. Capacity curves of hypotheses $H_{i,\ i\ =\ 1\text{-}4}$

The structural capacity (maximum total base shear) of the structures is almost the same for the four assumed hypotheses. However, the model without the collapsed buttresses and without the tie-beams (H_1) presents 40mm as maximum displacement at the top of the West wall, while the model with collapsed buttresses and tie-beams (H_4) presents 1.2mm. The substantial decrease on maximum displacement could be sufficient for the wall maintain the stability during an earthquake. Nevertheless, it should be emphasized that these values of displacement appear to be rather low for adobe structures and they can be justified by the fact that the walls are continuously connected.

5. CONCLUSIONS

The Church of Kuño Tambo, a representative structure of the Peruvian temples built with earthen materials, is modelled by means of the finite element method and its nonlinear and dynamic response assessed in order to study possible rehabilitation and strengthening measures. A compromise between preservation of authenticity and improvement of response under lateral loading, in an earthquake prone zone, is of paramount importance when dealing with heritage structures. The results presented above show that a substantial improvement on the structural response could be obtained by applying traditional and non-expensive strengthening techniques, which assure that this compromise is respected. However, it should be emphasized that a good plan of maintenance is also of paramount importance and the numerical analyses have been performed under the assumption of good material conditions. Material decay and more realistic simulation of the connections between the structural components will be considered in future refinements of the numerical models. Also, in the models presented above, it is assumed that the timber anchors are perfectly connected to the walls and their failure never occurs. Experimental work on traditional timber anchors, expected to be carried out within the SRP, will provide information on the failure of these connections, and this information will then be used to refine and calibrate the numerical models. Furthermore, non-linear dynamic analyses will be performed to further verify these preliminary conclusions.

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