Enfoque para el análisis estructural y protección sísmica de edificaciones patrimoniales, a partir de la caracterización de sus particularidades técnicas

Approach to the Structural Analysis and Seismic Protection of Heritage Buildings based on the Characterization of their Distinctive Technical Features

A. Chica ^{1*}, A. Fuertes *

* Universidad Nacional de Colombia, Bogotá, COLOMBIA

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Abstract

The structural behavior of heritage buildings is now a priority for restoration architects and structural engineers, because of the loss of human lives and the damages in the constructions caused by earthquakes. The conventional intervention, which applies the Colombian code for earthquake-resistant constructions (NSR 10), affects the conservation of their heritage values. This is a proposal for a structural analysis applying traditional methods, but including the integral knowledge of the building, as well as the structural principles that their behavior and the development of intervention proposals based on their own structural principles. A group of doctrinal churches in the high lands of Boyacá and Cundinamarca in Colombia (1579-1616) were selected as cases of study, using a basic architectural church model, which maintains the constant geometry, but modifies its constructive technique, with the purpose of understanding the differences and result interpretations for this type of constructions. The evidence shows the importance of involving the comprehension of distinctive technical features, as a way to achieve seismic protection solutions for human life, in the same way as historical construction values.

Keywords: Heritage buildings, structural reinforcement, seismic protection, traditional structures, traditional construction

Resumen

El comportamiento estructural de las edificaciones patrimoniales, es prioridad para arquitectos restauradores e ingenieros estructurales debido a los efectos de los sismos en pérdida de vidas humanas y daños materiales. Las intervenciones convencionales para alcanzar el nivel de exigencia estructural aplicando el Reglamento colombiano de construcción sismorresistentes- NSR/10 suelen afectar los valores patrimoniales. Se plantea aquí un análisis estructural usando métodos tradicionales, pero cuyo enfoque incorpora el conocimiento integral de la edificación, incluye los principios estructurales de su concepción y sus particularidades técnicas. Esto permite comprender su comportamiento y formular propuestas de intervención basadas en sus propios principios estructurales. Se estudió con este enfoque un grupo de iglesias de doctrina del Altiplano Cundiboyacense colombiano (1579-1616), tomando un modelo arquitectónico básico, manteniendo constante la geometría pero modificando la técnica constructiva, para comprender la variación de su desempeño en función de su materialidad. Se propuso una metodología de análisis e interpretación de resultados para este tipo de edificaciones coloniales, abriendo posibilidades de intervenirlas respetando sus valores patrimoniales, poniendo en evidencia la necesidad de involucrar la comprensión de las particularidades técnicas como alternativa para lograr soluciones de protección sísmica a la vida humana y al patrimonio construido y sus valores.

Palabras clave: Patrimonio inmueble, refuerzo estructural, protección sísmica, estructuras tradicionales, construcción tradicional

1. Introduction

Conserving a cultural heritage building means to preserve the heritage values that make it a cornerstone for building the identity of a society; the heritage and testimony of past generations and memory for the future ones. Its special features hinder the generalization of the study and intervention; a proper approach is necessary, which considers its needs and possibilities, by not altering the materiality nor losing what makes it relevant.

Structural engineers tend to overlook the heritage value and many of them ignore the structural behavior of non-contemporary techniques. Something similar occurs with architects and restorers with regard to seismic strength and special structural loads, because they forget the importance of this technical dimension, which is closely related to the conservation activity. The gap between the two knowledge fields avoids an integral work from meeting the objectives of

the standard NSR/10: the protection of human life and material goods, considering that a certain level of damage in the buildings is accepted. Applying this standard to cultural heritage buildings usually affects their conservation and does not enable to reconcile the mentioned objectives with the one that is crucial for the heritage, that is, the conservation of the building itself.

In this perspective, the proposals of structural intervention projects are often the result of trying to force the cultural heritage buildings to behave in a specific way, and are analyzed to comply with standards formulated for contemporaneous buildings. Their study and interpretation are subjected to structural principles, which were used to create the analysis and design software. However, this software is based on the material's mechanical properties under isotropic conditions, and elastic theories that apply constants for each material, such as the Young and Poisson modules. Most of the cultural heritage buildings are incompatible with this concept, and although these values are currently used in the analysis of these structures, they should be applied as orders of magnitude and not as absolute values of their behavior.

¹ Corresponding author:

Universidad Nacional de Colombia, Bogotá, COLOMBIA
E-mail: achicas@unal.edu.co

Some earth construction techniques (mud brick and rammed earth walls), and simple or mixed brick and stone masonries used in these buildings are characterized by the fragile nature of their materials, the absence of rigid connections, the system's discontinuities and the force of friction among their components, as a determining factor of structural performance, being the latter, one of the most relevant. Thus, even when using finite element methods, the contemporaneous structural analysis can entail interpretation errors in the results of mathematical models formulated for these techniques. On the one hand, they are simplified and do not take into account the integral work of the structural system with all its components. On the other hand, it uses hypothesis and analysis methods that do not correspond to the nature of this work. For example, embedment, rigid

connections, including rigid diaphragms, false rigid frames, and shell modeling in case of very thick walls. There is also the fact of speaking about drifts or deformations as a result of the computational analysis, when fractures have already and definitely been produced in the wall system before reaching these deformations, in addition to assuming the stress on structural elements as true, although there are actually important discontinuities in the materiality and in the system.

The above indicates that the analysis software is useful if the model is similar enough to the reality of the building, otherwise, it can lead to erroneous conclusions. An example thereof is Figure 1, which shows the cross sections of a church with a basilica floor plan and different interpretation models for the same structure, obviously with different results.

Figure 1. Evolution of structural models simulating the discontinuous nature of the historical building, without embedment and no rigid connection.

It starts by a simplistic condition in letter a), assuming a rigid diaphragm in the roof, introducing the loads directly to the walls and assuming an embedment at the base, a condition that differs from the own nature of the structure. Letters b) to e) are intermediate models that do not correspond to the reality either. Letter f), however, is a solid modeling that allows articulating the wall base and the roof structure, without going into an indetermination in the mathematical model, and simulating the friction connections of the ceiling joist with the wall by using springs. Thereby, it offers a better approach to the building's behavior, and the possibility of proposing intervention that is more appropriate for cultural heritage buildings needs.

The design engineers prior to the development of the classical theory of structural analysis (Romero Martínez,

2005), as well as contemporaneous engineers, promote safe, functional and economical buildings, based on structural principles such as strength, stability and stiffness. The main difference among them is the hierarchy level they ascribe to each principle when approaching the building. The contemporaneous design engineer bases the analysis on the material's strength, thereby searching a neutral equilibrium of the structure for specific loads. Design engineers prior to the structural analysis classical theory were concentrated on the search for balance, by dealing with the dimensions and ensuring that thrust lines were kept inside the structurally loaded section, thanks to the geometric lines that they empirically built and reflected in the architectural proportions. Table 1 shows the structural principles of each one.

Design engineers prior to the development of the classical theory of structural analysis	Contemporaneous design engineers
Make sure a building is:	
Safe, functional and economical	Safe, functional and economical
Priority in the configuration of the structure:	
Stability, stiffness and strength	Strength, stability and stiffness
Structural proposal of the building based on:	
An already built and sometimes already tested prototype.	A pre-defined architectural project.
Dimensioning:	
Of structural elements and wall system based on proportions established in treatises and adjusted according to past and/or similar experiences related to dimensions and materiality (observation and experimentation).	Of the structure considering site effects, by applying a mathematical formulation (matrix analysis), gathering standards and regulations based on a specific use, in order to achieve a specific structural performance.
Design methodology:	
Use of geometry for dimensioning, keeping thrust trajectories inside the wall system, achieving a stable equilibrium.	Use of computers, which makes mathematical modeling easier and allows setting the stresses and strains at each point of the structure for different loadings, as a consequence of factored loads for comparing these values with those of the material's strength and deformation obtained in the laboratory and affected by certain reduction coefficients.
You obtain a structure that:	
For a certain loading level, bases its balance on stability (stable equilibrium), suffers brittle failure and dissipates energy through fracture.	Given specific loads, bases its balance on the strength of the material and the system includes the capacity to deform, to resist loading/unloading cycles without yielding, thereby achieving a neutral equilibrium; is ductile and dissipates energy due to the relative movement of the elements and the materials behavior in the inelastic range.
The structure failure is:	
Sudden and progressive, generated when the thrust trajectory is out of the section, with a tensile stress concentration (it does not resist stress) that degrades the material, reducing the compressive capacity caused by section loss. Slender elements such as bell-gables, towers and bell towers are the first to collapse; subsequently, other failure mechanisms take place, and in the presence of loads exceeding the limit equilibrium state, the roof structures and supporting walls fall down. Because the failure is unexpected, there is not enough time to evacuate the site, with the possible loss of human lives and irreparable damage.	Ductile and progressive, the system's redundancy allows the gradual formation of plastic hinges in structural elements, enables loading/unloading cycles. Failure occurs when loads are exceeded, in which case the materials yield and the structural system loses capacity, without necessarily collapsing, which allows the user's timely exit and the subsequent structural rehabilitation.

Table 1. Structural principles of design engineers before and after the classical theory of structural analysis

According to the above, this type of buildings can be analyzed by using contemporaneous methods, such as the finite element method, with models that simulate the structural conditions and interpret the results as behavior and damage trends in the wall system, without neglecting the design's main structural principles proposed for intervention. The results from erroneous modeling of the system, which do not consider the discontinuities nor the support conditions, are not very reliable. Actually, the calibration of models should interpret their failure mechanisms for stability limit states, including the building's existing damages, as demonstrated during the study with the analysis of the system's successive degradation by the separation of elements until collapsing. Currently, existing software such as 3DMURI, 3DMACRO and EXTREME LOADING for STRUCTURES (ELS) model the discontinuity of masonry units based on Coulomb models, which allow analyzing the stability of the elements during the earthquake. Although they are in a developing stage and are not as widespread as conventional ones, they are an alternative for traditional modeling involving the mentioned problems.

In addition to the mathematical model issue, there is the wall system heterogeneity, which further complicates the analysis (even knowing the cultural heritage buildings special features), due to materiality conditions that have not yet been modeled, such as masonry bonds, element layout, shape, and a combination of constitutive and auxiliary materials (masonry units and mortars). Although it is possible to establish the mechanical properties of the material, the system's overall capacity is related not only to these properties, but also to the size, carving, layout, quality, etc.

We also should be aware that these constructions are the consequence of the knowledge of specific historical periods, derived from the often empirical experience, based on geometrical and mathematical principles, and trial and error. This allowed correcting, refining and establishing structural principles for buildings, which were later incorporated through different construction treatises and orally. Different formal and technical proposals arise thereof, with varying solutions that cannot be analyzed homogeneously, because each one develops in a particular technical way, although they correspond to an architectural type.

Therefore, the good criterion of the structural engineer is fundamental and should be based on detailed knowledge of the structure's configuration, materiality, state of conservation and constructive evolution. Equally important is the development of proper modeling of the identified distinctive features, a correct approach to failure mechanisms and the right interpretation of structural analysis results, thereby searching for intervention proposals based on the system's stability and not pretending to solely improve or modify its strength or capacity. It is imperative to apply specific design hypothesis for simple masonry structures; as (Heyman, 1995,17) suggests, there is no tensile strength in the constitutive material and the compressive strength capacity could be considered theoretically infinite, due to the considerable thickness of the wall system. Moreover, due to the layout of elements and bonds, no displacement failures are observed; and without doubt, the local stability is dependent on the overall stability of the construction, which is evaluated through the failure mechanisms according to the limit states established for the analysis. Finally, the building's earthquake resistance does not solely depend on the type of material, but also on the layout of the elements and their proportion.

2. Analysis Methodology and Procedure

In order to recognize the influence of these distinct features on the structural performance of Colombian heritage-construction solutions, the research project applied this approach to the analysis of Indian town churches located in the highlands of the Departments of Cundinamarca and Boyacá, which were built between 1579 and 1616. The research was based on technical diversity findings included in the PhD thesis of (Chica Segovia, 2015), which identifies six architectural models using base construction techniques introduced during the conquest of the American territory that are currently present in most Colombian cultural heritage buildings, built during the colonial period. Initially, the churches indicated in Table 2 were selected, among a large number of cases, for analyzing the structural vulnerability and the mentioned impact; therefore, they were modeled according to the parameters described above.

Table 2. Studied Churches

Church	Technique
Chía-Pasca-Saque (Cundimarca) 1579 Demolished	Rammed earth wall, brick vertical reinforcement and course Roof: Collar beam
San Pedro de Iguaque (Bocayá) 16 th Century In ruins	Rammed earth wall, adobe vertical reinforcement and course Roof: Inexistent
Turmequé (Bocayá) 1579 Intervened	Carved stone, brick vertical reinforcement and course Roof: Scissors truss
Chivatá (Bocayá) 1579 Intervened	Carved stone, brick vertical reinforcement and course Roof: Collar beam
Monquirá (Bocayá) 17 th Century In ruins	Carved limestone Roof: Inexistent
Oicatá (Bocayá) 1602 Intervened	Rammed earth wall, brick vertical reinforcement and course Roof: Collar beam

Initially, the specific analysis for these churches was found to be insufficient, given the uncertainty generated by their formal particularities. Therefore, it was decided to use

the basic architectural model introduced to the New Kingdom of Granada in 1579 by Spanish artisan builders, bricklayers and carpenters, as shown in Figure 2.

Figure 2. Chía-Pasca-Saque Church, according to the work contract description (AGNC.s.Colonia.f.Fl.t.21.r.45.f.850r and v [1579]), compared on site.

The analysis sought to eliminate the problems associated to the constructive diversity, including substantial structural improvements, trying to respond to local conditions such as earthquakes, climate, soils, materials, among others, thereby evidencing the structural deficiencies of the homogenous models initially applied (Chica Segovia, 2015). At the same time, this diversity is one of their most important values given the challenges of their construction and the

availability of materials, trying to adapt foreign models to new geographical conditions and, without knowing, of greater seismic loading. Nevertheless, they are still in place and are part of the local heritage, which was highly interesting for this project.

The particularity of this model with regard to other church solutions of the same period is that it involves the proposal of Spanish constructors, based on previous

experience and knowledge (Floor plan proportion 1:4, walls height = 5 Castilian Vara (vc) in the nave and 6 in the main chapel, thickness = 1 vc. Cyclopean foundation with stone stem walls, $h = 0.5$ vc. The nave walls has rammed earth wall cases with brick courses and 4 brick vertical reinforcement between them. For symbolic reasons, in the main chapel the walls are built with limestone masonry with 7 brick vertical as reinforcement. The only openings are a window in the main chapel and another one in the nave, and the main door. At the front, has two buttresses walls lateral to the façade wall measuring 8 castilian feet (cf), and above there is a roof-mounted masonry bell tower. The collar-beam roof structure has ceiling joists and angle braces in the wall head and paired tie beams separated 10 (cf) from each other, all of them supported on a round log beam. A brick transverse arch separates the nave from the presbytery, allowing the over-elevation of the chapel roof. In principle, there is only one lateral construction for the sacristy at the level of the main chapel of similar materiality, as well as two collateral altars forming a Latin cross plan.

The analysis model involved the mentioned components, including the roof, the wall system made of cases, brick/adobe courses and vertical reinforcements, with the aim of determining the influence of each one by using the

software SAP V.17.3.0, with solid-like discrete elements, in agreement with the actual conditions of the building, that allow considering the influence of the wall thickness and its response on the perpendicular direction thereof. The materials' mechanical strength was based on the works of L.E. Yamín (2007 (2003) and J.C. Rivera (2005), among others. The load variation of the roof, a soil profile type D (NSR/10), and a variation of the seismic acceleration coefficient A_e ranging from 0.10 to 0.30, were considered. The roof response to the structural system was measured with different wood types and wood groups 1, 3 and 5. Control points were determined in the models, with the aim of measuring deformations and stress states, understood as damage magnitude and their concentration zones. Subsequently, the areas presenting stress were degraded continuing the analysis until modeling the total capacity loss of the element, simulating a collapse. The model was verified for different techniques and combinations of materials indicated in Table 2.

Once the capacity results were obtained for each one, it was not possible to establish control points and comparison patterns among them, due to the excessive number of different variables.

Figure 3. SAP model of the church of San Pedro de Iguaque, seismic load analysis along the shorter span

Figure 4. SAP model of the Oicatá church, seismic load analysis along the longer span

This allowed demonstrating that both of them, and all heritage constructions in general, are unique and unrepeatable due to their great number of distinct features (see Figures 3 and 4). Therefore, it was decided to reduce the

number of variables and model the basic church unit, where only the materiality changed for different earthquake intensities, which allows establishing the capacity curve for the proposed system with different materiality (see Figure 5).

Figure 5. Model for the analysis of the prototype of rammed earth wall with adobe vertical reinforcements and courses

3. Results and Discussion

The first analyses of the seismic response of the roof were made with the purpose of verifying the need to reduce the loads as a frequently applied solution. First, to assume mezzanines and roofs as rigid diaphragms to skip their modeling does not reflect the behavior of these buildings. It is logical to think that reducing the roof loads (chusquea, lime mortars and clay tile) by replacing them up to 50% (fiber cement and clay tile), also reduces the base shear and the system's mass, but only by 6%. On the contrary, the function and influence of the considerable weight of the roof structure responds to the stability of the wall system, by increasing the friction among the masonry units. This ensures the continuity of the system, equalizing the deformations among the perimetral walls and contributing to connect the elements conforming the head of the walls, especially when they are

built with mixed techniques using vertical reinforcements and cases of different materiality. Finally, the weight of the roof deck helps to keep the wood units together in the absence of rigid connections.

The roof modeling was performed by introducing springs under the ceiling joist, simulating the force of friction generated between this joist and the walls. When the earthquake intensity along the shorter span of the church cause the inertial forces to exceed the forces of friction among the units, the roof is liberated and probably there is already considerable damage in the perimetral walls (see Figure 6). When analyzing the building in relation to the seismic load along the longer span of the church, we observe an unfavorable roof response to the system, due to the horizontal thrusts generated perpendicularly to the presbytery wall, the front wall and the transverse arch. It should be highlighted that when the roof was not modeled, it was easy to observe these elements in the areas with greater stress concentrations.

Figure 6. Model for the analysis of the church prototype with rammed earth wall, vertical reinforcement and adobe courses, with increased deformation of longitudinal perimetral walls by effect of the earthquake along the short span of the church.

The local constructive evolution of simple and mixed techniques documented by (Chica, 2015) was considered for the wall structure, with the purpose of finding an adequate structural performance of the buildings, by paying attention to their site characteristics. In different earthquakes recorded in the studied period (1594, 1598, 1600, 1616, 1617, 1629, 1644, 1645, 1646 and 1649), important damage was produced in the presbyteries usually supported by the perimetral walls of the naves, the bell towers and the roofs, even to the point of collapsing. The damage was more serious

when local factors, such as the soil or the bad quality work, increased the vulnerability of these buildings.

Earth techniques (rammed earth wall, adobe and rammed earth wall -reinforced with adobe) present the highest structural vulnerability. The generated tension degrades the wall section, reducing the compressive strength, which is more evident with small seismic loads, with A_e values below 0.10. The capacity of the material is exceeded and the overstress rates increase, as observed in Tables 3 and 4.

Table 3. Overstress rates – simple techniques

Material	Rammed earth wall (6 kg/cm)	Adobe (12 kg/cm)	Brick (24 kg/cm)	Stone ashlars (30 kg/cm)
Ae	Rate	Rate	Rate	Rate
	Rammed earth wall	Adobe	Brick	Stone
0.10	11.34	6.95	0.59	0.47
0.15	16.92	10.40	0.86	0.69
0.20	22.47	13.81	1.14	0.91
0.25	28.10	17.27	1.41	1.12
0.30	33.66	20.68	1.68	1.34

Table 4. Overstress rates – mixed techniques

Material	Rammed earth wall reinforced with adobe (12 kg/cm)		Rammed earth wall reinforced with brick (24 kg/cm)		Stone reinforced with brick (24 kg/cm)	
Ae	Rate	Rate	Rate	Rate	Rate	Rate
	Mud wall	Adobe	Mud wall	Brick	Stone	Brick
0.10	2.73	1.84	0.11	0.31	0.21	0.18
0.15	4.08	2.75	0.16	0.45	0.30	0.26
0.20	5.42	3.65	0.22	0.59	0.4	0.35
0.25	6.77	4.56	0.27	0.74	0.50	0.43
0.30	8.12	5.46	0.32	0.88	0.59	0.51

The chart in Figure 7 shows the capacity curve for each material and their combinations. The following stands out: first, the low capacity of earth construction techniques, since the curves are practically overlapped; second, the good performance of mixed techniques compared with materials of greater capacity, such as brick and stone ashlar. However, this is no reason for disqualifying earth techniques; on the contrary, it is demonstrated that the building's capacity is not achieved by its materiality only, but also by the system units' layout; the stability is achieved with the solution of the

constructive system and the geometric configuration of the whole. Therefore, it is very important to gain a profound knowledge of the building's structural system, in order to propose intervention alternatives that are compatible with the system. It does not seem consistent with conservation principles to propose external structures or exoskeletons for the sake of improving the material's capacity and pretend a certain ductility, which is often incompatible with the wall system, due to differences in the stiffness and deformation capacity.

Figure 7. Capacity curve for each analyzed technique

When designing a structural intervention, it can be more efficient and less invasive to control deformations by ensuring the stability of the structural system and, at the same time, to specifically consider the areas where tensile stresses are concentrated. Moreover, there is no need to be concerned if walls show cracks or fractures, because they do not necessarily imply the structure's collapse, but the seismic energy dissipation. The important thing is not to affect the stability of the components, which can be foreseen in the mathematical model, by means of a progressive analysis involving the material degradation in certain areas of the structure, as a result of a clear identification of the failure mechanisms in the system, when thrust lines are out of the bearing walls.

On the other hand, the structural system of walls built with masonries made of clay and stone ashlars show a better

performance, but they were very expensive at the time, so not many of them were ordered. A system with good structural performance at a lower cost is the mixed technique (rammed earth wall reinforced with brick and limestone reinforced with brick), which is an intermediate point between earth techniques and masonries with clay and stone ashlars. The role of the courses, besides leveling the rammed earth wall pieces, is to interlock the rammed earth wall vertical reinforcement in the form of chains, thus leveling the wall distortions due to mechanical differences between the materials. The stem wall evidences an important concentration of tensile and compressive stresses, because, in addition to fulfilling constructive and durability functions in the system, it is a key factor in the system's stability, as well as the top courses and the leveling of the wall supporting the ceiling joist, which supports the roof structure. All these

elements together maintain the continuity of the wall's combined system.

Table 5 shows a summary of the results, indicating the overstress rates and damage magnitude, represented by a

relative displacement value of the perimetral wall. In Turmequé, Chivatá and Oicatá, although they have been intervened, this condition was not taken into account and neither were the buttresses of the latter.

Table 5. Geometric comparison of the analyzed churches and their overstress rate

CHURCH	TURMEQUE	CHIPASIQUE	CHIVATA	OICATA	MONQUIRA	SAN PEDRO DE IGUAQUE
Total Area (m)	823	604	432	371	352	339
Width/Length Ratio	1: 4.5	1 : 4.0	1 : 3.0	1 : 5.3	1 : 4.0	1 : 4.0
Roof System	Scissors	Collar Beam	Collar Beam	Collar Beam	Collar Beam	Collar Beam
Truss Span (m)	10.5	9.6	9.14	6.6	8.0	8.8
Perimetral longitudinal Wall Height (m)	9.3 Slenderness 6.2	6.38 Slenderness 6.9	6.5 Slenderness 5.90	5.63 Slenderness 7.7	5.45 Slenderness 6.05	6.0 Slenderness 7.6
Total Area Walls (m)	221.18	109.8	102.4	82.2	83.3	69.4
Wall Index X	0.9	0.86	0.82	0.86	0.79	0.71
Wall Index Y	0.31	0.51	0.26	0.41	0.24	0.35
Seismic Risk Zone	Medium Ae=0.13	High Ae=0.16	High Ae=0.14	Medium Ae=0.13	Medium Ae=0.09	Medium Ae=0.10
Weight (ton)	4740	1850	1277	970	923	848
Wall Volume m ³	2464	856	687	450	445	394
Base Shear (V)	V=616 ton, shear stress 0.27 kg/cm	V=296 ton, shear stress 0.27 kg/cm	V=178 ton, shear stress 0.17 kg/cm	V=127 ton, shear stress 0.15 kg/cm	V=93.1 ton, shear stress 0.10 kg/cm	V=84.7 ton, shear stress 0.12 kg/cm
Perimetral Wall Overstress Rate	4.5	6.9	5.8	5.1	4.0	4.5
Type of Damage	severe	collapse	severe	severe	medium	severe

4. Conclusions

The obtained results lead to the following conclusions:

- Heritage buildings are special, unique and unrepeatable, which makes it difficult to compare their structural performance or analyze them based on a single materiality.
- In these constructive techniques, seismic loads are opposed to the forces of friction of the elements of the structural system.
- The permanence of the analyzed Indian town churches is mostly due to their location in medium-level seismic hazard zones, and because the basic model introduced by the spaniards was modified, by developing new materials and structural systems such as buttresses, which currently contribute to stabilize the system.
- Mathematical models are useful when they represent an idealized condition of the real structure, by means of a theoretical model that you can actually analyze with the available procedures, which reflect the geometry, materiality, loads, connection between the elements and real support types.
- The finite element structural analysis must go hand in hand with the calibration of the model, with regard to the damages set forth and the formulated damage mechanisms.
- The engineer's criterion is reflected on the profound knowledge of the building, its distinct features, the pathology, constructive evolution, failure mechanisms, among other essential aspects for analyzing the building.
- The total discontinuity of the materiality and the structural system that characterizes these buildings causes the magnitudes obtained in the computer, as a result of analyzed models, to follow behavior and magnitude trends of probable damage in the structure.
- Concerning the analysis of the construction's overstress rates, the failure mechanisms of the system should be interpreted in order to establish those that actually imply the structure collapse or a risk for the users.
- The damage is initially generated by the fracture and fall of the bell gables and bell towers; then, there is the loss of stability of the upper perimetral walls and the fracture of the tympanum on the presbytery wall and the façade, which is caused by the longitudinal thrust of the roof structure.
- The presence of cracks and fractures in the heritage construction built with these techniques does not necessarily represent the collapse of the structure.
- The configuration of the studied heritage structure is based on the following order of priority: stability, stiffness and strength, where stability is the predominant condition in the analysis, and this is the direction that structural consolidation interventions should take, together with the specific intervention of the zones concentrating the tensile stresses that imply the loss of equilibrium of the system.
- The basic models analyzed with different materials allowed establishing the importance of rammed earth wall vertical reinforcements, courses, roof, and the interaction of the whole system in general.
- Earth systems (rammed earth wall, adobe and their combinations) are the least favored by seismic loads, due to the sudden degradation of the material caused by tensile stresses and the reduction of the area subjected to compression in the same wall section.
- The unsuccessful search for giving ductility to the system by including reinforcement elements that increase the material's mechanical capacity are invasive, alter the nature of the system and, above all, threaten the heritage values of the property, which are, in the end, the purpose of the conservation work.

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