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SEISMIC RESISTANT ADOBE WALLS AND EARTHEN FRAMEWORK VAULTS AT THE COMPAÑIA DE PISCO CHURCH IN PERU

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Theme 7: Ancient/Historic and Innovative Solutions for Damage Prevention and Performance Improvement
Keywords: Dome, earth, seismic

Abstract

On the occasion of the reconstruction of masonry vaults of the cathedral of Lima in the 17th century, master builders demanded the need for construction systems that would lessen the impact of earthquakes on the building. This situation resulted in an expert debate to determine the nature of damage resulting from earthquakes, the problems validated as being due to horizontal forces, and possible seismic-resistant solutions to be adopted, leading to the eventual introduction of earthen framework vaults. Contemporaneously, La Compañía de Pisco church was destroyed by the earthquake of 1687, which is why the most suitable type of structure was analyzed for erecting the new building, based on the conclusions from the debate on the cathedral of Lima. Finally, both temples had their vaults rebuilt with frameworks in 1691 and 1725 respectively, supporting them on properly reinforced adobe walls. Three hundred years later, the Pisco area was shaken by an earthquake that destroyed La Compañía de Pisco church, which had endured until then, revealing the notions of earthquake-resistance that the builders had used in the earthen construction of churches, but which was forgotten in the modern consolidation interventions of this temple.

1. INTRODUCTION

Since the dawn of the Spanish presence in Peru, stone and brick were materials regularly employed to build vaults and domes, constructed following the method of proportions and stability (Huerta, 2004). Promptly, Hispanic builders noted that the newly settled lands were consistently shaken by earthquakes of a high intensity, causing the collapse of most of the vaults, which until then were not prepared to deal with events of this magnitude (1).

During the 17th century, different ways to build masonry vaults had already been experimented with in many cities of the Viceroyalty of Peru; however, without having found a reasonable response in terms of time, economy and stability against earthquakes. Amid this building landscape, earthen-framework vaults were introduced in the mid-17th century.

2. THE CATHEDRAL OF LIMA AND THE TECHNICAL DEBATE OF MASTER BUILDERS

A crucial moment for the development of framework vaults in the Viceroyalty of Peru was the case of the reconstruction of the vaults and the walls of the cathedral of Lima. The original masonry groin vaults, following the earthquake of 1609, were badly damaged, so an arduous debate between the main builders of the city occurred to determine the best way to repair or even to replace these vaults. The dialogue was focused on how to stabilize the thrust of the vaults towards the walls during an earthquake, by increasing their thickness. The subsequent findings of the damage that earthquakes caused in these types of vaults motivated an anachronistic use of ribbed vaults. The vaults of the cathedral of Lima were rebuilt with this system, with the conviction that the concentrated thrust in a ribbed vault would guarantee their stability during earthquakes. Therefore, it would be sufficient to provide the adobe walls with abutments, located at thrust points, with a thickness sufficiently able to absorb out-of-plane forces (2).

A new turning point was marked by the 1687 earthquake, which caused the collapse of the new vaults, leading again to the reflection on the best way to rebuild the vaults of the cathedral. Then, Fray Diego Maroto offered the Ecclesiastical Council a vision of structural safety from the framework vaults built by himself some years before in the Church of Veracruz and the Church del Sagrario, proposing to reconstruct the vaults of the cathedral using this same system (3). Pedro Fernandez Valdes wrote that adobe abutments could not

a) b)
Fig.1 Lima's cathedral vaults: a) Soffit; b) *Extrados* (credits: Pedro Hurtado Valdez, 2007)

contain the horizontal forces taking place during earthquakes, particularly in the upper parts of the walls. Therefore, it was preferable to decrease weight by building new vaults of earth and cane framework (4).

The Metropolitan Council instructed Maroto, in his competence as master builder of the cathedral, to design the new vaults, which would be made with trusses with camones and contracamones, i.e. curved timber plank, that are overlapped to form an arc, whose meeting points would occur at the edges and the nails to be staggered. The new vaults required the demolition of the old ones, leaving a part of brick or adobe at the start of the wooden structure to introduce greater stability in the lateral direction of the arches. The use of a chained base was also compulsory, in order to tie the walls together, and as a Tas-de-charge, would receive the trusses (wooden beams). Maroto also gave precise instructions to refill the inner parts of the vaults to contain the thrust from the arches (5).

By 1691, three framework vaults had been built, corresponding to the backside of the main façade of the cathedral. Again, the council asked the master builders for an evaluation of the new vaults considering the earthquake of that year, but the majority noted that their structural behavior had been satisfactory (6).

2.1 Lower-height walls

One of the first actions taken to reduce the effect of earthquakes on buildings was to reduce the height of the buildings, and this occurred especially during renovation and consolidation of buildings damaged by earthquakes. The master builders promptly confirmed the substantial importance given to the estimation of the maximum height that the buildings could withstand under the effects of earthquakes (7).

2.2 Larger-dimensioned abutments

Together with the reduction in the height of walls, greater thicknesses was also considered, thus increasing the mass resisting an earthquake, while also decreasing the slenderness of walls. This idea was also considered for the abutments of the walls that supported the thrust of the vaults (8). Subsequently, it would be verified that the increased mass and stiffness of the work by itself would only counteract earthquakes of moderate intensity. When horizontal forces exceeded the strength capacity of the building, the damage is great, due to the lack of ties between walls, facing the risk of immediate collapse.

2.3 Using a single type of vault

Considering that the original vaults of the cathedral of Lima were, in the nave, segmental arches, and on the sides, of ellipsoidal profile, two different thrusts occurred that did not nullifying each other. This caused a thrust at the top of the walls, which was increased during a seismic event. As a result, it was decided that the same building and design features should be applied to the vaults inside the church (9).

2.4 Tying adobe walls with wooden chains

It was also observed that the presence of a continuous wood tether (not only sleepers) at the top of the adobe walls helped to prevent walls from separating. For framing the vaults, the base of support is used as part of this bond, along with embedment knuckles on the wall.

2.5 Maintenance of the structures after each seismic event

The builders recommended that the structure of the cathedral should be evaluated and repaired after every earthquake, to prevent damage in the next one from becoming accumulative. Also particular meaning was given to ensure the continuous maintenance of the insulation and protection elements for walls and vaults, as well as the coatings of earth and gypsum.

2.6 New lighter and more flexible construction systems

The real breakthrough in earthquake-resistant construction in the Viceroyalty of Peru proceeded from the belief of the master builders, who claimed that it was better to find solutions that would absorb deformations, than to continue resisting earthquakes. The result of this insight was the introduction of the earthen framework, which endowed a reduction in weight to the upper parts of buildings, as well as in belfries and churches domes. This solution, not only slowed the incidence of the horizontal forces, but also, due to the characteristics of the construction system, bestowed structures with greater ductility (10).

Fig.2 The *Compañía* Church, in Pisco: a) In 1920, the church had endured the great earthquakes of 1746 and 1877 without collapsing; b) By 2007, before the earthquake, the building had a cement floor, and the paved streets prevented earthen substrate from expelling vapor (credits: Domingo Canepa, 1920; Pedro Hurtado Valdez, 2007)

3. THE COMPAÑÍA DE PISCO CHURCH

The Compañía de Pisco church was a remarkable religious architectural example of the southern coast of Peru. This temple had a Latin-cross plan, formed by two barrel-vaulted naves and intersected on the transept with seven niches' chapels located at the sidewalls of the nave. This church corresponds to the second construction phase that was built in 1704 by Juan de Almoguera, following the recommendations resulting from the discussion around the Cathedral of Lima, after the previous church has been destroyed by the earthquake and tsunami of 1687. In 1719, the vault of the nave and the dome of the church were already prepared, the walls having been reinforced with wooden beams (11). In 1746, a major earthquake struck the central coast of Peru, but the church suffered no major damage.

In 1767, a Royal Decree was issued ordering the eviction of the Jesuits from Peru and the confiscation of their property by the Spanish Crown. Thus, the church and school annex remained closed until the Superior Board of Uses decided to deliver the building to Pisco's parson in 1785, so as to prevent its decay.

In 1826, a decree was issued dictating that the convents that had no more than eight priests settled in them were to be abolished, and the assets of these convents should be applied to public education. In 1877, a tsunami struck the coast of Pisco, following an earthquake that occurred in Iquique, but there is no register that the church was affected. The Peruvian government issued a law on patronage in 1889, and instructed the Public Charitable Societies with the administration of religious property, leaving the church and a small sector of the school for chaplains, which was later administered by the Vincentians Fathers until 1929.

In 1942, a strong submarine movement, near Pisco, caused by an earthquake of 8.1 magnitude was recorded, but the church withstood it. In 1949, a new earthquake affected part of the temple, forcing maintenance work, although those in charge of the work caused the collapse of part of the vault, and even damaged the front wall. The temple became a repository for the construction materials left after the cessation of the work. The building was once again vacant until 1960, when the National Council of Conservation and Maintenance of Historic and Archaeological Monuments performed restoration work on the church. Further interventions incorporated cement coatings within the structure, while the streets were asphalted and the enclosures and the small square opposite the church paved. In 2003, the Municipality performed an intervention on the façades and the base of the walls, sealing cracks and coating detachments with cement and latex paint.

4. BUILDING AND STRUCTURAL FEATURES

The framework vaults built in La Compañía church corresponded to the arch system, which defines a step forward in the evolution of wood and framework vaults (Meschke, 1989; Balboni & Corradini, 2009). This system is characterized by trusses that discharge the weight of the entire roof, to their locking elements (*encadenado*), and are laterally braced by straps.

This building system is self-supporting, unlike lintel or beam systems that have a greater presence in Europe, where vaults are hung from these. Also, the system is not only intended to define an interior space, but to show the outer volumetric shape a building acquires, as the extrados curvature is evidenced on the exterior. To produce this effect, the curved timber plank (*camones*) profile must be cut twice, providing them with both extrados and soffit. Here are generated lateral thrusts that will be received by the locking elements (*encadenado*), which will transmit such exertions to the walls.

The arch system for framing a vault introduces a new element consisting of adobe fillers in the base area, which seeks to support the resulting force. The use of an adobe infill makes a substantial difference to the vaults proposed by De L'Orme, as well as Spanish wooden vaults (12). However, in the Viceroyalty of Peru, far away

Fig.3 The *Compañía* Church, Pisco: a) Adobe walls coated with cement at the bottom; b) Earthen-framework vault and dome left weathering without an earthen coating; c) Adobe arch with cementitious-coating renovation (credits: Pedro Hurtado Valdez, 2007)

from the new European debate about these structures, the sizing of the elements of the trusses continued, as well as constructive solutions dictated by the experience and suggestions of the respective guilds (13). There are no construction contracts or other documents from the time of tests to verify the behavior of earthen-framework structures, perhaps because construction experience had already shown its static reliability when subjected to vertical loads. Besides earthquakes, real and regular testing of the system's function against horizontal forces, served both to check design proposals, providing corrections and permanent adjustments to improve earthquake-resistant behavior.

4.1 Locking system of the walls

Locking Elements (*encadenado*): The connection between the adobe walls and the vaults was given by a perimeter wooden beam (sometimes double), acting as a locking element at the top of the wall, and as a base for the vaults. This locking system provided the effect of a diaphragm, responding jointly to the movement, since the roofs were flexible and weighed little; the top of the walls could vibrate as a free edge, with inertial force acting inside and outside the plane of the walls. The latter case could result in their separation and overturning, if the positive momentum grew large enough, especially when there was a sizable gap between the reinforcement stirrups of the walls.

4.2 Bearing structure

Trusses (wooden arch): These were constructed from curved timber planks camones and contracamones, placed alternately and united by nails to give shape to the projected arch. Sometimes leather straps were also used to tie the camones, which were installed wet so that while drying, they produced greater pressure through shrinkage, preventing the probability of failure of the camón in the direction of the fiber, motivated by trimming its curvature.

Straps: These were wooden pieces placed horizontally and alternating between the trusses to connect them in their full extent, being separated by a variable distance, but preferably about 120 cm. Their function was to transmit and redistribute the loads of the roofs, in addition to maintaining the separation of the trusses and providing lateral stability.

Adobe infill: At the base of the framework along the wall, between the locking element and the strap, struts were placed and this space in-filled with adobe. Thus, a partial diaphragm was formed to help prevent the lateral movement of the trusses and upright the resulting push. It allowed a safer transmission of the loads near the axis of the walls, and avoided risky eccentricities.

4.3 Locking elements

Laying cane: Locking was achieved by reeds woven and joined to each other by leather straps and attached to the trusses with nails through the straps. Complete reeds were placed at the upper surface that served as the substrate for the earthen coating, while at the intrados, the reeds were longitudinally cut and extended, thus increasing the contact surface used as the support for the gypsum plaster. By placing cross straps at the trusses, to which the rods were fixed, a continuous grid was formed, which improved the distribution of loads and forces on the surface of the vault.

Earthen plaster: This was an earthen layer with a thickness of around 10 cm, made with a ratio of 15% clay, 10% silt, 55% sand and 20% water, also incorporating straw or animal hair to avoid excessive shrinkage during the drying process. The combination of earth with wood and cane produced a lightweight structure, permeable to water vapor, as well as flexible and stable over time. Due to its own nature, the earthen coating also allowed easy repair of cracks caused by earthquakes, because it was simple to remove the damaged areas and put a new layer of earth on a grid of rods, which provided continuity to the coating. The layer of earth placed on the vaults is often stabilized by adding lime (14).

The earthen coating provided insulation and protected the various components of the framework from the environment, as it kept wood elements and reeds dry, due to its low equilibrium-moisture content of 0.4% for a sandy earth with 20% humidity air and up to 6% for a clayey earth with 97% humidity, a feature that was aided by the high capillarity of the earth (Minke, 2001, p. 32-36). Under such conditions, plant fibers have a high resistance to attack by insects and fungi, as insects need to be in an environment with humidity between 14% and 18% to survive; and for fungi more than 20% moisture (Navarrete, 1999, p. 8).

5. ANALYSIS OF THE STRUCTURAL BEHAVIOR OF THE *COMPAÑÍA* DE PISCO CHURCH DURING THE 2007 EARTHQUAKE

Damage caused by the earthquake of 2007 in Pisco permitted limited considerations on the behavior of the vaults and walls of La Compañía de Pisco church.

Fig.4 The *Compañía* Church, Pisco: a) Adobe walls with humidity and differential settlement; b) Adobe walls with loss of the original locking elements and the ties between themselves; c) Crack separating the walls of the tower and façade of the nave (credits: Pedro Hurtado Valdez, 2007)

5.1 Adobe walls

Up until that time, there was a marked deterioration of the walls from the continuous and accumulated damage of earthquakes in the second half of the 20th century, which had not been repaired. Most of the walls were cracked and separated from each other, making their slenderness increase significantly. Consequently, during the seismic action, each portion of wall acted independently in motion, colliding with each other.

In addition, the walls were sealed with cementitious products, as was the pavement of the patio annex to the temple, and the streets with asphalt. This produced high moisture content in the subsoil, which rose by capillarity up into the walls of the church, causing the moisture content inside the walls to be high, resulting in the softening of the adobes and loss of their bearing capacity.

With increasing humidity, the saline soil on which the church was founded led to the migration of salts and their subsequent crystallization within the walls, causing micro-fractures within them. Also, the wooden elements inside the walls, while in a moister environment, were attacked by wood-eating insects and decay fungi, and thus unable to provide ductility for the walls.

5.2 Earthen-framework vault

The collapse of the earthen framework vault was due to factors related to the state of conservation of the structure. This was firstly motivated by the sharp deterioration of the walls on which the vaults were supported, which, during the earthquake, could not withstand the thrusts, overturning at the top and leaving the locking elements (*encadenado*) without support.

As for the second cause, it was due to the deterioration of the vault wood and cane elements. As the coating had not been maintained, the locking elements and the camones had been exposed to the weather and showed attack from wood-eating insects and fungal decay. Having lost many of the pieces of the original vault, its central section had diminished mechanical ability. In addition, the leather straps had loosened, as the wooden pieces lost their consistency and the nails rusted. As the trusses are not continuous elements, and instead obey the effects produced by the rotation of the joints in the camones, stability was left compromised (Marzo, 2006). Equally, cane enclosures were in an advanced state of decay, and the gypsum plaster seemed to have exceeded its saturation capacity to water vapor, thus beginning to transmit even more moisture to the trusses. During the 2007 earthquake, trusses failed in the central area, incapable of controlling the rotation of the camones, while in the area of the camones abutments tended to rise, but without dissociating from the locking elements, and thus maintaining stability (15).

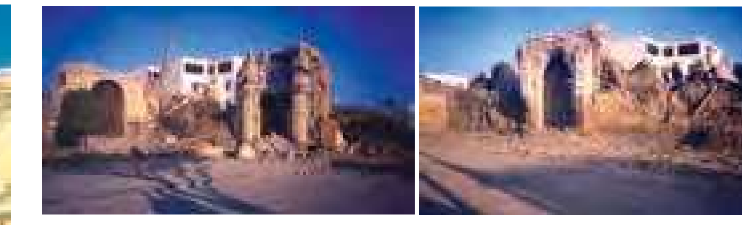

Fig.5 The *Compañía* Church, Pisco in 2007 after the earthquake: a) Area of the main façade and the entrance to the school, already separated from the rest of the wall pre-earthquake; b) Lateral façade also with separation cracks (credits: Pedro Hurtado Valdez, 2007)

6. CONCLUSIONS

Faced with persistent damage by earthquakes in colonial buildings, master builders were needed to adapt the original Spanish architecture to the seismic characteristics of the Peruvian territory, although initial construction difficulties were solved through a continuous process of trial, error and improvement. The result of this experience resulted in the correct construction relationship between adobe wall and earthen-framework vault. These considerations were not taken into account in the interventions to the church during the second half of the 20th and early 21st centuries, with the addition of materials incompatible with earth, and the lack of a basic maintenance of the structural elements. The result was that during the 2007 earthquake, the building, already structurally damaged, collapsed. Surprisingly, the temple that had withstood the great earthquakes of 1746, 1877 and 1942, showing the strength between the earth wall and the dome framework was perfectly stable. Therefore, the restoration of these earthen structures using traditional technology is appropriate. However, if the intention is to experiment with new techniques and materials, it is important to recall that the stability criteria revealed by master builders, 300 years ago are still current.

Notes

(1) In the south of the Iberian Peninsula, there are seismically active areas, though not as frequent (Martínez Solares, 2003). On the other hand, Spanish builders met in the Viceroyalty of Peru repeated earthquakes and of large magnitudes. The magnitude of the earthquake of 1746 has been calculated at 8.4 on the Richter scale, with an intensity of X-XI on the Mercalli-modified scale (García Acosta, 1997, p.12). At this time, the 1755 earthquake in Lisbon had not occurred yet.

(2) Original citation from Juan Martinez de Arrona, who mentions: *"que bajar las naves colaterales y hacerlas de crucería es el mejor remedio que puede haber para asegurar la nave principal… y haber pasado por ellas el temblor grande del año quinientos y ochenta y seis y los que más ha habido sin recibir daño porque son de crucería y en nuestra Santa Iglesia se ha visto lo mal que aprueban las bovedas de arista con los pocos que han pasado por ellas las han dejado tan lastimadas…"* [To go down the high of the side aisles and make ribbed vaults is the best remedy to ensure the nave ... and have gone through them the big earthquake of the year five hundred and eighty-six and others tremors more and has been no damage because they are ribbed vaults and our holy church has seen how badly approve the groin vaults with the few tremors who have gone through them have left them so hurt] (ACML, 1614-1615, 1: f.15r).

(3) Original citation: *"…la nueva forma se ha reconocido por experiencia ser fábrica más segura en tan repetidos temblores mayormente cuando las que hizo de esta manera este declarante en la Iglesia de su Convento siendo así que era de pocos fundamentos en lo tocante a la albañilería las bóvedas que hizo encima de los pilares y arcos que han padecido y no las bóvedas por haberlas hecho de cedro y yeso…"* [The new form has been recognized by experience to be safer than masonry one facing to repeated tremors, mostly when he made in this way, this declarant, in the Church of his Convent, being so it was with few resistances, when it comes to ancient masonry vaults that were built on the pillars and arches that have suffered and not the vaults that I have made of cedar and plaster ... "] (ACC, 1688, f.70r).

(4) Original citation: *"Y así mismo le parece a este declarante no ser buena obra la que se puede aplicar abrigando con albañilería el envano de los pilares para recoger las entradas y menor fuga a los rempujos de los arcos particularmente cuando la experiencia ha demostrado en la obra de la iglesia de san Pedro Nolasco donde se aplicó este género con mas cuerpo y asi en lo grueso como en lo largo y se vino con el temblor al suelo…le parece a este declarante que habiendo de ser de madera yeso y caña no necesita de más aplicación…"* [And so it seems to this declarant not be good work that the buttresses can be made with masonry into the pillars because the thrusts of the arches, particularly when experience has shown in the work of saint Pedro Nolasco church where this genre was applied with more mass and thickness, they fell down with the shake of the ground ... this declarant thinks to be the vaults with wood, plaster and cane needs no further reinforcement] (Id., f.71v - 72r).

(5) Original citation: *"…dicha crucería ha de ser de camón y contracamón encontradas las puntas de las cabezas…y para obrara dichas tres bóvedas ante todas cosas se han de obligar a demoler lo que ha quedado de ellas de ladrillo dejando tan solamente dos varas y media de alto en cada movimiento en los rincones sobre que se ha de asentar sobre yeso un tablón de ochava de grueso… como también se han de macizar todos los rincones de las bóvedas por detrás de la crucería de madera para su resistencia y seguridad…"* [This ribbed vault must be of curved timber plank (camón and contracamón) found their heads ... and for doing these three vaults above all things, it has to force demolish what is left of the ancient vaults with brick leaving only two and a half varas (200 cm) high in every movement in the corners of which has to put one strap of ochava (10 cm) thick on a plaster ... and filling all corners of the vaults behind the wooden rib for the strength and safety] (Id.).

(6) Original citation from Pedro de Asensio who commented: *"…con ellas se ha reconocido la seguridad para los temblores pues acabadas de hacer le sobrevino el temblor del día veinte de septiembre del año pasado de seiscientos y noventa que fue tan grande como el de veinte de octubre de seiscientos y ochenta y siete y causó mayores ruinas en otros edificios que los antecedentes y en estas tres bóvedas no recibieron daño ninguno…"* [With them has been recognized safety for earthquakes, finished doing these vaults occurred the tremor of the day on September 20th last year six hundred and ninety, which was as large as the earthquake of October 20th of the year six hundred and eighty-seven and it caused major ruins in other buildings in the neighborhood but the three vaults did not receive any harm] (Id., f.95v).

(7) Fernando de Cordoba and Figueroa argued that damage to the Cathedral of Lima should be avoided: *"… las torres no suban lo que la montea de la planta muestra que se le quite el tercio de su altura…"* [the towers should not raise the height that the building plans show and that it will remove the third of their hieght] (AAL, 1609, leg.6, exp.17). Earlier, it had been agreed that new construction should not exceed 15-ft high (5 meters), a standard that was ratified by the 1552 Carlos V royal decree. In the 17th century this was extended, in regards to the consolidation of buildings damaged by earthquakes.

(8) Alonso de Arenas argued that the earthquake of 1609 did not cause damage to the Cathedral of Lima. On the original citation: *"Y supuesto que el daño recibido fue la causa dicha y es sin duda no le tuviere el reparo de esto consiste en darle fortaleza y la podrá tener añadiendo a los estribos hechos seis pies y medio de aumento de pilar en la salida y de ancho nueve por manera que ha de quedar el largo del dicho estribo de quince pies y el grueso de otros tantos e ir formado juntamente con los dichos estribos las puertas para que toda la obra vaya a un tiempo trabada…"* [And of course the damage received was such cause and it certainly will it have the repair of this is to give strength and may be adding to the existing stirrups six and a half feet in long and nine feet in wide, so this stirrup will have the length of fifteen feet and similar in the thickness and go formed together with these stirrups the doors for doing all the construction work in enchained way] (Id.).

(9) Original citation: *"Y habiendo visto como tengo visto y entendido antes de ahora el cerramiento que está hecho en la misma Iglesia de las capillas de arista y los arcos aovados digo que están sin fuerza ninguna respecto de no tener estribos suficientes para que puedan hacer fuerza la nave menor en la mayor."* [But seeing as I have seen and understood before now the enclosure which is made in the church with the chapels with low groin vaults and high ovate arches I say there is no force because there is no enough stirrups for support the aisle over the nave] (ACML, 1614-1615, 1: f.8r).

(10) The specific weight of a framework vault is approximately 900 kg/m^3, while granite from Panama, of which much of the Viceroyalty of Peru was built with, is around 2,700 kg/m^3 and coastal brick 1,800 kg/m^3. The travelers of the Spanish scientific expedition of 1748, Jorge Juan and Antonio de Ulloa mentioned according to the original citation: *"… jugando todo el Edificio con los estremecimientos de los Terremotos, y estando ligados sus fundamento, siguen enteramente el movimiento de aquellos; y no haciendo oposición la fortaleza, aunque se sientan en parte, no caen, ni se arruinan tan fácilmente"* [Playing all the building with the earthquakes shakes, and being linked its foundation, it follows totally the movement of the earthquake; and without doing a hard opposition, although partly sit, it do not fall, nor do not easily ruin] (Juan & de Ulloa, 1748, p. 43).

(11) Original citation: *"… la obra de la Iglesia que se esta practicando cuyo cañón esta armado rellenandose y la media Naranja labrada y en…la madera nessesaria para acavar dicha Iglesia la clavaran porsian de llevar cal ladrillos adobe y cañas"* [The work of the church that is building is armed with a barrel vault being filled and the dome tilled and ... the needed wood for finish the church and nailed and to carry lime, bricks, adobe and reeds] (AGN, 1713-1745. Leg. 39, Sec.1).

(12) De L'Orme intuited that the distribution of forces in a structure, made up of many in-between parts and with multiple assemblies, enjoyed stability, because if a component failed, the remaining parts would adjust to this new configuration (De L'Orme, 1576, Ch. VI, f.8r).

(13) The first implementation of static in solving masonry-arch problems was accomplished by Lahire in 1695 using the funicular polygon in his analysis (Huerta Fernández, 2004). In 1825, Johan Voit, the construction Minister of Bavaria, refers to the characteristics of existing masonry arches to indicate the nature of trusses (Hahmann, 2006).

(14) Santiago Rosales in 1740 mentions that in the dome of the church of the Hospital San Juan de Dios, *"…también se me ha de dar la tierra necesaria para torta de por fuera sobre la cual he de poner su torta de cal…" [Also must give me the earth needed for mortar of the extrados and then I will put the lime mortar]* (AGN. Protocolos Notariales, escribano José de Torres Ocampo, 1740-1751, prot. 1048, f.17v, 1740-1751). Joseph de Robles recounted that he had to work on that dome (Sagrario Church) with a mixture of lime over a earth cover («*perfeccionando dicha media naranja (iglesia del Sagrario) con mezcla de cal sobre un jarrado de barro…"*) (AGN. Protocolos Notariales, escribano Alonso Martín Palacios, 1680, prot. 1402, f.1528, 1680).

(15) David Gilly can be considered the precursor for the structural study of wooden trusses, although he considered erroneously that they followed the same principle as masonry arches (Gilly, 1797). Also Johann Albert Eytelwein (1764-1848) assumed the edges of *camones* were rigid connections, speculating that the transmission of forces in compression in the trusses was from the same source as those produced in masonry arches (Hahmann, 2006, p. 1506). Zimmermann and Ardant applied to trusses the 19th-century French studies on the elastic behavior of materials, and they observed that these structures failed in shear joints, not as a result of the vertical system of cutting fibers, but rather as shear in the fibers' direction.

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