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RESEARCH ARTICLE

The Planked Timber Vaults Built in Seismic Zones of South America between the 17th and 18th Centuries: History and Construction Analysis

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ABSTRACT

The western coast of South America is a territory continually exposed to earthquakes, where architects had to experiment proposals that would allow them to maintain the safety of their buildings. Among the different solutions for earthquake-resistant constructions, planked timber vaults appeared in South American religious architecture during the 17th century. This paper explains how the construction technique of these vaults arose and developed in a context conditioned by earthquakes. For the study, architectural surveys of the different variants of South American vaults were conducted, which were confronted with data from archives and historical texts, to later be expressed graphically through the drawing reading method. This method is important to transfer textual information from historical documents to contemporary graphic language and permit to learn more about the architectural heritage, like the construction characteristics of the planked timber vaults and understand the structural criteria followed by the ancient master builders.

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1. Introduction

Since the beginning of the Hispanic presence in South America in the 16th century, master builders used masonry vaults over the naves of churches, according to the directives of the local ecclesiastical authorities. They, following the recommendations emanating from the Council of Trent, favored the vaulted spatial definition, considering it was the better type of roof for a place of worship and that it best expressed the cultural spirit of the Counter-Reformation, mainly in its evangelizing labor in America (Velarde 1980). Guamán Poma de Ayala (1615) drew many cities showing vaulted temples built with brick and stone, in a similar way Reginaldo de Lizárraga (1609) pointed out during his trip through the viceroyalty of Peru, which at that time included a large part of South America. However, the fact that the South American western region was constantly shaken by earthquakes, caused the collapse of many churches, which were not prepared to deal with phenomena of such magnitude. In the south of the Iberian Peninsula there are seismically active zones, but with a very spaced periodicity and with a historical maximum magnitude of 6.8 Mw (Martínez Solares 2003), while the Spanish builders found in the viceroyalty of Peru earthquakes little spaced between them, with magnitudes greater than 8 Mw (Seiner Lizarraga 2017).

Throughout the 16th century and part of the 17th, various ways of raising masonry vaults had already been experimented, without having found the necessary stability against earthquakes (Bernales Ballesteros 1972). In the constant research of construction proposals to guarantee the safety of the roofs, the ribbed vaults were taken up again, assuming their better resistance to earthquakes than the existing barrel and groin vaults, without achieving the expected structural performance (Hurtado-Valdez 2009).

During this building panorama, planked timber vaults were introduced in South America in the 17th century (Hurtado-Valdez 2009; San Cristóbal 2003). This construction system was consolidated and acquired a significant presence in the construction of churches, to such an extent that it ended up becoming a traditional resource and one of esteemed elaboration in these lands. Precisely the aim of the paper is to explain how the construction technique of planked timber vaults arose and developed in South America between the 17th and 18th centuries, in a context conditioned by earthquakes.

Despite the remarkable presence of these vaults in what was the viceroyalty of Peru, it is paradoxical that

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their study has not been approached with greater rigor, because they have been observed mainly from the perspective of the evolution of architectural styles, from which conjectures accepted as valid have been elaborated. Ideas that range from the belief in the use of these vaults only for aesthetic reasons to erroneous structural interpretations when considering them as a curved version of wattle and daub frameworks (Rodríguez Camilloni 2003).

There was even an indigenist vision in the attribution of paternities to its invention, when Diego Maroto was pointed out as the inventor of these vaults in La Veracruz church in Lima (San Cristóbal 1996) or when it is indicated that it was the Portuguese architect Constantino de Vasconcelos and his Peruvian assistant Manuel de Escobar, the creators of this construction system in the vaults of Saint Francis church in Lima (Rodriguez Camilloni 2003).

2. Materials and methods

A first approach to research on the planked timber vaults consisted of the study of historical texts and manuscripts, both those that described their construction characteristics and those that mentioned their behavior in the face of earthquakes that occurred in South America between the 17th to 18th century.

A second level of study was referred to the collection of data from specific examples to know the real praxis of these vaults. The data collection corresponded to a direct approach to the buildings, for which a photographic record, drawing and measurement of visible construction elements were made.

To compare the analysis of the documents with the data obtained from the architectural surveys the method of reading drawings was used, because it allows transferring textual information from historical documents to contemporary graphic language, through sections of construction details shown and explained in isometric drawings (Nuere 1990). Therefore isometric drawings were made to help interpret the details of the different types of planked timber vaults to catalog and explain more clearly the characteristics of this construction system.

3. Results

3.1. The planked timber vault

A planked timber vault is one made with wooden arches, made up in turn of two rows of curved planks, which are joined by their face and offset. The arches are laterally braced between them by means of joists, with a final closing of the extrados with boards or whole reeds. To this end, this vault constitutes a construction technique typical of wood, therefore, different from masonry ones and, as will be seen later, in the South American case, not only produced for scenic or economic reasons, as is generally thought, but because of its characteristics that gave it stability against the horizontal forces generated by earthquakes.

The oldest reference to a wooden vault is given by Vitruvius when he deals with the way plastering is done in Rome, explaining a different technique achieved with wooden strips and reed bundles: “When vaulting is required, the procedure should be as follows. Set up horizontal furring strips at intervals of not more than two feet apart … Arrange these strips to form a curve and make them fast to the joists of the floor above or to the roof, if it is there, by nailing them with many iron nails to ties fixed at intervals … Having arranged the furring strips, take cord made of Spanish broom, and tie Greek reeds, previously pounded flat, to them in the required contour. Immediately above the vaulting spread some mortar made of lime and sand, to check any drops that may fall from the joists or from the roof … ” (Vitruvius 1999). This construction corresponds to a false vault, which was executed by means of wooden strips of different dimensions that hung from the beams of the floor. Beneath those were whole longitudinal canes that helped to obtain the necessary curvature for the crushed reeds that defined the intrados of the vault, without having the help of curved planks or beams (Figure 1).

In the Middle Ages, curved wooden roofs appeared, but using techniques other than the planked timber vaults, with Villard de Honnecourt (1991) showing the ways of covering spaces with vaults using curved logs (Figure 2). Trying to achieve a vaulted ceiling with long curved beams had been a concern during the Renaissance as well. Thus, in the 15th century, Leonardo da Vinci made drawings of curved wooden beams obtained with threaded pieces placed one on top of the other, with sawtooth joints and metal pins (Hahmann 2006).

During the 16th century, the problem of the scarcity of long-length wooden beams became even more pronounced in Europe. Therefore, Alberti (1975) comment on the need to join various pieces to obtain a composite beam is not surprising. This context will serve as a catalyst for the development of the two major construction systems made up of pieces shorter than the span to be bridged, either in lattice structures or in element assembly methods, to obtain larger pieces from shorted planks (Gómez Sánchez 2006).

Within the predominant current, this century will see the presence of two writers who will address for the first

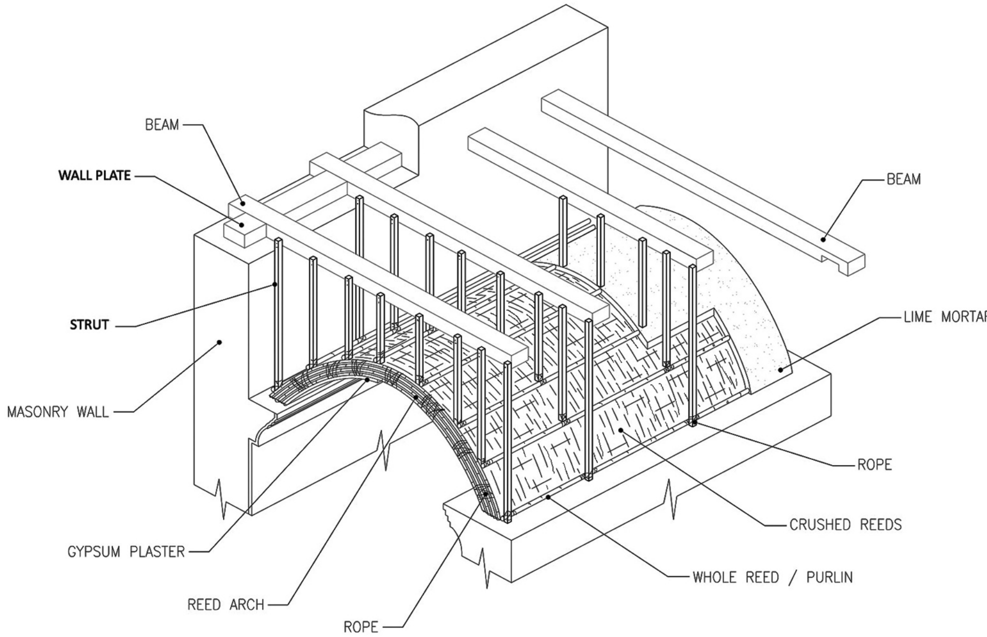

Figure 1. Vault of wood and reeds according to Vitruvius.

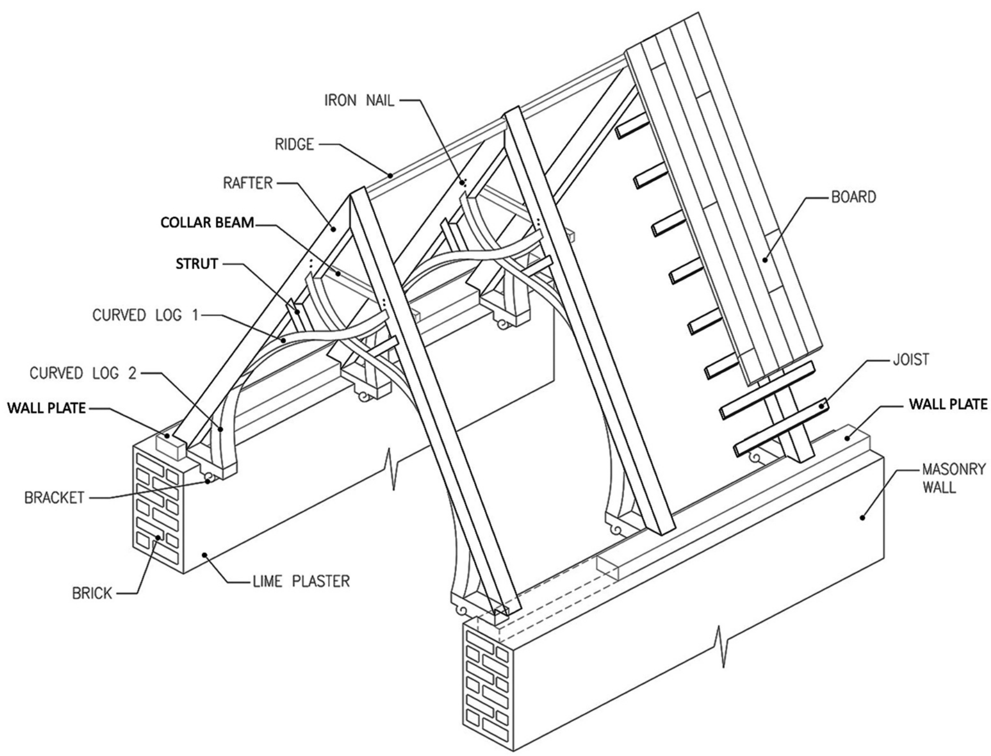

Figure 2. Wooden vault according to De Honnecourt.

time the way of building wooden vaults from small pieces, De L'Orme in France (1561) and Serlio in Italy (1600). But there is a difference between the two approaches, because Serlio briefly describes the characteristics of his proposal, assigning only a picture and a few sentences, omitting the details necessary to build

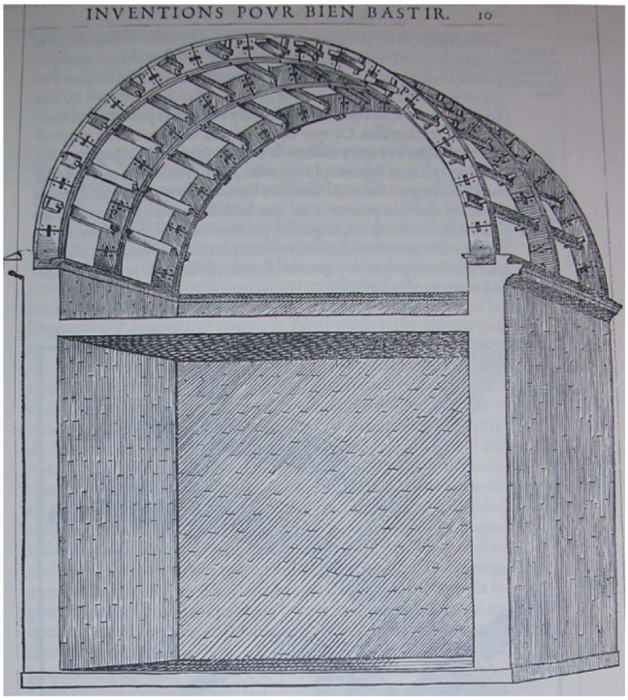

Figure 3. Planked timber vault according to Philibert De L'Orme treatise (De L'Orme 1561, f.10).

it. De L'Orme, on the other hand, included numerous drawings, which deal with wooden arches formed by laterally braced planks with through tenons, joined by wooden pegs until defining a vaulted roof (Figure 3). He proposed this system in 1555 in the castle of Limours, in 1559 in the dome project for the reconstruction of Montmartre monastery, in the palaces of La Muette and Annet. However, the Spanish construction context of the 16th century, which was already aware of De L'Orme's invention, was not influenced by him, despite sending his work to Spain. " … Besides the fame that will spread through strange nations, that such methods of carpentry are carried, as I have seen, by various men who have sent them to Italy, Germany, Spain, and various other places … " (De L' Orme 1561, 5 f.a).

It is curious that the sixteenth-century Spanish writers do not comment on De L'Orme, except for the anecdotal mention by Juan de Torija (1661, 73–5) about the use of that text as an aid for the elaboration of his own treatise, but only about stereometry and execution of vaults with stones, without devoting any chapter to the French vaults.

In the Iberian Peninsula, the initial wooden vaults that were erected obey the type of "rib" vault made with thick and long curved pieces of wood, arranged along an axis in the manner of ribs or in imitation of the ribbed vaults (Figure 4). Ribbed vaults of wood are ancient and have a huge presence in northern Europe, which were also used in Spain, mainly in Galicia and in the Basque provinces of Alava, Vizcaya and Guipuzcoa (Ayarza et al. 1996). While the planked timber vaults appeared in Spain at the end of the 16th century, being used mainly in the Castilian and Andalusian areas. In 1578 Nicolás de Vergara, in the reconstruction of Saint Dominic church in Toledo, mentioned that planked

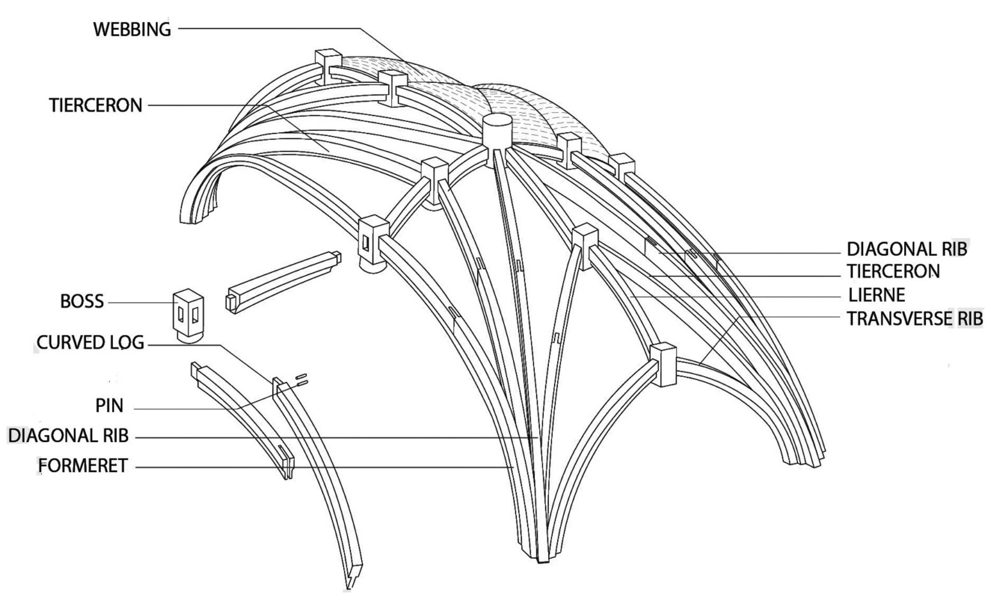

Figure 4. Wooden vault with "ribs" in Basque churches according to Ayerza et al.

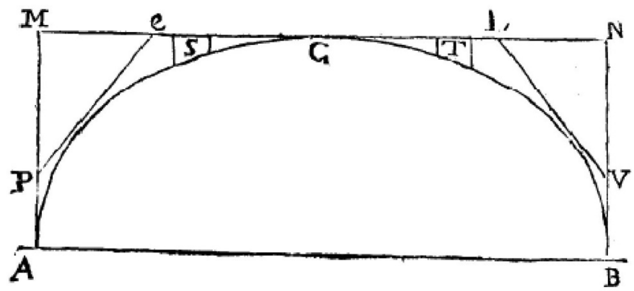

Figure 5. Planked timber vault according to San Nicolás treatise (San Nicolás 1639).

timber arches should be included in the dome (Marías 1987). The construction procedure was reflected by Lorenzo de San Nicolás in his treatise, which later spread throughout Spanish America: "In addition to what has been said, it is possible to offer a lowered vault in some hall and this one is sometimes made with timber planks … " (1639, 91). The Spanish vault was supported by the beams that make up the floor in the upper part, as can be seen in the San Nicolás drawing (Figure 5), which identifies the main beam as MN and the bracing joists as S and T, from which the wooden vault hangs, unlike the De L'Orme vault, which was self-supporting.

3.2. *The wooden vault in the Atlantic Ocean side of the viceroyalty of Peru*

The wooden vaults built during the Hispanic presence in South America present differences between them, related to the geographical area where they were built. To understand the changes in the construction proposals, one must imagine a viceroyalty made up of extensive territories that covered a large part of the South American continent. Those lands located on the side of the Pacific Ocean corresponded to the audiences of Panama (Panama), Lima (Peru), Santa Fe de Bogotá (part of Colombia), Quito (current Ecuador and southern Colombia) and Chile (central Chile). While those that belonged to the side of the Atlantic Ocean were the audiences of Charcas (Bolivia, north and south of Chile, Paraguay, and northwest of Argentina) and Buenos Aires (northeast and south of Argentina).

On the Atlantic Ocean side, the main vault was made by Philippe Lemaire in Córdoba (Argentina), on the roof of the Society of Jesús church in 1667, where influences from the De L'Orme system are evident, ratified by the presence from his book in the temple library (Gallo and Lerin 2001). This church displays a Latin cross plan, with a main nave 50 m long and a transverse nave, in the transept area, which is 24 m long, in addition to a dome 10.70 m in diameter. Each arch that makes up the vault is made with wood of the yellow guatambu species (*Aspidosperma olivaceum*) and white carob tree (*Prosopis alba*), while the arches of the dome are made of missionary cedar (*Cedrela fissilis Vellozo*) (Gómez et al. 2003, 83–8).

The arches form a double line of planks (right and left), with a curved profile cutout for both the intrados and the extrados. Each plank is 200 cm long, 30 cm wide and 7 cm thick, being perpendicularly braced by 7 × 3 cm section straps, separated every 53 cm, locked by passing wooden pegs on both sides of the arch, as established De L'Orme. However, the vault, which is partially attached to the beams of the roof, also uses iron nails to join some pieces, unlike the vaults of the French architect, which used to be built only with wooden pegs. In the case of the dome, in addition to the exposed forecasts, Lemaire opted to use leather cords to join the planks. An essential feature of the Lemaire vaults is the creation of pre-compressions using cladding boards secured with wedge-shaped pegs (Laner 2001), which curved during placement, which when trying to recover their original shape pressed against the arches, making the vault more stable to the seismic movements of this Argentine Andean zone (Figure 6).

Vaulted roofs of this type centered its influence around La Plata (Argentina), with similar examples during the 17th and 18th centuries in the Jesuit churches of Saint Charles in Salta (1666) and Our Lady of the Miracles in Santa Fe (1734), built by José Schmidt. In the Guarani missions of Paraguay, churches continued to be built during the 18th century, with vaults inspired by the Cordovan prototype of Lemaire. The result of this was the church of the Itapúa reduction, built by José Brasanelli between 1718 and 1725.

Similarly, thanks to the survey conducted in 1788 by the geographer Julio de Cesar, it is known that the roof of the disappeared Jesuit church of Asunción built by Orozco between 1685 and 1691, showed the characteristics of the Lemaire vaults (Figure 7). De Cesar also included a construction detail that expresses the initial influence of De L'Orme on the architecture of Lemaire and the rest of the architects of the La Plata region (Page 2008). Despite the destruction of many of these vaults in Paraguayan lands, evidence of the construction system used in the Yaguaron church, built between 1761 and 1785 by the Portuguese architect José Souza Cavadas, can still be found (Bayon and Marx 1989).

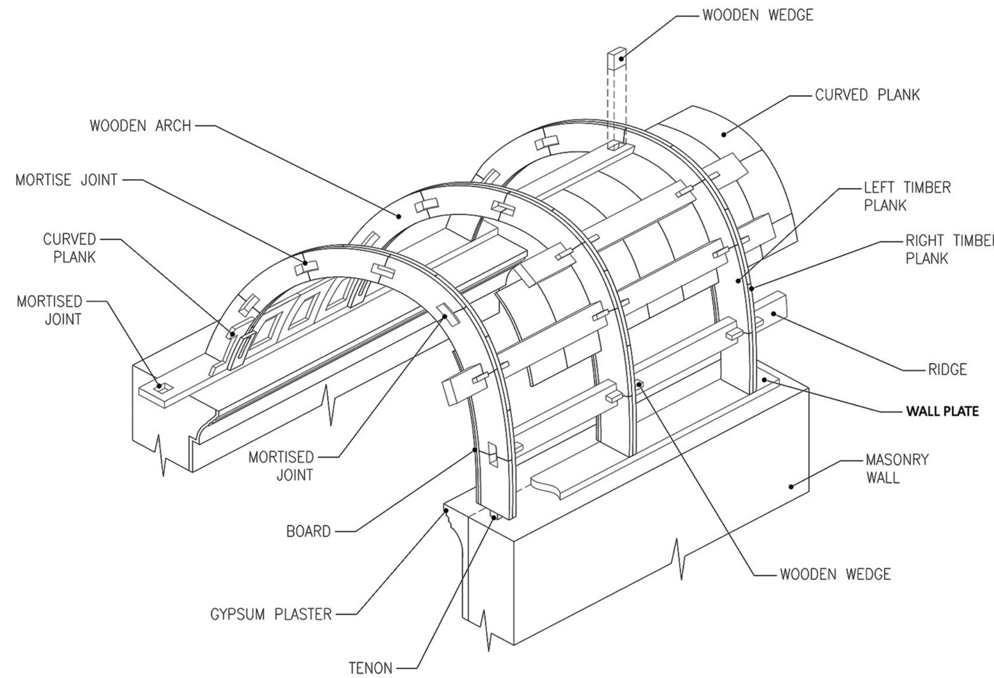

Figure 6. Planked timber vault in the Jesuit church in Córdoba, Argentina.

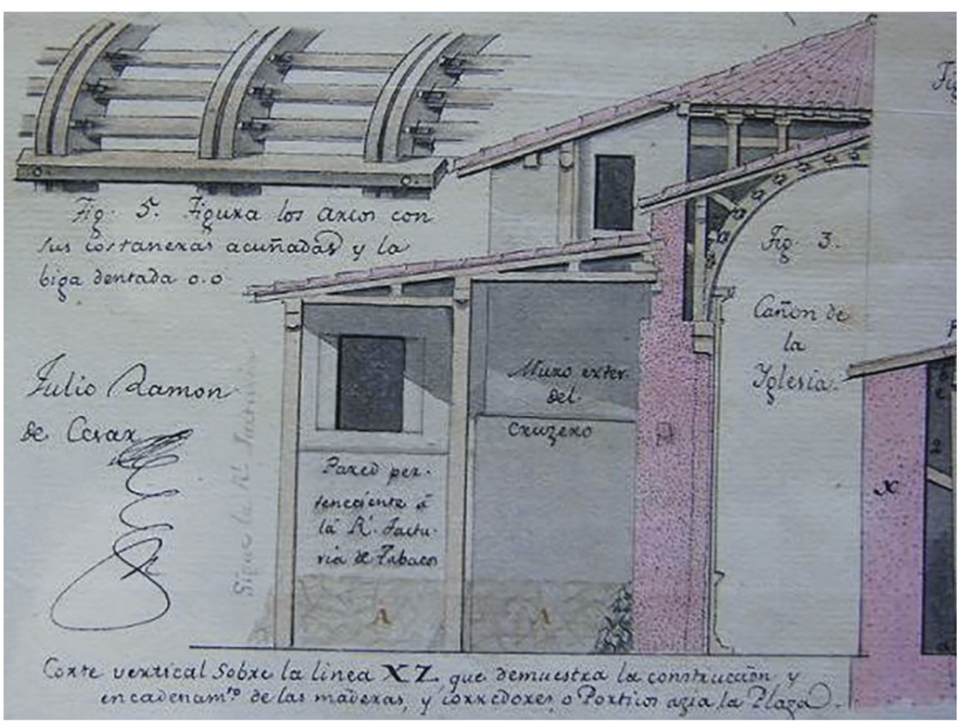

Figure 7. Ancient drawing of the planked timber vault in the Jesuit church in Yaguaron, Paraguay.

3.3. The wooden vault in the Pacific Ocean side of the viceroyalty of Peru

The rest of the wooden vaults that were built in the viceroyalty of Peru correspond to the Pacific Ocean side. Models of these vaults can be found on the roof of Saint Augustine church in Quito, rebuilt during the 18th century, in the Colombian churches Saint Clare whose roof was rebuilt after the 1785 earthquake, Saint

Nicholas of Candelaria (1702), Saint John of God (1723) and in the Jesuit church of Saint Ignatius (1763), all of them in the city of Bogotá (Bayon and Marx 1989).

The group of these churches presents wooden vaults with a different proposal to the type of Lemaire in the region of La Plata, and whose construction characteristics are closer to the Spanish vaults. In fact, these vaults mostly show planks without cutting the curve that defines the extrados of the vault, massively use forge nails to fix the joints and are suspended from a Mudejar style beams, which forms the roof of the buildings or masonry arches (López Pérez and Ruiz Valencia 2010). This type can also be considered the planked timber vault of the cathedral of Santa Cruz de la Sierra in Bolivia built in 1770 and rebuilt in 1838.

For example, the main nave of Saint Ignatius church in Bogotá is divided into six sections, with a total length of 28.43 m and a span of 11.00 m. The arches are made up of two lines of planks of 25 cm wide, 5 cm thick and 210 cm long, which are nailed and tied with ropes. These arches are approximately 100–110 cm apart and are braced perpendicularly by wooden straps that contact the planks in the intrados part. A reed weaving (*Chusquea spp.)* has been arranged on the extrados of the arches, grouped in bundles of eight pieces, which in turn are tied with vegetable ropes. The same happens in the intrados, facilitating in the end the fixing of the plaster render that covers this area. The vault is joined to the true roof structure composed of Mudejar beams by means of strips (Figure 8).

In the southern region of Chile (Chiloe area) there are churches built in wood with the use of planked timber vaults, but these temples date from the 19th century. The wooden vaults of this Chilean area are characterized by using of assembly systems and pins of De L'Orme type, saving on the use of nails. However, just like the Spanish vaults, they are usually suspended from a superior framework. In any case, all the constructions mentioned were built after most of the planked timber vaults were built in the audience of Lima (capital of the viceroyalty), corresponding mainly to the coastal area of Peru.

3.4. The viceregal capital and the cities under its architectural influence

3.4.1. The introduction of the planked timber vaults in Lima

As previously mentioned, the initial vaults built in the city of Lima from the 16th century were executed in brick with lime, as happened in the main chapel of the cathedral (1551), in the churches Our Lady of Mercy (1542), Our Lady of the Rosary (1547) and in the chapels of the hospitals Saint Ann (1564) and Holy Spirit (1573). In 1586 a strong earthquake damaged these vaults, which were rebuilt in masonry. Certainly, during the 16th and 17th centuries the temples were covered with

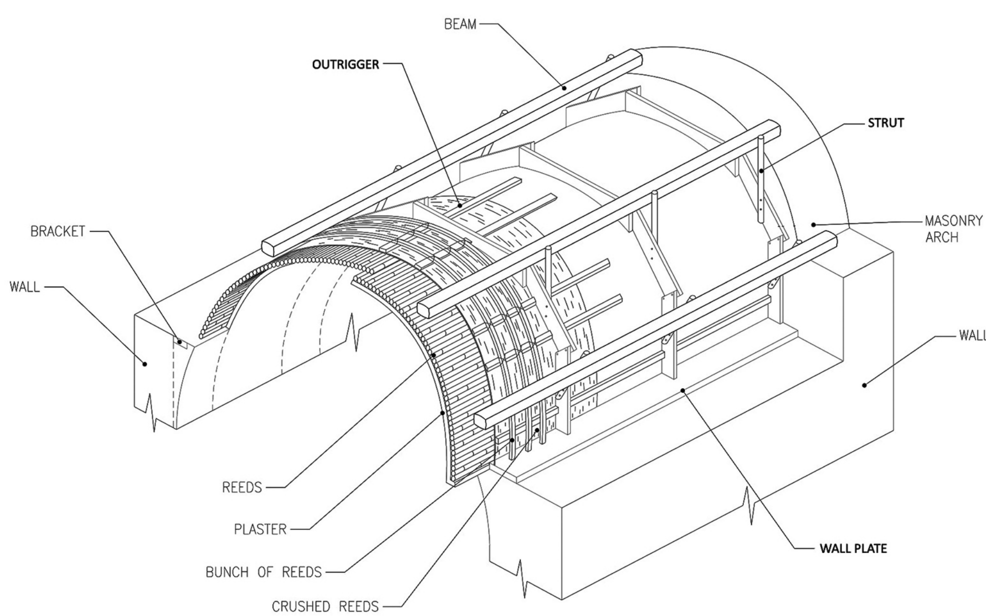

Figure 8. Planked timber vault in Saint Ignatius church in Bogotá, Colombia.

vaults in stone or brick and rebuilt with identical materials when they collapsed due to earthquakes.

Such events reveal that the masonry vault construction techniques that the Spanish builders brought to South America, did not yet have the appropriate refinement to function in such an active seismic environment, which did not happen in the Iberian Peninsula. In Spain, earthquake resistance as a construction concept for masonry vaults was not considered important to provide stability and as such they were also initially built in South America. But in the middle of the 17th century, the churches in Lima stopped building sail vaults or groin vaults and began to be covered with ribbed vaults, not as a stylistic anachronism but because they were thought to be more stable to the shocks of earthquakes. However, because of the constant damage that the earthquakes continued to cause in the masonry vaults, the construction system of planked timber vaults was introduced, encouraged by the verification of the good earthquake-resistant behavior of other wooden structures, such as the woven panel of reeds and daub called “quincha” or “bahareque”.

Some of the first experiences that have been established of the use of planked timber vaults were reflected in the sacristy of Saint Francis temple, in the first half of the 17th century, which in turn served as a model for the Mercy chapel into Saint Sebastian church built in 1657: “ . . . the said Mateo de Tovar is obliged to make the said chapel with two vaults, one will begin from the arch of the church to the arch of the presbytery that is made and the other from this said arch of the presbytery up to the wall that finishes off the said chapel of plaster and canes founded on mulatto oak wood similar to those made in the sacristy of Saint Francis . . . ” (GAN 1657). Equally early are the vaults of the Inquisition chapel and the small church of La Veracruz in Lima, (Figure 9) built by Diego Maroto in 1665 and 1666, respectively. In both cases, the vaults were built with similar characteristics to the Spanish vaults, being supported by another upper structure, a solution that was later repeated in 1678 in the main church of Saint Dominic convent.

On the other hand, Pedro Álvarez de Faria, upon inspecting the deteriorated roof of the chapel of the inquisition court in 1664, suggested that to repair it, the inquisitors “made a resolution after several conferences that it be lowered with a vault of cane and plaster as required practices in other churches and chapels of the same size” (GAN 1665a).

3.4.2. The influence of the Castilian planked timber vaults in the vaulted roofs of Lima

The data exposed in the previous section acquire particular importance on the construction genesis of the planked timber vaults in the viceregal capital. Kubler affirmed that perhaps “ . . . the technological side of the Iberian colonization comes more from Northern Europe and from Central European sources, than from the Peninsula itself . . ., and the introduction of the cane vault in the Central Andes by the work of Father Rehr, a bohemian Jesuit of the mid-eighteenth century” (1968). This postulate is based on the consideration that the ribbed vaults made by Johannes Rehr in Lima

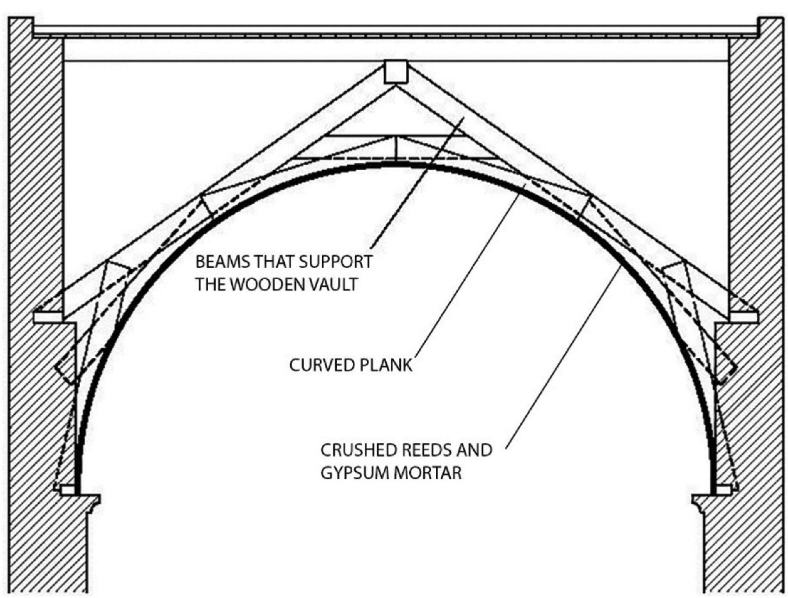

Figure 9. Planked timber vault in the church of La Veracruz in Lima, Peru.

cathedral after the 1746 earthquake were related to the wooden vaults of the Flemish regions. It was also suggested that the intervention in the vaults of the Lima cathedral meant the birth certificate of this construction system in the viceroyalty of Peru, and from there its use spread to the rest of the territory.

A careful look at the construction contracts of those times shows that the planked timber vaults were used in the viceroyalty of Peru from the mid-seventeenth century. Therefore, and in accordance with the dates in question, it can be argued that whatever Rehr's work may have been in the cathedral complex, it was only an adaptation to the existing technological environment, where the wooden vaults were already widely known by the local master builders.

At the opposite extreme are the autochthonous ideas of San Cristóbal, who affirmed that the vaults were an invention of Maroto in 1666 in La Veracruz church in Lima: "This new technology was developed in Lima by the Dominican Friar Diego Maroto, who was born and lived in Peru, and who never traveled to Europe. Consequently, the technology of light wood and plaster vaults did not reach Lima by way of some external horizontal transmission from Europe or from Spain" (San Cristóbal 2000, 18). He even came to deny any type of contribution of European architecture in the development of this constructive typology, arguing the impossibility of this influence due to the factor of earthquakes (San Cristóbal 1996). A careful examination of the dates on which Maroto assembled his first wooden vaults and the data of other early planked timber vaults, such as the sacristy in Saint Francis church or the Mercy chapel into San Sebastian church from 1657, note that before 1665 wooden vaults had already been built in Peru.

On the other hand, these first wooden vaults already showed similar characteristics with the planked timber vaults that are being built in the area of Castile (Spain) since the beginning of the 17th century, not only because of the pieces shape used in their execution, endowing them only with the cutout of the intrados, but rather due to their structural performance of not developing a load-bearing function, being subject to an upper reinforcement, which in turn was made up of beams, braces and wooden strips, so similar to the Spanish vaults. In this regard, Pérez and Domínguez (n.d.) investigate on the origins of Maroto, concluding that he was born in the town of Camarena, province of Toledo (Spain) in 1618, within a family of master builders, according to the entry of birth found in the parish of that locality, and he arrived in Peru in 1642. This person received training as a builder in Castilian lands, which explains his knowledge of Spanish vault techniques (Figure 10).

Undoubtedly, in the Iberian Peninsula these wooden vaults had their birth in motivations more of an economic nature than in the search for any earthquake-resistant efficiency. But once transferred to the viceroyalty of Peru, as a way of coping with the constant reconstructions imposed by the environment, its behavior against earthquakes began to be evaluated, subsequently finding its development under this construction condition.

Initially, the use of the planked timber vaults did not have sufficient impulse, because many master builders considered that the wood was not reliable and that it

Figure 10. Planked timber vault in Saint Anton church in Madrid built with Spanish techniques.

could cause fire or rot. On this subject Juan del Cerro during the debates for the reconstruction of the vaults of the Lima cathedral mentioned that: " … being a carpentry there are many risks of fire and the wood does not last long, and I say this from experience that I have in Spain of having disrupted and seen disrupt some churches and convents in Spain … " (AAL 1609). Significant statement that demonstrates not only the initial objection to using wood to cover the temples but also to evidence the existence of information exchange between builders who worked in Spain and in the viceroyalty of Peru, including the arrival in South America of Spanish architectural treatises.

It is interesting to note that the first churches whose roofs were rebuilt with planked timber vaults were small, such as those mentioned of Mercy chapel in San Sebastian church and the Inquisition Court or La Veracruz church. Likewise, Maroto, as a Dominican friar and with the important position of Master Builder of the Cathedral, could have built vaults in the main church of his religious Order, which were finally raised in a masonry. While in the small church of Veracruz Maroto managed to build vaults in the Castilian style. Due to the size of these constructions and the fact that the representatives of the great religious orders did not accept the wooden vaults but preferred to continue rebuilding their great temples with masonry vaults, it seems to show that the planked timber vaults were originally established as an intervention by religious congregations that had fewer economic resources.

These vaults were sufficiently stable to guarantee the realization of the cult after the earthquakes, while the congregations tried to obtain the necessary funds to undertake larger works again in masonry. The good performance shown by the initial planked timber vaults would attract the attention of the local master builders, who would not hesitate to experiment with this system in the construction of vaults in the newly churches.

During the reconstruction of Saint Francis church in Lima in 1675, Escobar and Vasconcelos perfected the Castilian-style vault, making the new vaults self-supporting and not supported by another structure, partially reminiscent of the solution proposed by De L'Orme a century ago (Figure 11). The fact that the union regulations were less rigid than in Spain and the local resources, motivated the local master builders to experiment with other solutions to improve the efficiency of the construction of wooden vaults. Thus, the planks are provided with curved profiles for both the intrados and the extrados of the vaults, lateral outriggers, and a wooden plate to tie the walls in the upper part, on which the wooden arches would also be fixed. To all these elements proposed by De L'Orme at the time, other new ones are incorporated, the result of continuous experimentation, such as the adobe wall at the base of the vaults to counteract the thrusts, and the flexible joints with leather strips.

The great earthquake of 1687, which caused the collapse of many masonry vaults in Lima, revived the technical debate on the earthquake-resistant efficiency of masonry structures, especially after having seen the good performance of the planked timber vaults made in some churches a few years before the earthquake. The catastrophe situation was also taken advantage of not

Figure 11. Planked timber vault in Saint Francis church in Lima, Peru.

only to change the materials of the vaults but also to adapt them to a new morphology of floor plans, which went from being "Elizabethan-Gothic" style with a single nave and presbytery arch to another with a Latin cross floor plan with short arm cruiser. This architectural reconversion of the temples meant another added impulse to the use of the new system of wooden vaults.

3.4.3. The change of the vaults of the cathedral of Lima

A crucial moment for the development of the planked timber vaults was the case of the reconstruction of the vaults of the Lima cathedral (Hurtado-Valdez 2009). The original groin vaults made in masonry, because of the 1609 earthquake, were severely damaged, so a debate was held between the main master builders of the city to determine the best way to repair or replace these vaults. The master builders had to answer a questionnaire " . . . in particular, what repair seems convenient for what is built and if it will be that what is done is lowered and not so high and that what is missing is continued with a vault or wood . . . " (AMCL 1614).

In this regard Alonso de Arenas refers: "in what is proposed if for safety and perpetuity it is convenient to undo and lower the said building and cover it with wood, there is no answer to this because it is not fair to put something so unreasonable in the discussion and path that cannot be presumed there is someone who touches on this" (Archiepiscopal Archive of Lima (AAL) 1609).

Pedro Blasco argued that: " . . . as regards whether it is convenient to cover the said church with wood, I answer that I am not of the opinion due to many respects and inconveniences and the first is that in order to wood the said church, it has to be lost everything manufactured in it . . . and the pillars must be lowered to the lower thirds so that the reinforcement of said wood does not rise more than necessary, having to be five panels more than having to load the wood on pillars and brick arches if due to lack of buttresses the tremor knocks them down, the wood must also fall and if, because these arches are well supported, they must also have vaults and without these there are other very ordinary inconveniences in wood, which are fires corruptions and wood worms because in less than fifty or sixty years they breed worms that eat it and it itself becomes corrupted and ends up . . . " (Archiepiscopal Archive of Lima (AAL) 1609).

These statements show that until the beginning of the 17th century it was believed convenient from the structural and ornamental point of view to make the barrel or groin vaults in masonry, preferring stone and brick over wood. The subsequent verification of the damage caused by the earthquakes in the existing masonry vaults, mainly groin vaults, led to the reuse of ribbed vaults. With this system, the cathedral vaults were reconstructed, because it was thought that they would provide greater resistance by having the thrusts concentrated. Therefore, it would suffice to provide the walls, at the thrust concentration points, with buttresses thick enough to provide stability to the structures during earthquakes. Thus, Juan Martínez de Arrona mentioned that: " . . . lowering the collateral naves and making them ribbed is the best remedy there can be to secure the main nave . . . the ribbed work is the best as can be seen due to the long time that it has been they held the main chapel and transept with the other niche chapels of Saint Dominic convent and having passed through them the great tremor of the year five hundred and eighty-six and the ones that have occurred the most without receiving damage because they are ribbed and in our holy church it has been seen how badly they approve of the groin vaults with the few who have passed through them, they have left them as damaged as can be seen and the same is seen in the main chapel of the Conception convent for being ribbed with the buttresses and walls on the outside, all open and cleft, have been supported and are supported because it is not as heavy or loose a work, nor does it have thrust like the groin vault . . . " (AMCL 1615, file 15 r).

A new turning point was the great commotion of 1687, which caused the collapse of the new ribbed vaults, so that once again there was a debate about the best way to rebuild the cathedral's vaults. In this scenario, Diego Maroto offered to Ecclesiastical Council a vision of structural safety of the vaults built by him some years before in La Veracruz church and in the Tabernacle church into the cathedral complex, proposing to rebuild the vaults of the cathedral under this same system: " . . . and consequently the said facade is not disturbed mostly when the immediate vaults are made of cedar and gypsum counter-balancing and mending the other ribbed ones, major and minor tiercerons and their ties relieving with the same moldings that they have the brick ones without being able to recognize whether they are or not because these and the new form have been recognized by experience to be a safer construction in such repeated tremors, mainly when the ones that this declarant made in this way in the church of his convent being like this that he had few foundations in terms of masonry, the vaults he built on top of the pillars and arches that have suffered and not the vaults that I have made them of cedar and gypsum . . . " (ACC 1688, file 70 r).

For his part, Pedro Fernández de Valdés noted that the buttresses could not contain the horizontal forces that occurred during earthquakes, mainly in the upper parts, so it was preferable to reduce weight by making the new vaults of wood, cane and gypsum: " And likewise it seems to this declarant that it is not a good work that can be applied by sheltering the opening of the pillars with masonry to collect the entrances and less leakage to the thrusts of the arches, particularly when experience has shown in the work of the church of Saint Peter Nolasco where this genre was applied with more body and both in the thickness and in the length and it came with the tremor to the ground without this application being useful, only by repairing the whole of the work it could take shape to remove the arches that are the ones that make work with their thrust the sides that look at the walls of their sides and that took shape in the upper part damaging the whole of the work with which it seems to this and declaring that having to be made of wood, gypsum and cane, it does not need further application ... " (Archive of the Cathedral Council (ACC) 1688, file 71 v-72 r).

From the same point of view, Manuel de Escobar mentioned that the characteristics of the wood and the use of iron nails give greater security to these vaults than brick, recommending that the reconstruction of the vaults of the Lima cathedral should be carried out with the planked system: " ... the vaults that were previously made of brick now they will built with wood, apparently it will be convenient to remove the horror of the brick ... because it is made of long wood and with iron nailing it is more resistant to the motions of the earthquake and in this way the greatest safety is known by being made of wood ... " (Archive of the Cathedral Council (ACC) 1688, file 72 v-73 r).

In these circumstances, the Metropolitan Council entrusted Maroto with the design of the new vaults. He detailed in the Construction Book the characteristics that these wooden vaults would have in imitation of the ribbed ones, describing that to execute each vault of the central nave, eleven keystones would be taken with fixed points that would organize the number of tiercerons and transverse/longitudinal ridge-ribs, being fixed to each other with brackets and iron straps, in addition to closing this vault with wooden slats (AMCL 1688, file 38 r-39 v).

The vaults of the cathedral would be made with arches made with cedar planks, 28 cm deep and 14 cm wide. Maroto indicates that the contact between planks would be simple, made at the butt, and that the profile of their intrados should also reproduce the finishing molding of the ribbed arches that showed the old masonry vaults. Then, to finish these vaults a boarded filling was made with planks 20 to 28 cm wide were nailed to the extrados of the arches, although leaving a distance between them, sufficient for the gypsum plaster to completely cover the structure (Archive of the Metropolitan Council of Lima (AMCL) 1688, file 38 r-39 v).

Figure 12. Planked timber vault in the Lima cathedral, Peru.

By 1691, three planked timber vaults corresponding to the back of the main façade of the cathedral had been built and the rest still had to be done (Figure 12). Once again, the Metropolitan Council asked for the opinions of the master builders on the behavior of the new vaults in the face of this year's earthquake. Thus, Pedro de Asensio stated that by having made the wooden vaults, the thrusts were reduced and their stability was guaranteed compared to those of the masonry: " ... having made the wooden vaults immediately to said façade, removing the thrust that it caused, and regarding the matter that must be made, all the said vaults must be made of incorruptible cedar wood and gypsum, as are the three again made behind said facade, since with them the safety for tremors has been recognized, since they have just been finished to do, the tremor of the twentieth of September of the last year of six hundred and ninety hit them, which was as great as that of October twenty of six hundred and eighty-seven and caused greater ruins in other buildings than in these three vaults, they did not receive damage ... " (Archive of the Cathedral Council (ACC) 1688, file 95 v).

3.4.4. Expansion of the planked timber vaults in the viceroyalty of Peru

Since the reconstruction of the vaults of the Lima cathedral with the wooden arches system at the end of the 17th century, this construction technique with its various variants gained renewed impetus and became widespread throughout the region of the western coast of South America. Precisely this territory has been characterized by presenting the greatest seismic activity of the viceroyalty, due to its location in front of the Nazca plate subduction line. The temples of the viceregal capital belonging to the orders of the Dominicans, Franciscans, Mercedarians and Jesuits, only managed to change their masonry vaults for wooden vaults after the former were continuously damaged by multiple earthquakes. In the case of the parish churches, they had already changed their masonry vaults for wooden vaults long before the great churches, and in some cases when new buildings were built, they opted for the construction of their vaults from the beginning under the planked timber vault system.

The viceroyalty scenario shows as contemporary two events whose conjunction would be of enormous importance in the subsequent development of its architecture, these were on the one hand the introduction of wooden vaults and on the other hand the search for stability solutions for masonry vaults. All this produced that during the same period vaults made with different materials and construction systems coexisted. "Having made of five large arches of plaster the nineteen threaded rods, two collaterals and another to the Chapel of La Sola, three large ones of lime and brick and eight transverse and ten vaults of cedar wood and two of plaster and the sacristy of the priests made of oak and gypsum … ". (ACC n.d.).

On the other hand, the architects of the 17th century, when explaining the reasons for the collapse of masonry vaults during earthquakes, argued that there were defects in the construction of these arches and vaults derived from a technique that was not sufficiently mastered by officers and assistants. In general, three were the most frequently exposed causes:

i) Weakness of the buttresses: Pedro Blasco mentioned that " … having seen with the diligence possible the masonry of the said temple and the damages that it also caused the said tremor in what was manufactured in it for having found it lacking buttresses that received the encounters of the arches and vaults because it really does not have them convenient or in accordance with good architecture because if it did have them, the said tremor would not cause any detriment in the said building, since not having them, the damage it received that it did nothing but warn that there were necessary and because my purpose is to try to repair and support the said temple so that at any time it can easily receive any earthquake or tremor that may occur … " (Archiepiscopal Archive of Lima (AAL) 1609).

In turn, Martín de Aizpitarte pointed out that "Although I understand that in this opinion I cannot stop saying what I feel about it and to speak clearly I say that I do not find firmness in all this work that is made because the work is very high and poorly mounted to resist tremors, even if the walls and pillars are twice as thick, and because when the tremors come they do more damage in one part than in another in the masonry, so that the blows of the sea, which are not all the same, and thus make the masonry dislodge and the lime is falling and giving the work of itself because naves of forty feet wide are not for this land nor even of thirty they have to be insured even if all the buttresses they want are thrown because the causes said sooner or later with the continuous tremors the work will come below and it will be to those who are below" (Archiepiscopal Archive of Lima (AAL) 1609).

ii) Deficient construction process: Master builder Alonso de Arenas mentioned that "One of the most important things that needs to be remedied are the materials and officials that have to be worked … Regarding the buttresses that have to be placed at the head of the church, it seems to me which is a great objection, but with all that, with strong tremors, the new work will not fail to detach from the old somewhat because the mixtures in this land nor the tempering help for it" (Archiepiscopal Archive of Lima (AAL) 1609).

iii) Bad design of the vaults: Aizpitarte pointed out that the relationship between the width of the naves and the height of the keystone was essential to ensure balance: " … I say that it is not convenient to continue the said work with the trace that the one begun has because the collateral chapels are wrong because they do not keep the design because according to the width of the naves it is not kept and in the arches the points are very high … because it is loose work and that it is in its weight with the main nave that for the tremors it is a matter of great inconvenience for not having buttresses" (AMCL 1615).

Diego de Guillen observed that "having seen how I have seen and understood before now the enclosure that is made in the same church of the groin vaults chapels and the oval arches, I say that they are without any strength in respect of not having sufficient buttresses to that they can force the smaller nave into the larger one because all three naves are made into one body and thus it is an enclosure so out of line and art that it has no foundation whatsoever and to this day I have not seen or even heard practical masters and experts in the art of masonry or stonework deal with such outline and so I say that the outline and finish work that the master who made this was nothing more than a new invention without art or strength" (Archive of the Metropolitan Council of Lima (AMCL) 1615).

In any case, all the experimentation that had been conducted for two centuries with different types of vaults, whether stonework, masonry, or wood, to improve the earthquake-resistant efficiency of each one, was stopped by the colonial administration, when Viceroy José Manso, following the recommendations of the kingdom cosmographer, Luis Goudin, made the use of planked timber vaults mandatory after the 1746 earthquake. In the opinion that Goudin addressed to the Viceroy, he stated that " … it does not allow high buildings or heavy constructions and the walls are made of stones, bricks, or adobes, when all of them require that in their nature a certain thickness … likewise wood for the vault, which according to custom will be made of wattle and daub … vault and masonry arches were prohibited" (Bernales 1972, 305).

It should be noted that these South American vaults had an impact on the other side of the Pacific, to be more exact in the Philippines, because during the construction of the Manila cathedral in 1752 there was the Canon Esteban de Rojas y Melo, from Peru, commissioned to spread the solution adopted in the Lima cathedral. At that time, it was decided to also make wooden vaults, in anticipation of the strong earthquakes that also occurred there (Morales 2003, 106). In Spain, after the Lisbon earthquake of 1755, the King constantly asked for opinions from South American academics and master builders, who arrived in the Iberian Peninsula, on the best way to provide buildings with seismic resistance (Languillo and Crespo 2007).

Figure 13. Wooden vault according to the lintel system in the Virgin of Loreto´s chapel in Lima, Peru.

4. Discussions

4.1. Construction typology

4.1.1. The beam or lintel system

The beam or lintel system constituted the basic experience of the use of the wooden vaults in the viceroyalty of Peru, appearing in the mid-seventeenth century. This kind of vault anchors its roots directly in the Spanish vaults, coinciding with their construction characteristics. This system is characterized by the fact that the arches are supported by another structure, which made with the horizontal beams that make up a floor, by the braces or by the rafters of a roof.

The arches of this type of vaults, as they do not have the need to establish the curvature of the extrados, present planks only with a cutout of the curved profile in the intrados, which saves work and avoids the risk of weakening the piece in the direction of the fibers on the side of the extrados. Due to the way they are arranged in the structure, the arches do not collaborate in unloading the weight of the roof nor do they generate lateral thrusts, because these arches are used only to shape the space to be covered. It is the upper structure that unloads the weight of the roof onto the walls (Figure 13).

The work agreement signed in 1665 by Joseph Moreno and Lorenzo de los Ríos for the construction of the chapel roof of the Inquisition Council in Lima, explains in detail the construction characteristics of the kind of vault with a beam system, confirming the presence of common construction elements with their Spanish counterparts: "First, all the walls must be raised two rods in the round of a thick adobe, plastered and edged on the outside. Must be twenty-two beams each that make eleven pieces of wood. It must have forty-four struts in the said twenty-two main beams. Plus, twenty-two arches, one for each beam. The vault must be covered with cane cut in waning and divided in half with its gypsum plaster of three fingers of thickness. It must be laid on top with ordinary brick plastered with lime and settled with mud … After forming the vault … has to be plastered with the gypsum … " (GAN 1665b).

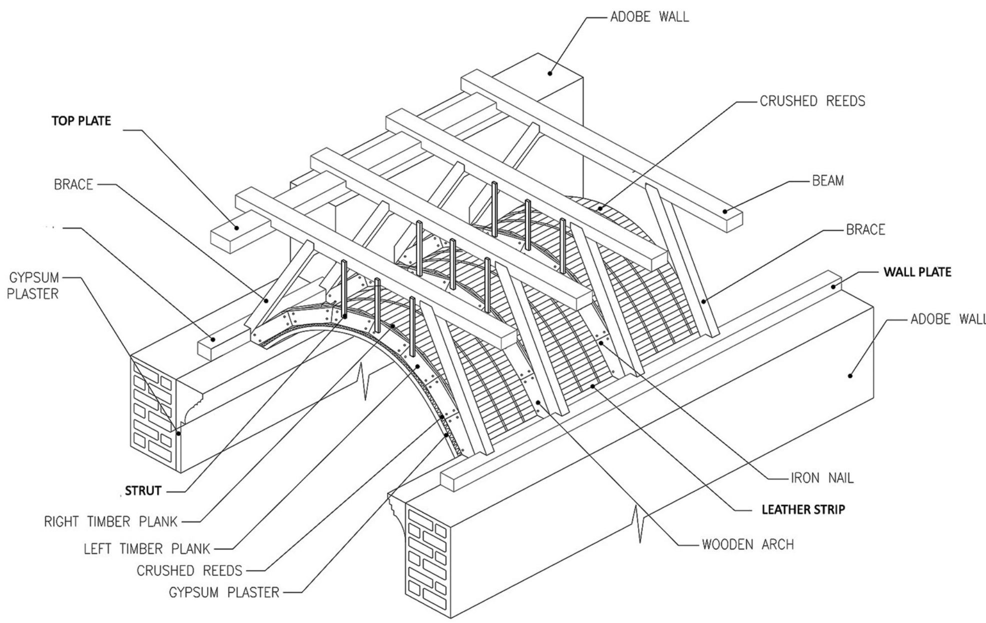

Figure 14. Wooden vault according to the lintel system in the Inquisition chapel in Lima, Peru.

According to this description, the height of the adobe wall was initially raised in the entire perimeter of the chapel 1.67 m, which in turn established the rise that the vault had. Inside the wall, a wooden chain or wall plate were placed that would serve as support, mainly for the main beams, on which tongue and groove planks would be arranged. Next, the braces were fixed to the walls as supports at each end of the main beams, which in addition to reducing the beam span have would help to fix the wooden arches. These construction considerations show similarities with those revealed by the treaty of San Nicolás in the seventeenth century (Figure 14).

Nailed to each of the main beams and braces, twenty-two arches were placed, giving the curved profile to the intrados. Above the boarding, a mesh formed by braided reeds was extended, then a layer of mud, to finish with a brick floor settled with lime and earthen mortar. The intrados vault was made by nailing a layer of crushed reeds, plastered with a layer of thick gypsum and with a finish of fine plaster.

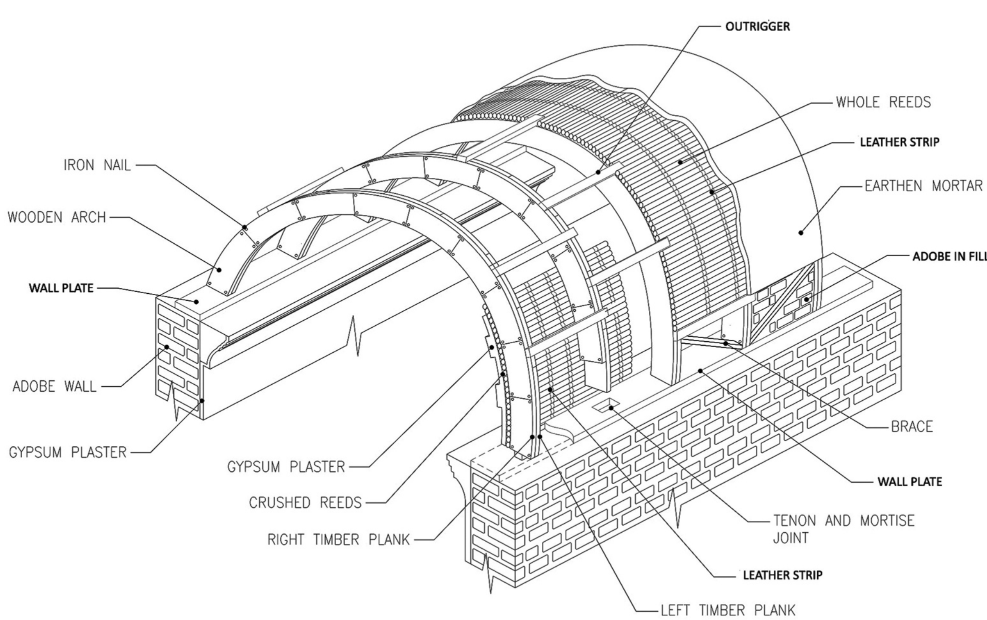

Figure 15. Wooden vault according to the arch system in the Jesuit church in Pisco, Peru.

4.1.2. The arch system

The arch construction system for planked timber vaults defines a step forward in the evolution of wooden vaults in South America (Figure 15). It is characterized by being formed with arches that discharge the weight of the roof to the wooden plate that serves as support. These arches are laterally braced by joists and the whole structure looks like the De L'Orme vaults.

In this type of vault, unlike the lintel or beam system, it is not only of interest to define an interior space but also to show the exterior volumetry that the building acquires, for which the curvature of the extrados is externally evident. To produce this effect, the profile of the planks had to be cut twice, providing them with extrados and intrados. Here lateral thrusts are generated that will be received by the wooden plates that will transmit these forces to the walls.

The arch system for the vault introduces a new element made up of the adobe fillings in the lower side, which seeks to verticalize the thrusts resultant. The use of adobe fill marks a substantial difference with respect to the vaults proposed by De L'Orme and with the Spanish wooden vaults. This type of vault was the most widely used in South America.

4.2. Construction elements, assembly techniques and joints

4.2.1. Wall confinement elements

Wooden wall plate: Its function is to brace the walls on the upper side. They are pieces that run horizontally around the perimeter of the ceiling, marking the beginning of it, and are generally embedded in the wall.

It must also have served to level the upper side of the wall for the beginning of the work of the master carpenter, trying to provide a suitable horizontal surface for the support of the arches, subject to stricter tolerances. They also fulfilled the function of receiving and distributing the thrusts generated by the arches.

4.2.2. Bearing structure

Arches: They were built from cedar or oak planks, placed alternately on their face, and joined by nails to give the shape of the arch that had been projected. Sometimes leather strips were also used to tie the planks, which were placed wet and when they dried, they produced a greater pressure due to the retraction of the material.

Possibly the search for flexibility also motivated the use of leather strips for the joint of structural elements. To the master masons, it would have sufficed the use of nails to fix the joint of the wooden pieces as it was done in Spain, but they concluded that tying the elements of a structure with leather strips meant to increase their ability to absorb greater deformation energy.

This system provided a high level of rationalization of the construction process, avoiding excessive waste of wood by assigning a cutting module that could be repeated as needed. In the case of self-supporting arches, where the planks were curved both in the intrados and in the extrados, a greater face length was provided to avoid the probability of failure of the plank in the direction of the grain.

Lateral outrigger: They were pieces of wood placed horizontally and alternated between the arches to join them in their path as a continuous grid, being separated by variable distances, although preferably about 120 cm. Its function was to transmit and redistribute the loads and efforts of the roofs on the vault surface, in addition to maintaining the separation of the arches and providing lateral stability.

Adobe filling: Braces were placed in the starting area of the ceiling next to the wall, between the wooden plate link and the first brace, and then this space was filled with adobe or brick. Master builder Santiago Rosales commented on the requirement to fill the first section of the arches with heavier elements: "Firstly, I force myself to make the wooden frame in which the entire vault is loaded and formed … forcing myself to fill the lower side of the frame brick and lime" (GAN 1740-1751).

4.2.3. Closing elements

The accounts of the works carried out in the Holy Trinity monastery in Lima in 1746 give an idea of how the vaults used to be closed: " … 50 pesos I paid a master to cover the joints of the planks with plaster, the vault of the church …, 415 pesos and 2 reals that were spent on placing the reeds in the arches of the upper choir, putting in the ones that were broken, re-nailing them and putting mud … " (AAL 1746-1755).

The first part refers to the finish of the intrados and the second to that of the extrados. In any case, the differentiating elements of the types of finish work that have been found are the following:

Wooden boarding: The roof with wooden boarding was one of the first to be conducted in South America. This roof was made up of tongue-and-groove planks, with thicknesses between 3 and 5 cm, which were placed under the wooden arches. In this case, it was customary to leave the planks visible or put in some mural painting.

Reeds layering: In some cases, the finish was made with reeds joined together with leather strips and connected to the arches by nails placed on the strips. Generally entire reeds were placed on the extrados, which served as the base for the earthen covering, and on the intrados, the canes were split longitudinally and extended, increasing the contact surface as a support for the plastering of gypsum.

The finish with reeds joined with leather strips can be considered as an improvement of the construction system by reducing weight in the roof and achieving greater flexibility, in a search to improve the behavior of the structure against earthquakes. In this case, it was a matter of adapting the reeds to the shape of the vault, becoming a widely used finish during the 18th century, since the reeds were relatively easy to obtain on the banks of the rivers, proceed to dry it and work to get the curved surface, unlike the wooden boards that had to be obtained from the regular beams and have a more precise work, which made the construction more expensive.

Earthen covering: The arid climate with little rainfall on the South American central coast created an environment conducive to the use of mud as a final covering material. It was a layer of mud with an average thickness of 8 cm, made with a proportion of 15% clay, 10% silt, 55% sand and 20% water, also incorporating straw and animal hair to prevent excessive shrinkage during the drying process. While, in raining places, the vaults were protected with a wooden structure ceiling over them.

Ceiling moldings: On the intrados of the planked timber vault, a final gypsum coating was made that was fixed on the boards or canes that defined its curvature, to later obtain different types of finishes, seeking a visual effect of a vault made with masonry. Tied to the reed layer were placed wooden boards with cutouts of the shapes chosen for the decoration of the intrados, to prepare a base for the plasterwork that would define multiple types of moldings.

5. Conclusions

Philibert de L'Orme's proposal on wooden vaults did not have a direct impact on the viceroyalty of Peru, being the most relevant experience of its influence in the Jesuit church of Córdoba in Argentina, with a construction date after the introduction of the planked timber vaults in the capital of the viceroyalty.

Due to the characteristics of the first vaults built in South America, it can be said that this construction system had a Hispanic origin, apparently the technique was brought to these lands by Spanish builders. By the time Diego Maroto included it in the ceiling of the Inquisition chapel (1665) and in La Veracruz church (1666) in Lima, many of these vaults had already been manufactured in Spain, like which refers Lorenzo de San Nicolás (1639). In addition, the beam system that appears in the church of La Veracruz corresponds to the hanged type (the wooden arches were not self-supporting) very common in Spain, with cutouts of the planks only on the side of the intrados, unlike of proposal of De L'Orme, who promoted a cut of the plank giving it a concave and a convex profile.

Once the knowledge of how to build a vault according to the Spanish type was established in viceregal territory, an autonomous development began to take place, motivated mainly by the search for solutions to earthquakes. The planked timber vaults sought to reduce the weight of the churches' roofs, trying to lessen the effect of earthquakes on them. The various elements that made up these vaults (wood, cane, and leather strips) were designed not only to discharge their own weight, but also to absorb deformations without compromising the stability of the ceiling. Certainly, the design criteria of the master builders of the time were based on providing stability to the structure with flexible elements rather than opposing seismic movements with elements of greater rigidity. Criteria arising from field experience were applied, as in the case of the constant change of the vaults of the Lima cathedral after earthquakes.

There is no news in the construction contracts or any other document of that time, of tests made to verify the behavior of these structures. Possibly the experience accumulated in Spain and South America demonstrated the static reliability for vertical loads. In addition, earthquakes as real and constant tests of its function against horizontal forces would serve both to verify the design hypotheses and to correct and permanently adjust it to improve its earthquake-resistant behavior. Members of the Spanish scientific mission of 1738 noted that the use of the planked timber vaults did not depend on an economic factor but on safety: " … this invention is not economy; because it forces them to use the danger of tremors, which do not allow these pieces to be made of heavy material without imminent risk … " (Juan y Ulloa 1748, 50).

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