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MEXICAN RIBBED VAULTS OF THE SIXTEENTH CENTURY: ORIGIN AND STRUCTURAL BEHAVIOR

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Abstract. *During the sixteenth century there was a strong construction activity in Mexico, following the process of evangelization of the indigenous population. The hundreds of buildings constructed during this period that have survived, represent good building practice achieved at that time. The monastic buildings are the most representative architecture of that age. Particularity the Mexican monastic temple is characterized by a heavy barrel vault, but there are some of them with other type of roofs vaulted. They are fully covered with ribbed vaults and are the subjects of study this paper. Among the buildings that exist in Mexico with those characteristics were chosen four of which are located in the center of the Country (towns of Cholula, Tula, Acatzingo and Oaxtepec). The aim is to identify how the vaults were designed covering the nave of these buildings and have a solid basis for identifying which one is more efficient in their structural behavior, although they have similar characteristics; there are study of the application of rules given by different ancient writers in theirs construction treatises, especially Spanish. The case studies were built in different periods, this allows us to identify the evolution of the construction activity of this type of vaults in the New Spain. This revision is a base to study the structural behavior by means of non-linear analyzes with tridimensional models.*

1 INTRODUCTION

The sixteenth century was a time of great changes in Mexico from the fall of the Aztec Empire capital, Tenochtitlan, in 1521. This event was the start of the evangelization of the indigenous people, carried out mainly by three mendicant orders: Franciscans, Dominicans and Augustinians. The conversion of Native Americans to the new religion needed new spaces to celebrate the Christian rituals. At the beginning, the mendicant orders took advantage of the pre-Hispanic palaces to celebrate their religious rites [1]; in other cases temporary buildings were made of perishable materials. Later, during the first decades of the colonial period began an intense construction, which lasted until the end of the sixteenth century.

The religious buildings built in that time constitute a new architecture, the result of the union between the Mesoamerican and European building tradition. They built new structural forms that were not developed in the Mesoamerican world, as masonry vaults. The mendicants took advantage of the significant indigenous labor qualified to undertake great masonry works. The constructive systems used in these buildings were adapted to the possibilities of the site, the overall conditions to which Europeans constructors had to adapt, like seismicity of the area. Since these buildings remain in conditions similar to the original they constitute a relevant proof of the constructive practices of the time [2]. Studying them allows us a deeper understanding of the foundations of their design and intervene them properly when this is necessary.

After 1550 was built hundreds of convent temples in the biggest and most prosperous communities (figure 1). The prototype of these temples was a single nave, with no transept, polygonal presbytery and thick masonry walls reinforced by large buttresses that support a barrel vault [3]. They have withstood the test of time and have experienced severe earthquakes which have caused some damage, but have remained relatively resistant to the effects of those movements. To study them in detail it is first necessary to identify and understand they are the product of the inheritance of two building traditions that gave rise to new architecture.

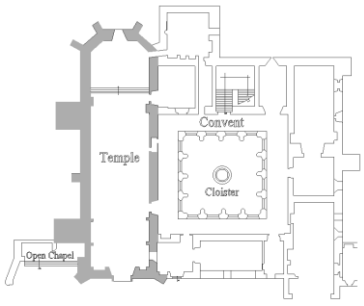

Figure 1: Typical floor plan of a convent and temple.

Although the barrel vault was the most common type of cover, some churches were also built with ribbed vault ceilings, which, although in much lower numbers than those with barrel vaults, constitute a relevant cover system, which has not been studied in depth and is the purpose of the present work. The convent temples totally cover by ribbed vaults has particular construction and structural features, as well as, design characteristics.

The main purpose of this paper is the study of the tracing of ribbed vaults, as well as the characteristics and origin of dimensions of their buttresses; the objective is to investigate the source of their design and to set the basis for a better understanding of their structural performance. The starting point for this study was the review the background of ribbed vaults in the

countries where this cover system originated; as well as, the review of Spanish construction treatises, and the study of their possible use in Mexican religious buildings.

The most relevant aspects of their building tradition, were studied, and it was possible to identify multiple guidelines for their tracing and building in construction treatises. These procedures were tried in certain Mexican convent temples whose features are representative from the geometrical point of view, and for their possible influence in their structural performance.

2 BACKGROUND OF RIBBED VAULTS

The oldest precedents of ribbed vaults are the roman groin vaults generated by the intersection of two barrel vaults of the same height; their advantage over their barrel vault ancestors is that, as they concentrate their weight on specific points, they only need support in their four corners. To overcome the constructive difficulties of the cross ribs, medieval building covered them with arches, known as cross arches. A constructive and structural progress of great relevance occurred when these arches were made semicircular [4], as they generated less thrust than those that were elliptic and the curvature of each voussoir remained unchanged. The change from elliptic to semicircular cross arches marks the beginning of the construction of ribbed vaults [4]. The adoption of the semicircle in cross arches fostered the emergence of covers that were very similar to sail vaults, which actually had outward curved shapes because their origin was a cross arch vault and the lines did not completely adapt to a sphere.

2.1 Spanish cross ribbed vault

When additional ribs were built to the perimeter and cross arches – known as tierceron, ligatures and cambered-, the construction of star ribbed vaults began in Europe. It was created a variety of geometric shapes in masonry webbing, which were widely developed in Spain between the thirteenth and the sixteenth centuries [5]. *Quadripartite* vaults were very popular in that period in Spain, especially the one with tiercerons and five keystones; there were also a great number of them with complicated designs consisting of networks or mesh, which served as guides and control of the geometry, and not as formwork [6].

In the sixteenth century, domed shapes were built in Spain, almost with no cross ribs and with ribs, they are as nerves with no structural function. The Spanish star ribbed vaults emerged basically from two schools: *Toledan*, and *Burgalese* [5]. The first one is distinguished by straight-line designs, and the second, for the use of curved or cambered, secondary ribs. The geometries achieved by these schools were varied and can be classified according to the geometry of their rampant [7] as level, round, spherical, outward curved, and convex. These Spanish star ribbed vaults constitute "the Renaissance version of the European cross vaults of the classic French gothic" [3], and they are similar to those built in Mexico during the sixteenth century.

2.2 Basic features of the Spanish ribbed vaults and their buttresses

The Spanish treaties by Rodrigo Gil de Hontañón, Alonso de Vandelvira and father Tomás Vicente Tosca, describe methods for the tracing of ribbed vaults. The first one of them indicates the constructive sequence, and the others describe procedures to define the geometry of each rib. These methods, known as *fixed rampant tracing*, have been extensively studied by several Spanish researchers [6, 7, 8]. In particular, the tracing of tiercerons in the plan use to be generated starting from three methods. One of them consists cross points of geometrical traces; it was the most common in Spain, and it consists of placing the tiercerons starting from a circle that is circumscribed to the plan of the vault and its intersection with the orthogonal axes.

Rodrigo Gil de Hontañón developed rules to establish the dimensions of the ribs and their keystones, as well as those of the buttresses that support ribbed vaults. He set the hierarchy of each rib according to the load they support, and proposed the required rise for each one of them. To determine the dimensions of the buttresses, he proposed a rule for church halls ribbed vaults; Sanabria [9] and Huerta [10] describe this rule with the formula that appears in Table 1.

Table 1: Rule Rodrigo Gil de Hontañón for the depth and breadth of buttresses supporting rib vaults

Symbology	Formulas
C = Total depth of the buttress P = Depth of the buttress E = Thick wall E_p = Thick pilaster L_n = Length of a rib from the impost to the keystone T = Buttress height A = Buttress width	$C = P + E + E_p = \frac{2}{3}\sqrt{T + \frac{2}{3}}\sum L_n$ $A = \frac{1}{3}\sqrt{T + \frac{2}{3}\sum L_n}$

3 MEXICAN RIBBED VAULTS

3.1 First constructors of ribbed vaults in New Spain

The most relevant features of the Mexican ribbed vaults built in the sixteenth century have been identified by several authors, mainly Kubler [3]. These vaults are made of thick masonry conglomerates, and similar to those built by Rodrigo Gil de Hontañón in Spain. The first master builders of these vaults in Mexico were friars Juan de Alameda and Claudio de Arciniega. The vaults of the temples of Huejotzingo, Cholula, and Tula, among others, are attributed to Juan de Alameda. It is possible that Claudio de Arciniega participated in some construction works in the ribbed vault temples of Acolman, Metztitlán, and Actopan. Francisco Becerra, another architect of the time, may have been involved in the construction of the ribbed vaults of the presbyteries of Cuauhtinchan and Totimehuacan.

3.2 Period of construction and location

The construction of temples that are completely covered with ribbed vaults started after the first half of the sixteenth century. Currently fifteen temples exist with these characteristics, of which only one has a coffered vault in the presbytery. In most of them, the choir loft is also supported by a flat ribbed vault sustain on segmental, or basket-handle, arches. More than half of these temples belonged to the Franciscan order and they were built in Puebla State and one in Hidalgo State; the remaining temples were Dominican, three of them in Oaxaca, and one in Morelos. The Augustinians also used this type of vault, but only to cover the presbytery of their temples, one section of the nave, or the place below the lower choir; they also used them for the corridors in some convent cloisters, in larger numbers than the Franciscans and the Dominicans.

3.3 Nave proportions

The fifteen monastic temples completely roofed by ribbed vaults are single nave; the plan of each bay is almost square and the length-width ratio of their plant is between 4 and 4.5. Only Oaxtepec temple, which has "*corillos*" (small spaces to the choir) has a little less 5

length-width ratio. This ratio was recommended by Rodrigo Gil de Hontañón for churches with transepts. The height-width ratio of the nave of Franciscans churches is close to 1.7 in most of these temples, regardless of the construction period. This is not the same in Dominican churches, among which the most and least slender of all the temples completely covered with ribbed vaults are found; located in Oaxtepec and Yanhuitlan respectively.

4 CASE STUDIES

4.1 General characteristics

So far the study of the trace of the Mexican ribbed vaults has been based on four case studies. They are the convent churches located in Cholula, Tula, Acatzingo and Oaxtepec (table 2). The first three are Franciscans and the last is Dominican. These buildings were chosen for their geometrical and structural differences. They belong to different periods of construction: the first two were built in the decade from 1545 to 1555, the others from 1555 to 1561.

Table 2: Case studies (units in meters).

Construction period	Location	Length	Width	Height	Length/ Width	Height/ Width	Depth Buttress	Wall thickness
1545-1555	Cholula	53.0	12.0	20.5	4.4	1.7	3.0	1.70
	Tula	49.5	12.0	20.3	4.1	1.7	2.9	1.80
1555-1560	Acatzingo	53.0	12.2	21.2	4.3	1.7	2.5	1.75
After 1561	Oaxtepec	53.5	11.3	15.8	4.8	1.4	1.7	1.90

The profile of the extrados or upper surface of the vaults studied is different in each of them. The two oldest, situated in Cholula and Tula, have nearly flat roofs, with haunches totally loaded, in which visible only the summit of the vault. The temple located in Acatzingo is practically free of filling and have a spherical or domical vault system. Finally, the extrados of the temple of Oaxtepec is an undulated profile vaults (figure 2).

Figure 2: Intrados and extrados of the case studies.

Among the temples studied, only the vault of Acatzingo does not have loaded haunches because its geometrical shape contributes to its stability; the vault section near the front of the temple has no ribs, which indicates that its dome-shaped geometry, closest to a sail vault, supplies stability on its own. This can be seen in figure 3, which shows a horizontal section at the height of the keystone perimeter arches. The geometry of this vault saves material because

its thickness at the summit is the smallest of all, about 50 cm, while the thickness of the remaining case studies is around 70 cm.

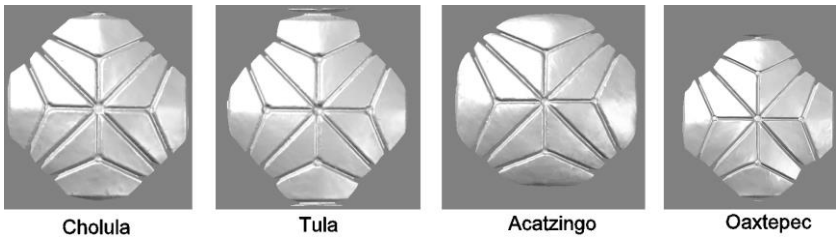

Figure 3: Horizontal section of the vaults at the height of the keystone of the perimeter ribs.

The vaults of the temples of Cholula, Tula and Oaxtepec would be closer to the "Gothic filiation", which consists of webbing resting on the nerves. From the structural point of view, the recommendation of "loading the haunches" of vaults, as described in ancient construction treatises, gives them greater stability, and it was common practice in Mexico [11].

4.2 Trace of the ribs

The actual geometry of the vaults was compared with that of the procedure described by two Spanish treatise authors (Alonso de Vandelvira and father Tosca), which have been investigated by multiple contemporary authors from that country [6, 7, 8]. Although these treatises did not come to New Spain in the sixteenth century, their content refers to the Spanish building practices of that time and prior, which was very probably known by the constructors of Mexican conventual buildings.

The study of the tiercerons consisted in drawing the methods proposed by treatise authors on each plan. The method of "intersecting points" was used in the case studies. The Tosca´s treatise is close to the vaults of the temples of Cholula and Oaxtepec. Only four of their eight tiercerons follow the "intersecting points" trace of the churches of Acatazingo and Tula; the trace of other four tiercerons are obtained by drawing a circle whose center is the keystone of the cross points, and its diameter is equal to the distance between the previously traced tiercerons (figure 4).

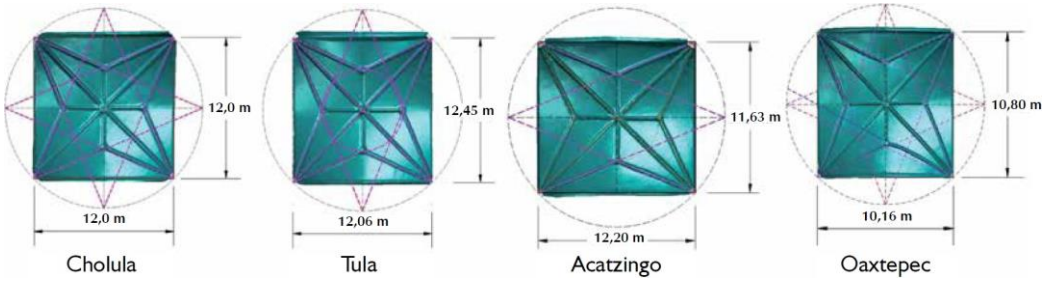

Figure 4: Trace of tiercerons in plan.

The rampant (height difference between the keystone of the diagonal and perimeter arches) and the cross-sectional profile of three case studies, match a semicircle that has its center in the intersection of the cross ribs in the plan. Although the ligatures do not perfectly follow this curvature, in general they adapt to it. The temple of Oaxtepec has liernes practically straight, as opposed to the rest of churches studied.

The perpend ribs and wall ribs have the same rise in each case; only in the church of Tula the keystone of wall ribs is a little below that of the perpend ribs. The perimeter arches of the

four temples are slightly pointed, with the exception of those in the church of Acatzingo, which have a semicircular profile.

The trace of the cross ribs of the four temples follows the method of father Tosca´s treatise. Only the vault in Acatzingo has slightly pointed cross arches, and the vault in Oaxtepec has a slight descent in the keystone. The trace of the tiercerons in the temples of Cholula and Tula is more similar to the method in Vandelvira´s treatise. In contrast, the tiercerons in the church of Acatzingo are closer to the curvature of their cross ribs and do not follow any of the two treatises. The same happens in the tiercerons of the church of Oaxtepec, but the radius of the curvature of its tiercerons is smaller that of the cross ribs.

4.3 Geometric features of the buttresses

For the study of the dimensions of the buttresses supporting these vaults, Spanish treatises were consulted. The buttresses are located throughout the sidewalls, and their function is to balance the thrust generated by the vaults; hence their importance for the stability of the building. These elements are necessaries especially in the longitudinal façade opposed to the convent. However, in some temples the top of the wall adjoining the convent may have trouble generating cracks in the vaults [2].

The actual depth of the buttresses has been compared with the rule developed by Rodrigo Gil de Hontañón for abutments to counteract the thrust of ribbed vaults in hall type churches (table 3). The buttress dimensions in the churches of Acatzingo and Tula are very close to Hontañón´s rule (the corbel to which ti rib bundles arrive was considered); it is worth mentioning that the buttresses in the church of Tula are pentagon-shaped and those in Acatzingo are rectangular. On their part, the dimensions of the buttresses of the temple of Cholula are the most conservative, more than those obtained with the rule. Only the buttresses on the church of Oaxtepec are much smaller than those given by Hontañón´s rule.

Table 3: Hontañón´s rule applied in the case studies (units in meters).

Location	Width wall	Depth Buttress	Total depth	Rule
Tula	1.78	2.90	4.65	4.60
Cholula	1.73	3.00	4.76	4.55
Acatzingo	2.15	2.45	4.60	4.55
Oaxtepec	1.90	1.70	3.60	4.20

4.4 Structural behavior

Three-dimensional models of each case study will be developed to analyze the structural behavior. The non-linear analysis will be to bring each model to the failure to vertical and horizontal loads. The membrane that represents the intrados of the vaults will serve to this purpose (figure 5). The analysis in the finite element program Ansys, allow to compare which of the roofing system is more efficient, that is, which case studies have further progress in structural design. This study is in order to compare which of the roofing systems is suitable to withstand the applied loads (own weight and seismic actions). Since the chosen buildings were built in different periods, this allows us to identify the evolution of the construction activity of this type of vaults and how it was changing the way we conceive from the structural point of view.

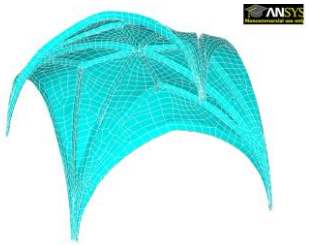

Figure 5: Intrados model of the Oaxtepec vault.

5 CONCLUSIONS

An overall review was conducted on Mexican temples that are completely covered with ribbed vaults that have remained to this day. For the detailed study of the trace of the vaults, the convent churches located in Cholula, Tula, Acatzingo and Oaxtepec were chosen. The actual geometry of these vaults was compared with that of the procedure described by two Spanish treatise authors, which have been investigated by multiple contemporary authors from that country. The method used to trace the ribs in plan and elevation, as well as the dimensions of the buttresses, is similar to those proposed by the treatise Writers studies in this work.

Deep knowledge of the geometry of the vaults studied here is a basis for studying the evolution and improvement of construction techniques imported in the sixteenth century and how they adapted to the conditions of the New Spain. This aspect will be studied by modern analytical techniques such as finite element method in the next step of this research.

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