Two Flat Ribbed Vaults in San Juan de los Reyes (Toledo, Spain)

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ABSTRACT: Late gothic flat ribbed vaults have special interest since they are considered as a technological work that belongs to a specific period of change in which the medieval ideas are living together with the new humanistic view of Renaissance. At that moment, a new kind of vault was built using a deep geometrical and technological knowledge, that was never seen in the Middle Ages. The main purpose of this paper is to analyze and compare two of these vaults that are built in San Juan de los Reyes monastery, in Toledo (Spain), in order to extract the geometrical ideas and the technological knowledge that made them possible.

INTRODUCTION

The historical periods of change have much interest since they show the specific features of the previous age mixed with the new ideas that come with the next period of time. It is fascinating to analyze how during the fifteenth and sixteenth centuries in Spain, the medieval way of understanding the world coexisted together with the new humanistic view that came form Italy. The gothic technology produced the most brilliant works, and at the same moment the Renaissance architecture was developing new forms. Although the Humanism brought a different conception of the world, the society still had in mind the medieval values that represented the gothic architecture, specially related to the religious and government institutions. That produced a complex situation in which the gothic ribbed vaults were still built together with the new classical style vaults; there was a great flexibility in using several resources and different building systems. The arriving to Spain in the fifteenth century of several north-European architects gave a boost to the design of late gothic buildings. Simon de Colonia, in Burgos, was one of the main architects of that period. Juan Guas arrived to Toledo, and after them Antón and Enrique Egas developed their projects, but they had not the importance of the previous one, who was really brilliant. Before these builders came to Spain, the usual vault had just two diagonal ribs and only one keystone. It is not strange that the new designs of the European masters caused great impact and surprise, and also the later architects had much influence from them. During that period of mixed continuity of the Middle Ages and the renovation caused by the Modern Age, a new kind of monastic church was developed in Spain. They were designed with one nave, no aisles, and several chapels built inside the walls, with influence of pilgrimage churches that were built in France. But the innovation of the Spanish churches was the elevated location of the choir at the west end of the nave. A platform was created for the monks, on which they could hear, sing, and follow the liturgical rite, but they were not an obstacle in the way of the nave; the functional criterion still remained. This platform had to be hold up by a vault that could not be as high as the usual vaults in the nave, but a flat one. Two examples of these flat vaults are in San Juan de los Reyes convent, in Toledo (Spain). This is one of the most important late gothic buildings in the whole country, and was begun to be built at the end of the fifteenth century. The first flat vault is located at the west end of the church (10.00x11.75m), supporting the choir, and was designed by Juan Guas. The second vault is at the entrance hall of the convent (7.00x7.00m), and was created by Enrique Egas.

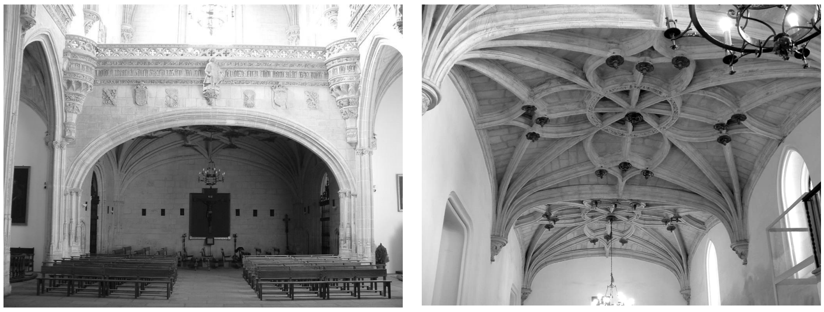

Figure 1: Choir of the church (left) and entrance hall of the convent (right)

OBJECTIVES AND METHODOLOGY

The study has two main purposes. On one hand, it is expected to get a deeper knowledge about a specific kind of vaults. On the other hand, the study is focused on the geometrical principles and the technical resources that made possible the construction of these vaults. In this way, the vaults have been analyzed as technological landmarks, so that their geometry and their building system have been investigated, in order to define the contribution to the knowledge of that period of time. To begin the study, both vaults have been measured with topographical devices (total station Leica TCR-403). As a result of this process, several points, corresponding to the three-dimensional geometry of the vaults, have been obtained. Using that information, an interpretation has been made to analyze the geometrical resources that were used during the design of the vaults, and the constructive process that made possible the building of these masterpieces. A summary of this interpretation and the main ideas are shown as follow.

THE GEOMETRICAL KNOWLEDGE IN THE MIDDLE AGES

In order to understand how the medieval architects designed their works, it is very important to understand the state of knowledge in the Middle Ages, and which kind of resources did they have at that historical moment. We have to try to think with the ideas of a medieval architect. The design process was based on the plan drawing of the vault's horizontal projection, and the elevations of each rib. It was a process of "*vertical development*", so that each rib was located on the plan drawing (x,y coordinates), and then the height of each point was determined by the elevations. Finally, web spandrel was executed supported by the ribs, but without a previous geometrical conception (Rabasa 2000, p.132). The main elements of the process were the lines (corresponding to each rib), and the surfaces were a consequence of these lines' tracing development. Although the same system based on a plan drawing and individual elevations of ribs were still used during the last period of the Middle Ages (fifteenth and sixteenth centuries), more geometrical resources were developed, and more complex designs were created. The medieval design based on lines began to change into a modern conception of surface generation.

Geometry of basket arches

The oval shape that has been generally used in architectural designs, is a plane line with three centers and two symmetry axis. Then, a basket arch is the one which follows an oval shape. It has two great semi-axis (A), just one small semi-axis (B), two curve-radius (Ri is the lower curve-radius, and Rs the upper curve-radius) according to three centers, and the point (T) where the curve-radius changes.

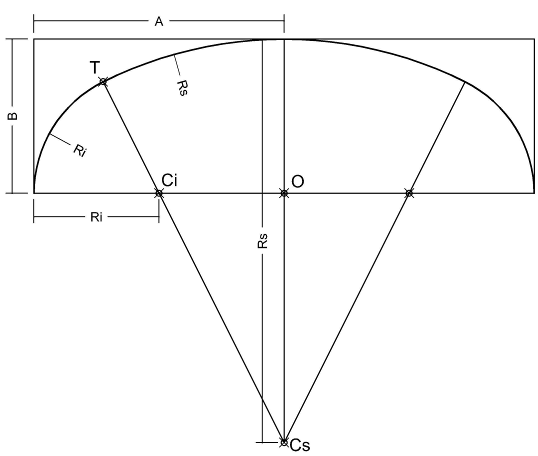

Figure 2: Geometry of the oval shape

One special feature of this geometrical line is that there are infinite ovals that have the same semi-axis. That gives a great versatility to the designer, because there are many possibilities of tracing basket arches with fixed dimensions of the semi-axis. However, it is much more difficult to analyze these arches because of their higher irresolution degree in comparison with the single radius arches. In the Middle Ages, a general system for oval tracing was not known yet. Even though, they knew some methods for tracing particular cases. Robert Willis (Willis 1842, p. 25) shows two systems for tracing groups of oval arches with the same lower curve-radius (Ri) that begins at a fixed point (P1) and reach another fixed point (P2). The first system follows the hypothesis that the point where the curve-radius change (T) is also fixed, so that the upper curve-radius (Rs) has to be determined. The second one supposes that the upper curve-radius (Rs) is fixed, so that the point T is the variable to be found.

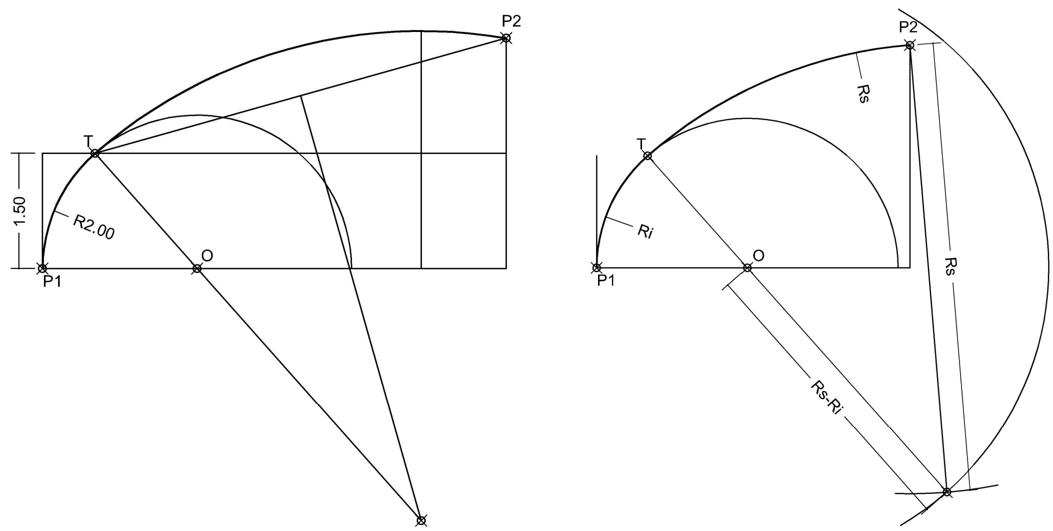

Figure 3: The point where the curve-radius change (T) is fixed (left). The upper curve-radius (Rs) is fixed (right)

It is remarkable how the designer is able, with the first method, to trace ovals with the same point T that reach to several points P2 by just changing the upper curve-radius (Rs); on the other hand, with the second method, it is possible to obtain ovals with the same upper and lower curve-radius (Ri and Rs) that reach the point P2, just by moving the point T. Another system that was used in the Middle Ages (Huerta 2007, p. 222), consists of dividing the great axis in several parts (M), so that one of them is equal to the lower curve-radius (Ri). The upper curve-radius (Rs) is determined also using this module (M).

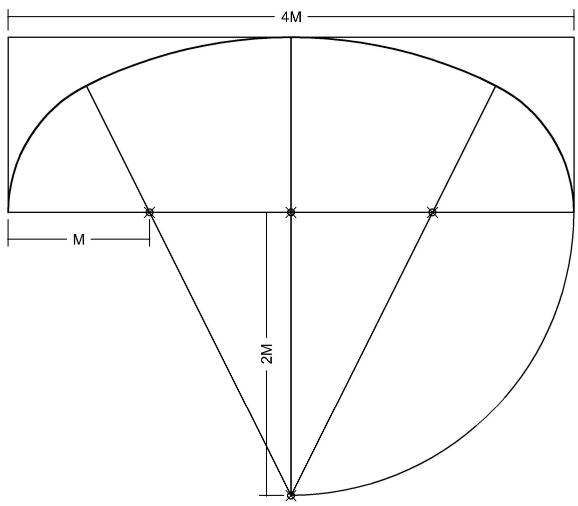

Figure 4: Oval tracing method by dividing the great axis in several parts

ANALYSIS OF THE VAULTS

Masonry movements

One of the main problems when analyzing the geometry of the stoneworks, is the fact that they always are distorted. Since the first moment that the masonry structure begins to work, several movements cause distortions, and they can be detected at all historical buildings. When analyzing the geometry of such buildings, it is necessary to set the actual distorted forms to a hypothetical initial “pure” form. That is why a “setting” process is needed, and such process is always subjective. In this case, the following hypothesis has been established:

1. There have not been any settlements. The walls have moved only on their upper parts.
2. The length of the intrados line of the arches has not changed.
3. There have not been any distortion in the region of the springer’s fork (it has a solid constitution).

Design of the vaults’ plan

The vaults’ plan used to be a result of a simple geometrical development, and the medieval designers did not use numerical methods as we nowadays do. After analyzing the vaults, two possible geometrical methods have been found, that could have been used in the Middle Ages. The choir vault’s tracing system may be based on a geometrical frame. That frame may be generated using a specific module which sets the distance between the lines. At the entrance hall, the vault could be traced using an angle bisector system. The angle bisector lines, corresponding to the tiercerons, were drawn with the help of a circumscribed circle that touchs each corner of the vault’s plan.

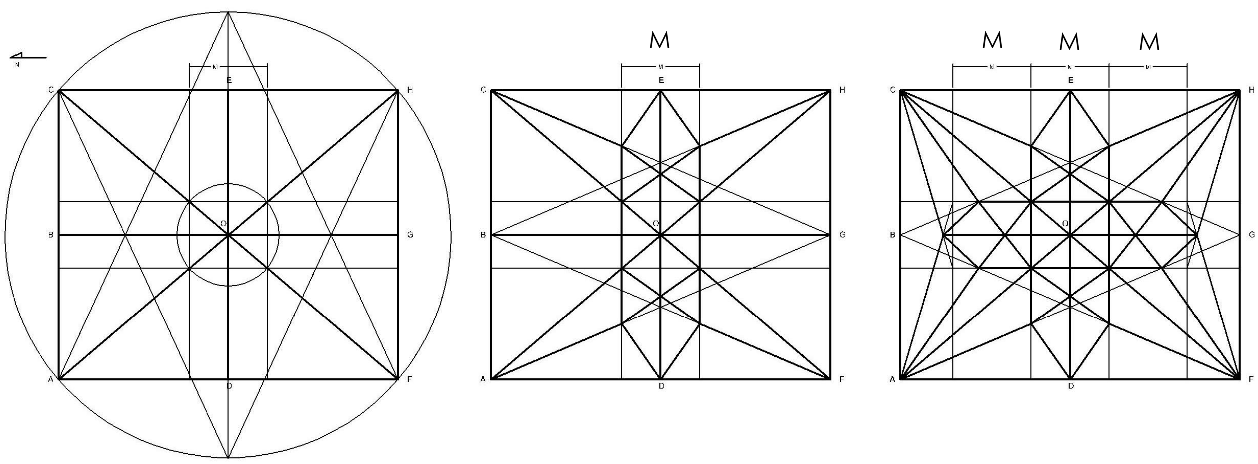

Figure 5: Vault’s tracing system at the choir, based on a geometrical frame, using the module M

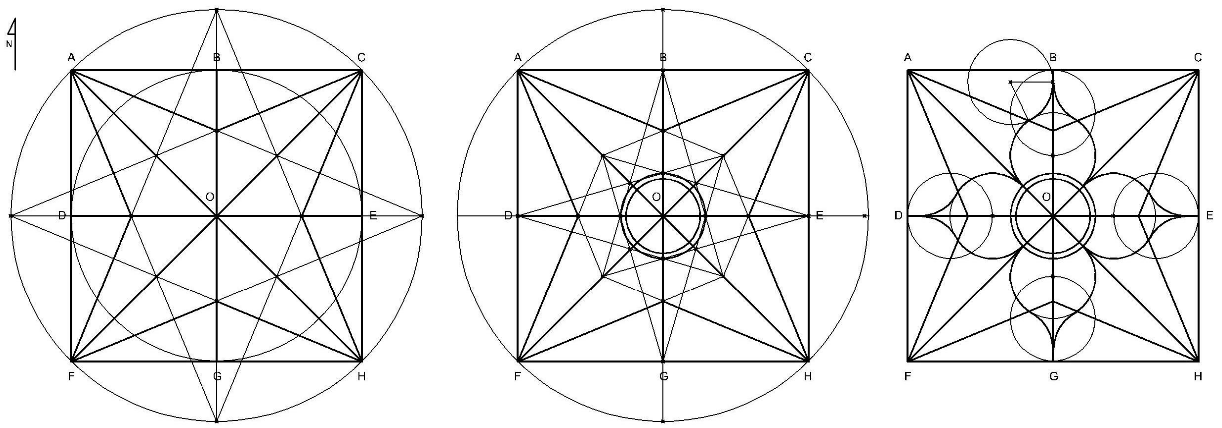

Figure 6: Vault’s tracing system at the entrance hall, based on an angle bisector

Geometrical analysis of the vaults

The analysis that has been made has two main purposes. The first objective is to find the original form of the ribs that are nowadays distorted. Then, it is possible to know how the whole geometry of the vaults was developed, and how the arches were traced. Besides the deformity of the masonry, there is another problem when analyzing the ribs: there are oval arches, and they have two curve-radius, so that there are more unknown factors than in the case of a single-curve arch. Considering these problems, the analysis has been divided in three parts.

First part: Setting of individualized ribs

The geometrical analysis of the vaults begins with a setting process of each individual rib, from its current distorted state to a hypothetical original form. At this point, it has been considered that the initial arch was symmetrical, so that this condition has been forced.

Second part: Setting of equivalent ribs

The objective of the second part of the geometrical analysis is to set the arches following a logical criterion of equivalent ribs. In other words, all the arches in an equivalent position have to be the same: diagonal ribs have to be equal; wall arches have to be equal; transverse arches also have to be equal. These are the "main" arches (wall, transverse and diagonal), and they configure the whole geometry of the vault. The setting of the arches allows the analysis of them. All the transverse and wall ribs are oval curves, but there are some differences between the two vaults. At the entrance hall, all the ribs have the same form; they are complete basket arches. On the other side, at the choir, the wall arches are different from the transverse arch. Besides, the west wall arch is not the same as the other equivalent arches. In this vault, the ribs are incomplete basket arches; they start with a tangent line that is not vertical (as it would be at the start of a complete one). That means that the centre of the lower curve-radius is below the starting point of the arch. The diagonal ribs are in both cases complete basket arches, but at the choir they have a vertical supplement to make them higher. As it can be seen, the vault at the entrance hall has an homogeneous design, and besides being all basket arches, they could have the same lower curve-radius. That makes the elaboration process easier. On the other hand, at the choir, the arches have remarkable differences from each other. There are complete basket arches, vertical supplements and incomplete ovals that begin with an oblique tangent line. The geometrical design is more complex, but the resources that have been used give more options to define the position of each point on the final surface.

Third part: Whole geometry of the vaults

The global geometry of the vaults is determined by the main arches. After defining them, it is possible to design the tiercerons and the liernes (straight and curved secondary ribs). The tiercerons have been set using the lower curve-radius (Ri) that can be traced at the springer's fork. The upper curve-radius is determined trying to use as less variations as possible (it has been assumed, that if it is possible to use only one upper curve-radius value, that would be the method used by the medieval architects). As a result of the setting process, the tiercerons have a similar configuration as the diagonal ribs, but although they start with a vertical tangent line, they are not complete, but partial ovals. Finally, the liernes are determined by their extreme points, following the plan drawing and the already determined height of the main arches and tiercerons. Then the geometry of the vaults is complete. After defining each rib, the analysis of the global surface has been developed. The ridge ribs show how the surface is: in both cases the ridge ribs are not horizontal, but lightly curve, so that they fall down from the vault's keystone until each wall arches' keystones. While at the entrance hall's vault both ridge ribs descend the same distance (symmetrical and homogeneous geometry), at the choir's vault the geometry is not symmetrical, and the surface is not so high at the west side as it is at the east side (somehow, the surface is "opened" till the nave). Also it has been analysed how flat are the vaults in comparison with a reference vault with a semicircular diagonal rib. The vault at the entrance hall is flatter than the vault at the choir, which is roughly half the height of the reference vault.

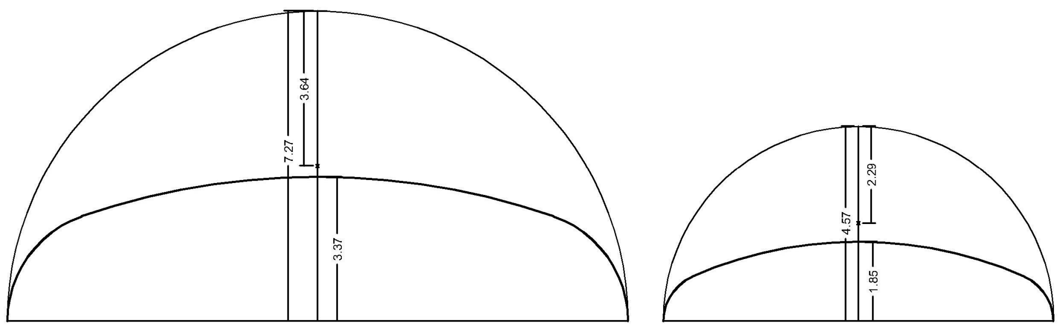

Figure 7: Height comparison of the choir's vault (left) and of the entrance hall's vault (right)

Finally, it has been analysed which medieval methods might have been used to trace each arch, in order to understand how the geometry was designed. The main arches could have been traced using the method of dividing the great axis in several parts, so that the lower curve-radius (Ri) is equal to one of these parts. The upper curve-radius (Rs) is also compound of a certain number of parts [Rs=xRi]. It is necessary to know the whole length of the great axis to trace the arch, so that it is not possible to use this method when the oval is not complete. That happens when the arch begins with a tangent line that is not vertical, because the span is not equal to the great axis of the oval. It would be quite difficult, according to the medieval knowledge, to trace an oval whose great axis is unknown. That is why it is more reasonable to think that in these cases there was used a “two steps” method. First of all, a complete arch was traced (knowing the great axis). Then, the figure was moved up or down, according to the point(s) to which the arch had to reach. When moving up, the result was a vertical supplement, and the oval was still complete. When moving down, the oval was “cut”, so that the span got slightly smaller (the span was not equal to the great axis), and as a result, the tangent line at the beginning of the arch was not vertical, but oblique.
Also the tiercerons are not complete ovals. Even though, they are a portion smaller than half-oval, so that the method explained before could not have been used. When comparing the height of the point where each rib get separated from the side ribs (upper level of the springer’s fork), with the height of each arch’s point where the curve-radius changes (T), it can be deduced that this point (T) is located at the same position of the upper level of the springer’s fork. This hypothesis has a constructive reason. That point (T), is the limit between the upper and lower curve-radius, and it is much easier to make the pieces if this change is located just at the upper level of the springer’s fork. In this way, the whole springer’s fork would have only one curve-radius (which would be the lower curve-radius, Ri), while the individualized ribs that are over the springer’s fork would also have only one curve radius (which would be the upper curve-radius, Rs). The most important advantage of this method is that all the voussoirs would be the same. Taking in consideration this hypothesis, the tiercerons might have been traced used the previously described Willis’ methods for partial ovals. Finally, the geometry of the vaults is completed with the liernes.

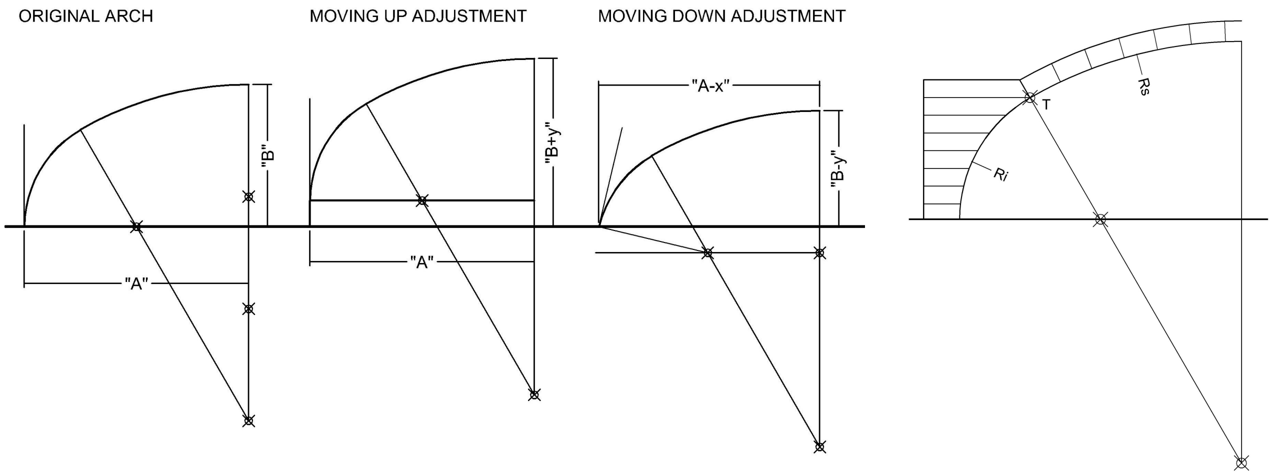

Figure 8: Adjusting methods by moving the original arch (left). Location of the point where the curve-radius changes at the upper level of the springer’s fork (right)

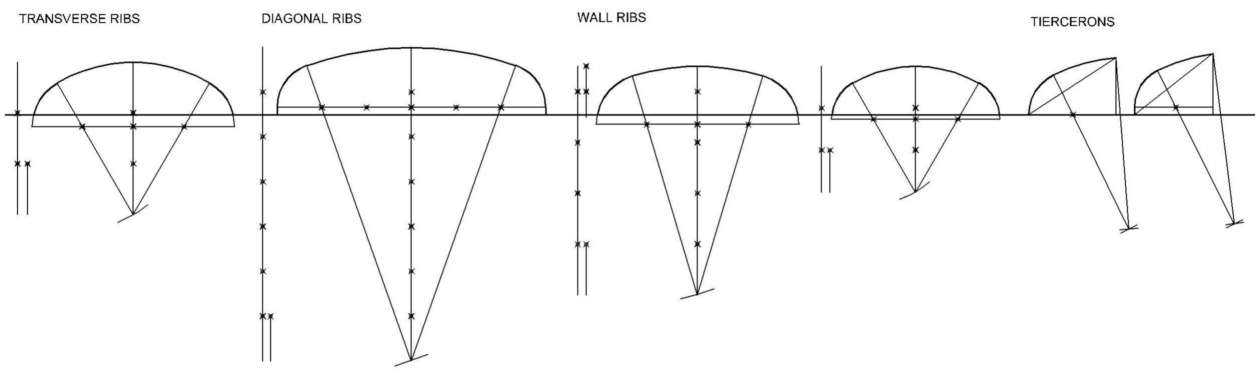

Figure 9: Hypothetical medieval design of the arches of the choir’s vault

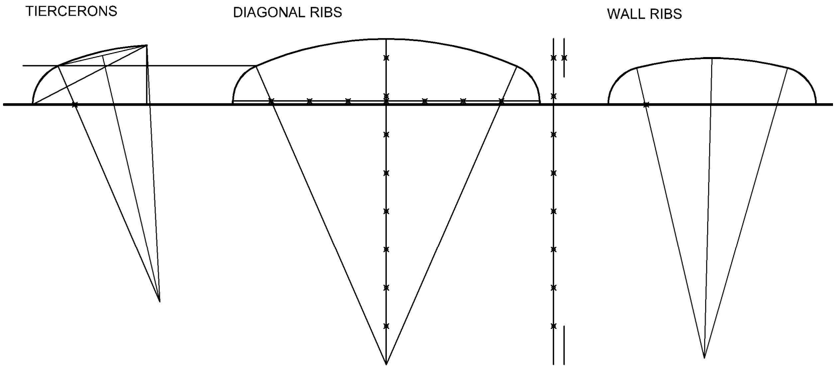

Figure 10: Hypothetical medieval design of the arches of the entrance hall's vault

Figure 11: Whole geometry of the vault at the choir (left), and at the entrance hall (right)

Constructive elements of the vaults

After analysing the geometry of the vaults, a constructive study of them has been developed. First of all, the supporting system of the vault at the choir is different from the vault at the entrance hall. In the first case, the vault leans on circular section's piers built adjacent to the walls. Due to the wide range of ribs that begin on each pier, the pieces of the springer's fork have a really complicated tracing and carving. The upper level of the springer's fork is not a horizontal plane, but a crooked surface. On the other side, at the entrance hall the vault leans on brackets, and all the ribs that begin on them are equal. That is why the upper level of the springer's fork is a horizontal plane, so that the arches are all separated at the same height. In this case, the pieces are simpler and more homogeneous.

Figure 12: Springer's fork of the vault at the choir (left) and at the entrance hall (right)

When analysing the ribs, the differences are not so clear between both vaults. However, the entrance hall's vault has a more homogeneous design of the ribs than the choir's vault. The general higher complexity of the choir's vault has an exception with the keystones. The pieces belonging to the entrance hall's vault are well carved and have an outline related to the ribs that reach them. On the other hand, the keystones of the choir's vault are basic volumes (cylinder or polyhedron), without any kind of carving. The pieces are bigger, and they are not supposed to be seen, but hidden by ornamental devices. In some places there is a rib's crossing without keystone, so that the difficulty of carving is higher.

Figure 13: Keystones of the vault at the choir (left) and at the entrance hall (right)

In both vaults, web spandrels are made of regular light stone pieces, whose ends lean usually on the ribs. The pieces are not always situated in the same direction, because they are located following the geometrical frame created by the ribs. That makes the carving process easier, and avoids diagonal cuts, so that the quality of web spandrel is higher.

Figure 14: Web spandrel of the vault at the choir (left) and at the entrance hall (right)

CONCLUSIONS

The analysis developed with the two vaults shows how deep the geometrical knowledge was, and the constructive skills that their authors had. It is possible to appreciate a whole catalogue of geometrical resources to design the ribs. The initial condition is the small height that produces a flat design of the vault; there is a functional criterion. In this way, there is a previous idea of the general geometry that determines how each arch is traced. In other words, the conception of the surface is previous to the design of the lines. This process has the opposite order as the usual medieval method, and this change could be related to the moment in which the vaults were built: the period of transition from the Middle Ages to the Modern Age, in which the humanistic ideas, that gave predominance to the surfaces against the lines, came up from Italy.

When comparing the vaults, it is possible to appreciate in both cases a good carving quality and an excellent building technique. However, the vault at the choir, designed by Juan Guas, is more elaborate than the vault at the entrance hall, created by Enrique Egas, which is more homogeneous and simpler. The reason could be the different location inside the building. Also the skills of Juan Guas were more developed, and he could design a more innovative and advanced vault in comparison with the more conservative geometry of Egas' vault.

The medieval design system is based in simple geometrical methods, without the use of numerical developments. In that way, the plan of the vaults could be traced by using only geometrical resources. Also the ovals tracing methods consisted on easy developments that could be reproduced at the *loggia* where all the pieces where cut and carved. But these simple methods were complemented with adjusting movements (up or down). The addition of these developments produced a very precise result that would be very difficult to obtain at that time by other ways. That shows us the deep geometrical abilities of those medieval architects.

The changes that take place during the transition period into the Modern Age are not only aesthetical aspects. There are functional criterion and the innovations are part of a global technological development. The design of vaults which contains a greater number of ribs during the late gothic period is not just an aesthetical idea, because it gives some constructive advantages. First of all, the ribs create a whole spatial frame to support the web spandrel, so that there is no need to use wooden centerings to hold them up, and it is possible to save material. This spatial frame, with a longitudinal and transverse ridge ribs, also helps to arrange the pieces of the web spandrel in several directions, avoiding oblique cuts of these pieces. Almost all the arches are oval, and the number of different curve-radius has been reduced as much as possible. In this way, there has been a unification aim when designing the vaults. That makes easier the voussoirs' cutting and carving process, and it reduces the number of different centerings needed to build the vaults. If the point where the curve-radius change is situated just in the same place of the upper level of the springer's fork (as it is been detected), that means a remarkable constructive advantage. As it may be deduced, there is an optimization of the building process, and although the design of the vaults gets more complicated, some resources are applied in order to make the building process easier. Also the carving skills are developed and the quality of the pieces of springer's fork, ribs' crossings and keystones is quite high.

In this way, the development of the gothic architecture may be understood not only as an aesthetical change, but also as a technological improvement, a progress of the geometrical knowledge about shapes and surfaces, as well as an evolution of the society's mind during that period.

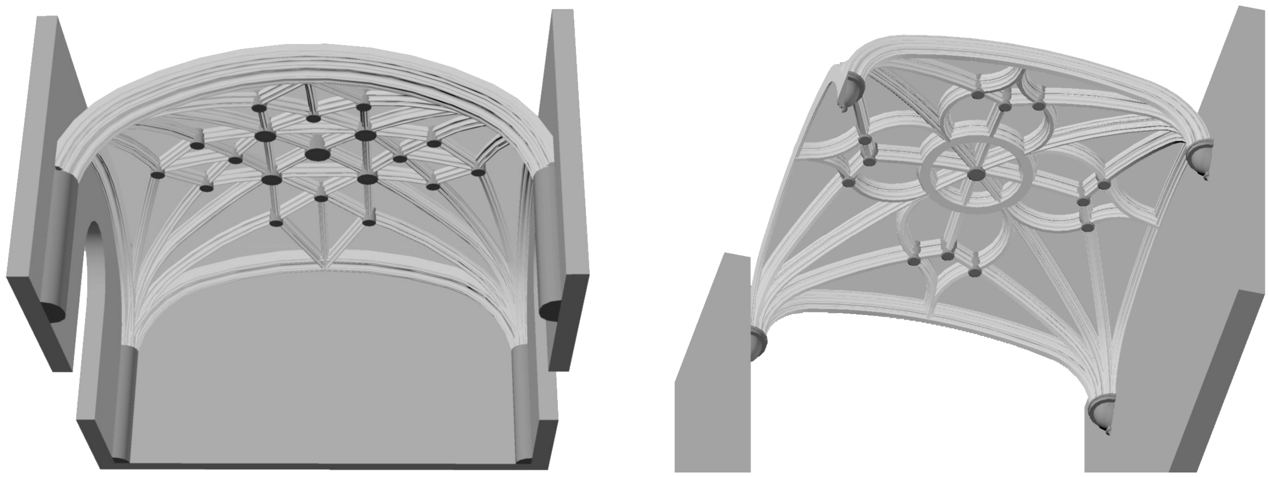

Figure 15: View of the geometrical model of the choir's vault (left), and the entrance hall's vault (right)

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