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RIBBED VAULTS WITH RENAISSANCE CHARACTERISTICS: SINGULAR DESIGN AND CONSTRUCTION IN SOME OF DIEGO SILOÉ'S VAULTS

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Abstract

The Renaissance architect Diego Siloé designed the parish church in Iznalloz in 1549 in the Renaissance style but covered the nave and aisles with medieval ribbed vaults. The analysis of these vaults reveals that the architect sought a consensual solution and designed "Roman-style" ribs to integrate the vaults into the general discourse of the church. This adaptation, commonly found in mid-sixteenth-century Spanish architecture, produced singular solutions that highlight the state of the technique and the thinking of Diego Siloé.

Keywords

Diego Siloé, ribbed vault, Renaissance, Gothic, tracing, montea, laser scanning, photogrammetry

1. *Case study and aims*

This study examines the ribbed vaults in the parish church of Nuestra Señora de los Remedios, located in Iznalloz (Granada) and designed by the Renaissance master Diego Siloé (c. 1490–1563). The vaults were built between 1549 and 1558 with stone ribs and brick webbing (Fig. 1a). Their study is particularly illuminating because they have been preserved in excellent condition: the ribs are bare in the intrados and the extrados reveals the vaults exactly as they were built (Fig. 2).

Although the Iznalloz vaults look Gothic, detailed observation discloses the presence of characteristics typically found in Roman-style architecture. The inclusion of these medieval vaults in the classicist discourse of the church generated a series of problems related to their integration. This aspect provides an interesting topic of study because it evidences the decisions made by the master and sheds light on the development of vaulting in the mid-sixteenth century and the author's architectural conception.

The study has four aims. The first is to analyse the geometry and construction of the ribbed vaults in the Iznalloz church. The second is to identify the singularities that emerge from the combination of two different architectural worlds: Gothic and Renaissance. The third aim is to evaluate the solutions adopted in the context of stone masonry techniques in the mid-sixteenth century in general and in the architectural practice of Diego Siloé in particular.

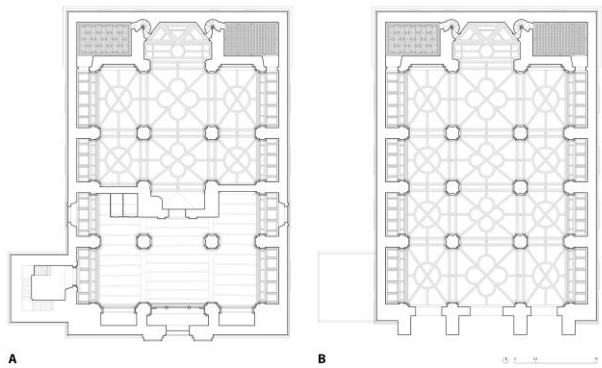

Fig. 1: (a) Present-day ground plan and (b) possible original plan

These three aims are accompanied by a fourth aim related to methodology. This is prompted by the use of various techniques to collect data about the vaults, which produced two point clouds with different resolutions and attributes that were subsequently merged to form a single cloud. The aim is to propose a flexible methodology for merging digital models quickly, accurately and in aggregative manner in future research projects, therefore establishing a methodological standard to facilitate the research and analysis of similar architectural structures in the future.

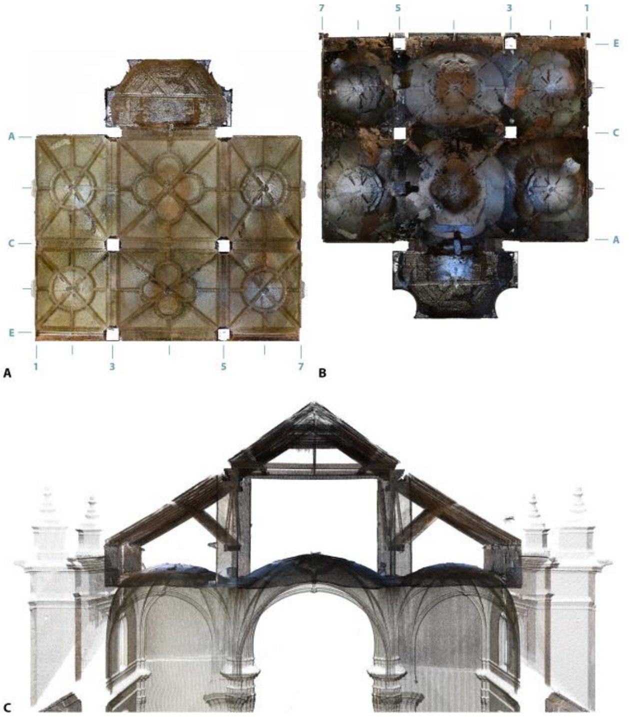

Fig. 2: Point cloud: (a) front view of the intrados, (b) front view of the extrados and c) perspective view of a bay

Based on what we consider to be a methodological principle, the structure of this article follows a strict chronological order corresponding to the steps the master took to build the vaults. Rather than conducting a geometric analysis from an external perspective, we adopt a hermeneutic approach to facilitate a greater appreciation of the design and construction process.

process of the master and his team, and hence a greater appreciation of the decisions made in each stage of the creation.

2. Data collection

The data collection process involved certain important and inherently complex aspects. We used two different capture techniques to conduct the detailed study of the vaults in the Iznalloz church. The first consisted in laser scanning the entire church with the Riegl VZ-400i, with a resolution of 2 centimetres at 20 metres. We collected data from more than one hundred points throughout the church and used the scanner's integrated camera to colour the resulting point cloud.

However, since this exercise was intended to collect data about the church in general, rather than detailed data about the vaults, the point cloud did not cover certain parts of the extrados and we therefore decided to conduct a complete photogrammetric survey of this surface. Using a Sony a7RII camera, a Sigma Art 24-70mm f2.8 lens, a tripod and adjustable LED lights as recommended by Adami & coll., (2018, p. 8), we took 380 photographs.

We used the RiSCAN PRO software supplied with the scanner to process the scan and Agisoft Metashape, with the Mayer, Pereira & Kersten (2018) workflow, for the photogrammetric survey. The result was two point clouds: one of both the intrados and extrados, and the other of

Fig. 3: (a) Scanner cloud, (b) photogrammetric cloud, (c) combined cloud and (d) deviation map

The information is therefore presented in vector format to create a workflow that explains this progression: from the tracing to the *montea* (life-size working drawing), to the particular case of the curved ribs and finally to the singular solutions. The study ends with examples of other contemporary buildings that share characteristics with these Iznalloz vaults. The result is a more detailed and complete insight into the creative

only the extrados but with a higher resolution (Figs. 3a and b).

To simplify the study, the two point clouds were merged into a single cloud using the free software CloudCompare and the Fine Registration option (Fig. 3c). This tool applies the Iterative Closest Point (ICP) algorithm, which searches for the best transformation matrix to minimise the distance between both point clouds (Besl &

McKay 1992). We evaluated the quality of the result by analysing the deviation map (Fig. 3d).

The resulting point cloud was imported to McNeel Rhino 7 to process it and create the flat geometry. Although we could have used a BIM environment for this process (Acosta, Spettu & Fiorillo 2022), we opted for this CAD software to ensure greater interoperability and ease of use of the drawing tools.

The first step was to define a local coordinates system to identify the vaults and specific ribs (Fig. 2). Next, we drew the axes of all the ribs and then sliced them into 10-cm vertical pieces (Fig. 4a), thus ensuring a sufficient quantity of points in each piece. To simplify these operations with point clouds, we use the Cockroach plug-in for Rhino (Vestartas & Settimi 2020).

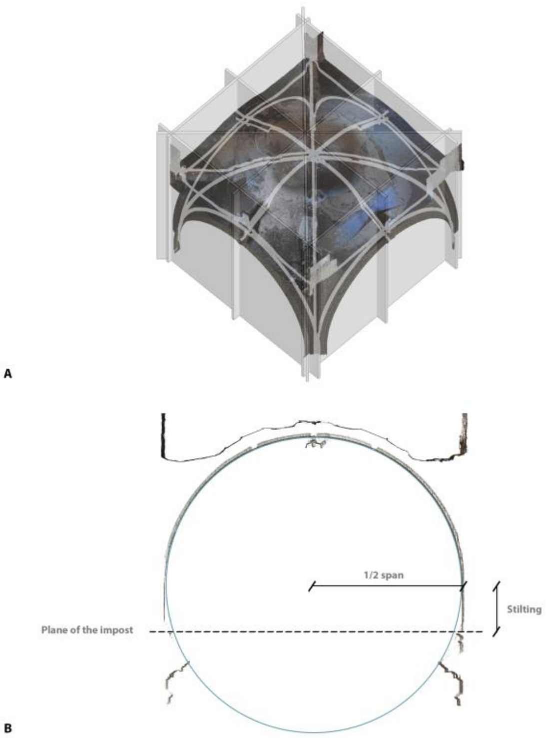

Fig. 4: Drawing process: (a) sections of each rib in a vault and (b) detailed section of a rib superimposed with a circle of many fit points

The next step was to obtain a front view of the cuts and draw circles to match the real curvature of the rib (Fig. 4b). We repeated this process iteratively to find the circle or level that (i) coincided with the largest possible number of points in the section (using the command "Circle > Fit points"), and (ii) had relative error of less than 5 cms compared with the values in the table presented below. Given the rigorous construction of the church, this was established as the maximum acceptable value.

To analyse the tracing on the extrados of the voussoirs, we used general photographs obtained in the second data collection. To improve the visibility of these fine incisions, we applied an algorithm based on automatic learning (Super Resolution) in Adobe Camera RAW, which quadrupled the resolution of the photographs and significantly enhanced the clarity.

3. *State of the question*

3.1 The parish church in Iznalloz

Diego Siloé designed the church in Iznalloz in 1549 (Gómez-Moreno 1983, p. 82). The building had a generous budget, allowing for the construction of a large church with high-quality materials (Gómez-Moreno Calera 1989, 139 and ff.). Three aisles and four bays divided by a slender order form the interior space (Fig. 5a), surrounded by a ring of chapels with classical vaults. The chancel, sacristy and vestry occupy a large volume whose external appearance resembles a grand civic building (Fig. 5b).

Fig. 5: General views of the church: (a) north end interior, (b) north facade, (c) south end interior and (d) south facade

The works commenced circa 1549 and continued via different building stages practically until the present day. Most of the building was erected during the first stage (1549–1559), including the foundations for the church perimeter, the north end with the first two bays and the ribbed vaults analysed here.

The master builder was Juan de Arredondo, a highly skilled master who, following the interruption of these works in 1558, was appointed master builder at another major religious construction: Guadix Cathedral (Gómez-Moreno Calera 1989, p. 140). During this building stage, the church in Iznalloz displayed great uniformity in its construction and a high degree of perfection in the stone works, as reflected in the vaults.

Construction proceeded much more slowly during the following stages, to the extent that the completed part was temporarily walled off to allow its use while the building works continued (Fig. 5c). A recent architectural analysis of the church (Acosta 2022) prompted the hypothesis that Siloé planned to cover this incomplete section with another six ribbed vaults like the ones already built (Fig. 1b). The south end never achieved the height of the vaults and in the 1950s was covered with a sheet metal roof and finished with a masonry wall of inferior quality (Fig. 5d).

3.2 Evolution of the ribbed vault in the sixteenth century

Several factors illuminate the evolution of ribbed vaults and webs in Spain during the sixteenth century, such as technology, building tradition and economy of materials.

With regard to the technical factor, arches and vaults were the most complex architectural structures at the time (Huerta Fernández 2004, 3 and ff.), and the design of vaults with stereotomy presented very different challenges from those of the traditional practice: a linear structure of ribs evolved into a structure where the entire surface was load-bearing, with pieces that had to be assembled perfectly (Palacios Gonzalo 1990, p. 14). The design of these pieces required advanced formal control instruments that would not be developed for a number of years (Calvo López y Rabasa Díaz 2016, pp. 82-83).

These instruments encompassed human resources and tools which, at the time, remained in the hands of teams and technicians trained in the medieval tradition at closed stone-cutting workshops (Alonso Ruiz 2009, p. 169).

Vaults with linear elements could be built of cheap materials like gypsum, wood and brick, as well as stone, whereas vaults with stereotomy required quality stone and their construction entailed great extraction, transportation, cutting and installation costs (Gómez Martínez 1998, p. 187).

Despite these factors, by the mid-sixteenth century in Andalucia the method for building vaults was evolving to new models and languages. Andalucia was the testing ground for the incipient stereotomy. It was Diego Siloé and his contemporary masters who, with their innovations in technique and design, spearheaded the transition to the methods that would be recorded in writing by the following generation, in the manuscript of Hernán Ruiz II (circa 1550) or in the *Libro de trazas de cortes de piedras* of Alonso de Vandelvira (circa 1588) (Cruz Isidoro 2001).

Unlike vaults, all the other stone elements of buildings could be easily moulded to a new language because of only minimal changes to their structural logic (Heyman 1999, p. 119). This technical difference gave rise to two different paces of adaptation to the classical world (Marías Franco 1988, p. 118), as is clearly observed in Andalucia in numerous buildings that display fully-fledged Roman ornamentation but whose vaults preserve reminiscences of the medieval period.

Fig. 6: (a) Lantern tower of the monastery church of San Jerónimo (Granada). Vaults at Granada Cathedral: (b) radial chapels and (c) ambulatory

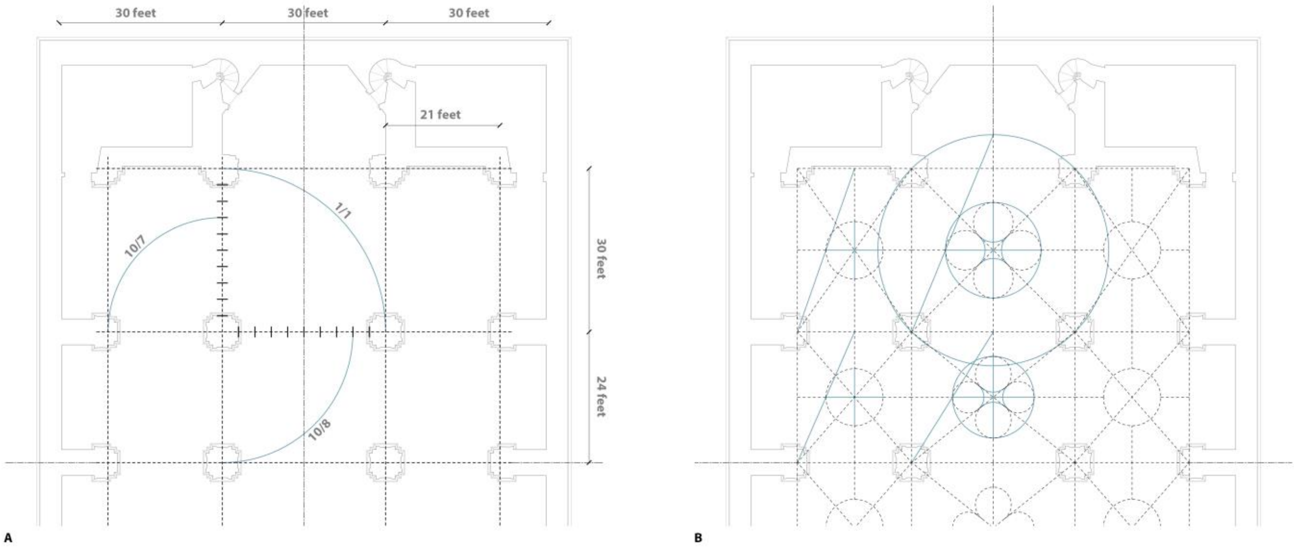

Fig. 7: (a) Tracing of the modules and (b) tracing of the vaults

Granada and Diego Siloé are examples of this formal dichotomy that emerged in numerous sixteenth-century churches where the classical language and traditional structures, both medieval and Arab, existed side by side. However, the presence of both styles was not static, because Siloé altered the traditional structures, freely adapting them to the classical language he knew so well to ensure consistency with the rest of the building (Ampliato & Acosta 2022).

One example of the combination of Gothic and classical elements in Siloé's work can be found in the church of San Jerónimo in Granada, where the vault over the lantern tower has double the number of diagonal ribs with smaller ribs between them and around the windows, producing a hybrid between a ribbed vault and a Roman vault (Fig. 6a). Another is Granada Cathedral, where the vaults in the ambulatory, radial chapels and nave are ribbed but the ones that cover the chapels unambiguously mix Gothic ribbing with Roman caissons (Fig. 6b) and the ribs in the ambulatory vaults are arranged in a heterodox orthogonal grid (Fig. 6c).

Both the mixed use of traditional and Renaissance structures, and the freedom of thinking evidenced in their combination, can be observed in the design and construction of the Iznalloz church in general and in the ribbed vaults in particular.

4. Design and construction of the Iznalloz vaults

4.1 The tracing

Diego Siloé began the process of the vault design by defining the aisle modules, for which he used the Gothic system of geometric proportions. In this system the module dimensions are obtained from a simple measurement (García Ortega y Ruíz de la Rosa 2017, pp. 221–222), which in the case of Iznalloz is the width of the nave: 30 Castilian feet (Fig. 7a). With this reference, Siloé continued with proportions of whole numbers commonly used in the medieval tradition (Ruíz de la Rosa 2005). This produced one square vault (1/1) and five rectangular vaults, two of them very close to the square proportion (8/7=1.14).

This basic geometric grid defines the wall and transverse ribs and, as an immediate consequence, the diagonal ribs. Next, the basic geometric references for the liernes and curved ribs were obtained using the traditional method to calculate tiercerons in Gothic vaults: for the rectangular ones, a corner was simply joined to the centre of the opposite side, while the square vault was based on the circumscribed circle (Fig. 7b).

The ribs were carved with quadrangular profiles and Roman mouldings instead of the triangular profiles commonly found in the medieval tradition (Fig. 8a). Unlike the Gothic modes, the sections of the different ribs in the

Iznalloz vaults are formally derived one from the other: from the transverse type, the diagonal and curved ones; and from those, the wall type and the liernes.

These transformations do not only alter the appearance of the profiles with respect to the traditional Gothic ones; they also reflect a new formation logic that obeys a formal hierarchy present throughout the building. As we explain below, this rib configuration presented specific needs that were both new and alien to the tradition.

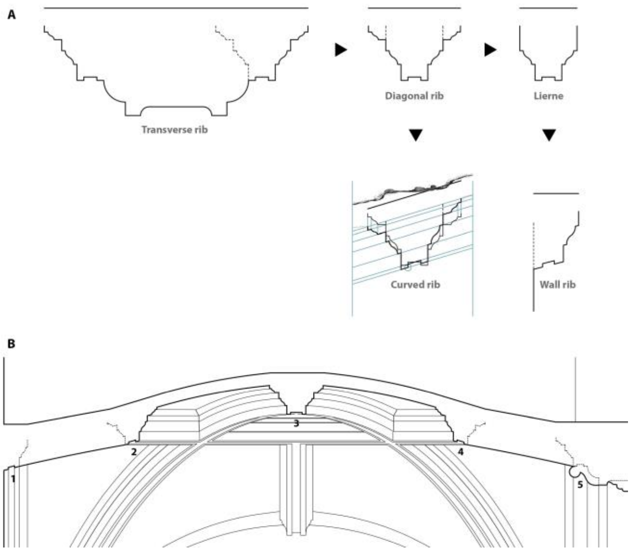

Fig. 8: (a) Generation of the ribs and (b) section of a lierne and key points

4.2 The montea

We created a table (Table 1) to analyse the curvatures of the ribs and compare the similarities between spans. The plane of the impost was defined as the upper limit of the attic that rises from the classical support, from which we measured the stilting and the height of the keystone (sum of the radius of the arch and the stilting) (Fig. 4b). We calculated the average of these attributes for each group and noted the error produced by subtracting the average height of the group keystones from the height of the specific rib.

The analysis of the sections in the point cloud (Fig. 4) reveals that, except for the liernes, the vault ribs are arcs. This three-dimensional network of ribs does not form a sphere, and the webbing is therefore made up of spherical segments, like a conventional ribbed vault.

Tab. 1: Analysis of ribs

ID	Rib		Span	Stilting	Keystone height	Error	Shape
1		**▫ Position**					
2	AC13-**A13**	Wall rib	4,89	1,28	3,73	0,55	**Distorted**
3	AC13-**C13**	Transverse rib	5,11	1,69	4,25	0,03	Quadrangular
4	CE13-**C13**	Transverse rib	5,11	1,69	4,25	0,03	Quadrangular
5	CE13-**E13**	Transverse rib	5,11	1,72	4,28	-0,00	Quadrangular
6	AC57-**A57**	Wall rib	4,89	1,30	3,75	0,53	**Distorted**
7	AC57-**C57**	Transverse rib	5,11	1,72	4,28	-0,00	Quadrangular
8	CE57-**C57**	Transverse rib	5,13	1,72	4,29	-0,01	Quadrangular
9	CE57-**E57**	Transverse rib	5,07	1,78	4,32	-0,04	Quadrangular
10		**Average values**	5,11	1,72	4,27		
11		**▫ Position**					
12	AC13-**AC1**	Wall rib	7,39	0,71	4,41	0,01	**Distorted**
13	AC13-**AC3**	Transverse rib	7,32	0,77	4,43	-0,01	Quadrangular
14	AC35-**AC3**	Transverse rib	7,30	0,80	4,45	-0,03	Quadrangular
15	AC35-**AC5**	Transverse rib	7,35	0,73	4,41	0,01	Quadrangular
16	AC57-**AC5**	Transverse rib	7,37	0,76	4,45	-0,03	Quadrangular
17	AC57-**AC7**	Wall rib	7,40	0,68	4,38	0,04	**Distorted**
18		**Average values**	7,36	0,74	4,42		
19		**▫ Position**					
20	CE13-**CE1**	Wall rib	5,68	1,58	4,42	0,01	**Distorted**
21	CE13-**CE3**	Transverse rib	5,76	1,54	4,42	0,01	Quadrangular
22	CE35-**CE3**	Transverse rib	5,71	1,55	4,41	0,02	Quadrangular
23	CE35-**CE5**	Transverse rib	5,78	1,52	4,41	0,02	Quadrangular
24	CE57-**CE5**	Transverse rib	5,80	1,56	4,46	-0,03	Quadrangular
25	CE57-**CE7**	Wall rib	5,74	1,59	4,46	-0,03	**Distorted**
26		**Average values**	5,75	1,56	4,43		
27		**▫ Position**					
28	AC13-**A1C3**	Diagonal rib	9,35	0,25	4,93	0,03	Quadrangular
29	AC13-**A3C1**	Diagonal rib	9,09	0,39	4,94	0,02	Quadrangular
30	AC57-**A5C7**	Diagonal rib	9,07	0,44	4,98	-0,03	Quadrangular
31	AC57-**A7C5**	Diagonal rib	9,31	0,31	4,97	-0,02	Quadrangular
32		**Average values**	9,21	0,35	4,95		
33		**▫ Position**					
34	CE13-**C1E3**	Diagonal rib	7,77	1,18	5,07	0,03	Quadrangular
35	CE13-**C3E1**	Diagonal rib	7,66	1,23	5,06	0,04	Quadrangular
36	CE57-**C5E7**	Diagonal rib	7,49	1,39	5,14	-0,04	Quadrangular
37	CE57-**C7E5**	Diagonal rib	7,67	1,29	5,13	-0,03	Quadrangular
38		**Average values**	7,65	1,27	5,10		
39		**▫ Position**					
40	AC35-**A35**	Transverse rib	7,28	0,81	4,45	-0,02	Quadrangular
41	AC35-**C35**	Transverse rib	7,27	0,80	4,44	-0,01	Quadrangular
42	CE35-**C35**	Transverse rib	7,20	0,81	4,41	0,02	Quadrangular
43	CE35-**E35**	Transverse rib	7,23	0,80	4,42	0,01	Quadrangular
44		**Average values**	7,25	0,81	4,43		
45		**▫ Position**					
46	AC35-**A3C5**	Diagonal rib	10,50	0,34	5,59		Quadrangular
47	AC35-**A5C3**	Diagonal rib	10,49	0,34	5,59		Quadrangular
48	CE35-**C3E5**	Diagonal rib	9,39	0,91	5,61		Quadrangular
49	CE35-**C5E3**	Diagonal rib	9,41	0,90	5,61		Quadrangular

Despite the apparent discontinuities, the lierne operates along its entire length like a rib (Fig. 8b), as explained in more detail below. Besides, as a lierne it could not have a circular trajectory because it had to adapt to the different key points through which it had to pass: the transverse/wall ribs (points 1 and 5), the curved ribs (points 2 and 4) and the central cross piece (point 3).

Having established the curvatures of all the vault ribs, the next step was to define the height of the keystones. To create a hall church, the height of the keystones of the transverse and wall ribs, and of the diagonal ribs, had to be uniform.

Despite differences of up to 15 centimetres in the span of similar ribs (Table 1) and a difference of 5 centimetres between the heights of the wall attics of the Gospel and Epistle sides, the keystones of these vaults situated at a height of 17 metres reveal a difference of only 2 to 3 centimetres. This uniformity of height was maintained by absorbing the error margins in the stilting.

These facts demonstrate that the tas-de charges played a crucial role in the geometric control of the vaults, as was typical in this type of construction. There are only two ribs, wall ribs A13 and A57, which deliberately ignore these error margins, as we explain in more detail below.

4.3 The curved ribs

The design of the curved ribs contains several remarkable characteristics. In the side vaults, the curved ribs are arranged on a horizontal plane to the floor (Fig, 9a), while in the central vaults they are arranged on symmetrical oblique planes, two for each foil (Fig. 9b). This layout ensured that none of the ribs had a double curvature, therefore facilitating both the stone cutting and the assembly.

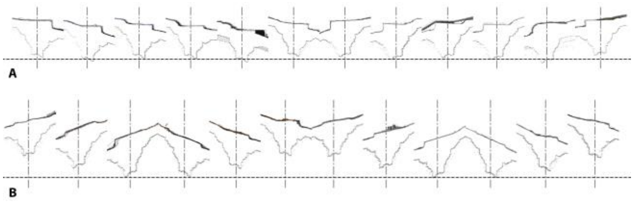

Fig. 9: Sections of a curved rib: (a) side vaults and (b) central vaults

It also facilitated something else. As already pointed out, the curved ribs have the same section as the cross ribs, but unlike them, they have a geometric anamorphosis in the intrados, along the entire length of the rib, where the vertical lines are preserved but the horizontal ones are slanted (Fig. 8a). This slant occurs because of the convergence with the diagonal ribs, producing a clean intersection of the mouldings of both types of rib. These design strategies adopted in the intrados ensured that a viewer situated at the central vertical axis of the vault would perceive the different ribs as individual elements (Fig. 2a).

The curved ribs were fitted into place with vertical and radial joints in the centre of their plan circle (Fig. 10a). Furthermore, the layout is symmetrical and the angular distances are repeated wherever a cross piece coincides with the diagonal ribs and the liernes. All of this reduced the number of cases to cut.

For the voussoirs, a tongue-and-groove system was adopted instead of the conventional method of joining flat sides (Rabasa Díaz 1996, pp. 429-431), although we do not know the reason for this choice.

To guide the masons with the cutting and assembly of these special ribs, a series of lines were traced on the upper side of the cross pieces (Fig. 10b). This side, level and smooth, was the "surface of operation" described by Willis in relation to the common method for medieval vaults in England (Willis 1910, p. 24).

Our analysis of these incisions, which include lines and mason's marks, etc., enables us to draw the following conclusions:

1. All the cross pieces indicate the direction of the diagonal rib by means of a straight line along the axis of the piece and the direction of the curved rib by means of a curved line, also along the axis.
2. Some cross pieces have another straight line forming an angle of 90º with the direction of the diagonal rib, which could be an *escuadría*.[1]
3. These straight and curved lines are accompanied by less frequent regulating lines, such as straight parallel lines corresponding to the width of the rib in the intrados, oblique lines whose function we do not know, and little sketches that bear no relation to the piece in question.
4. As for figures, we found the numbers 1, 2 and 3: number 1 on its own or with the other numbers, and 2 and 3 always in a group. These numbers were made with a thicker chisel than the one used for the other incisions. They may be assembly marks indicating the correct position of the cross piece during the installation.
5. These auxiliary lines could have performed a similar function as the stone-cutting guide lines traced on keystones by medieval masons, as Willis described.

[1] Two perpendicular lines that stone masons sometimes traced to begin a drawing.

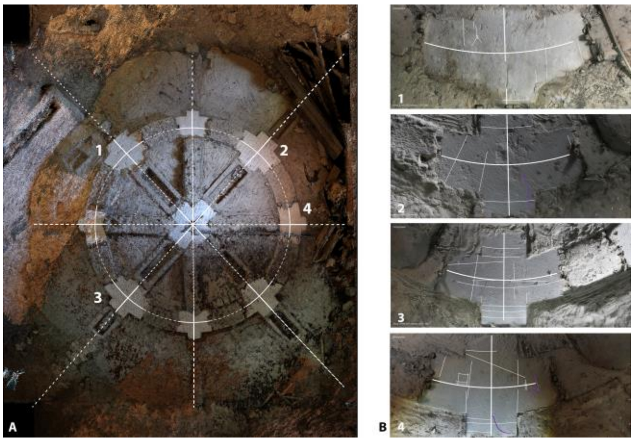

Fig. 10: (a) Extrados of a voussoir with superimposed lines and axes of ribs. (b) Close-up photographs of the cross pieces

Lastly, there is one vault that does not conform exactly to the system described above: vault AC13. In the first place, the lower mouldings of the ribs visible on the intrados continue and intersect with the diagonal ribs, curved ribs and liernes, whereas in all the other vaults the mouldings change direction in the bisector to form a corner (Figs. 11a and c). This recalls the characteristic behaviour of mouldings in the Gothic and Renaissance worlds, respectively (Rabasa Díaz & Alonso-Rodríguez 2017, pp. 310-311).

In the second place, on the extrados, the upper side of the voussoirs of the curved ribs is horizontal instead of oblique (Fig. 11b and d), which produces an awkward joint in the tongue-and-grooving between the cross pieces and the voussoirs of the curved rib.

Fig. 11: Detail of vault AC13: (a) intrados and (b) extrados. Detail of vault CE57: (c) intrados and (d) extrados

These two very specific aspects – mouldings that follow the medieval logic and a building complication (in our opinion, unnecessary) – suggest that vault AC13 may have been built before the others and that subsequently a different approach was followed for all the other vaults.

5. *Singular solutions due to classical formal approaches*

As we have in these vaults, the use of Gothic methods in the tracing coincides simultaneously with Roman-style formal solutions in the sections of the ribs. This duality gave rise to a series of joints that required specific solutions, some of them genuinely innovative.

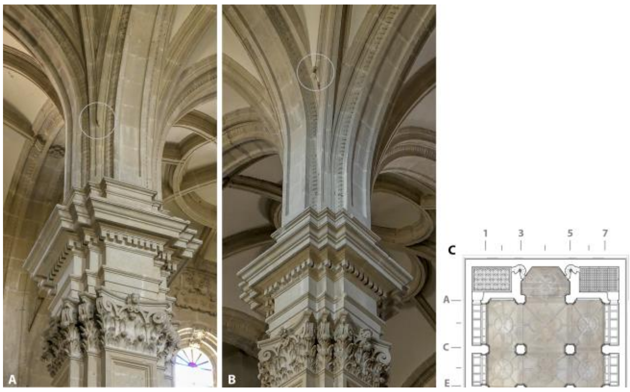

Fig. 12: (a) Detail of an abrupt interruption in the rib mouldings, (b) detail of a scroll on a diagonal rib and (c) site plan

5.1 Adaptations of ribs in tas-de-charges

In three of the six vaults built, we observed that some of the diagonal ribs have mouldings that begin abruptly (Fig. 12a) or spring from a classical scroll (Fig. 12b).

To illustrate this fact, we chose tas-de-charge C3 (Fig. 12c) and cross-sectioned it at different heights to examine the development of the ribs that spring from it. For this example, we only represented the transverse ribs and the diagonal rib corresponding to vault AC13 (Fig. 13a).

On plan, the diagonal rib forms an angle of 58º with the transverse rib. As we proceed higher, the diagonal rib and the longitudinal transverse rib begin to separate from the tas-de-charge (Fig. 13b). This causes a forced solution in the webbing at the corner between the transverse rib and the diagonal rib (Fig. 13c). This setback is preserved up to the height of the classical scroll (Figs. 13d and 12b), above which the diagonal rib is fully developed, i.e. with all its mouldings (Fig. 13e).

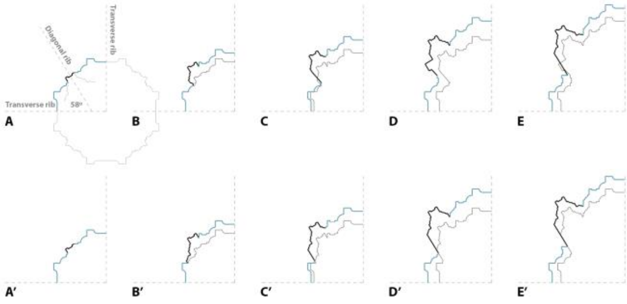

Fig. 13: Tas-de-charge C3: (a) present-day trajectory of the ribs and (b) proposed trajectory

If the outermost mouldings of the diagonal rib had appeared from the beginning of the tas-de-charge, they would have ended up overlaying the transverse rib and the visual continuity of that rib would have been lost (Fig. 13a'-e'). Instead, the diagonal rib was cut, forcing the webbing at the corner, and the missing mouldings were disguised with a "fat point".

This misalignment occurs in the three vaults that are perfect rectangles (AC13, AC57 and CE35), and therefore where the diagonal ribs separate from the more regular bisector of a right angle (Fig. 12c). In addition, there are stilting differences between the transverse and diagonal ribs (Table 1). In vault CE35, the transverse rib conceals the springing line of the diagonal rib and the mouldings were therefore simply interrupted to solve the problem (Fig. 12a). In a purely Gothic practice, all the mouldings would have continued regardless of the loss of the rib's independence.

5.2 Adaptations of wall ribs in keystones

This desire to ensure the visual continuity of the ribs and mouldings adopted a different form in the wall and transverse ribs. Two aspects must be considered in this respect: the perception of the complete rib, and the fluid contact between the transverse/wall mouldings and the lierne mouldings. The section of the transverse arch remains intact throughout, producing an angle where it meets the lierne (Figs. 14a.1-2 and 8b.5). However, the mouldings of the wall arch share the same plan as those of the lierne because the rib is distorted as it springs from the tas-de-charge (Fig. 14a.3-4 and 8b.1). Although the nature of the convergence of the lierne with the wall rib is the same as that of the convergence with the transverse rib, different solutions were adopted for each case.

For Siloé, the wall rib was a "weak" rib and therefore malleable, since it is perceived as little more than an element projecting from the wall. However, the transverse rib is a major element and spatially more complex: the same arch belongs to different vaults and its geometric conditions are determined by its perceived continuity with the classical support beneath it. Due to this design decision, distorting part of the transverse rib would have resulted in the loss of its classical integrity. The solution adopted to conceal this misalignment in the contact with the lierne was once again a scroll.

Fig. 14: (a) Transverse rib non distorted (1-2), wall rib distorted (3-4), and voussoir on top of the keystone of a transverse rib (5). (b) Hollowed out diagonal ribs and low wall on the haunches

5.3 Geometric differences in the wall ribs on the chancel wall

Another formal transformation affects the wall ribs. As already mentioned, wall arches A13 and A57 are lower than the other wall arches (Table 1). The importance of the way in which the vaults are perceived also applies to all other wall surfaces in the church, and specifically to the front of the north end viewed from the nave and aisles (Fig. 15). The chancel, transverse arch, side niche altars and wall A with the shields of the promoter, Archbishop Guerrero, are perceived as a triumphal ternary structure which creates a great front that provides a scenography for the liturgy and emerges as the true protagonist of the entire architectural experience (Acosta 2022, p. 356).

The expression of this triumphal structure could explain why arches A13 and A57 are lower than the transverse arch. Siloé may have been aiming to create a specific impression on the viewer and had no qualms in altering the rules of play.

The singular characteristics of these vaults seem to have demanded particular attention to the distribution of weights and their thrust. The slender piers receive more pressure from the diagonal ribs in the central vaults than from those in the side vaults. To balance the distribution of stresses that reached free-standing piers, the following decisions may have been made.

In the first place, the weight of the diagonal ribs was reduced by hollowing out the extrados (Fig. 14b). This was performed for the voussoirs and also for the cross pieces of the central vaults. Part of the stone was removed from the core, leaving a homogeneous edge around the upper surface.

Fig. 15: Cross-section of the church looking towards the north end: wall ribs with the corrected height (in blue) and triumphal front (superimposed point cloud)

5.4 Differences in lierne sections, distribution of weights and thrust

In the intrados of the vaults, the liernes spring from the wall and transverse ribs and end at the curved ribs. However, this posed a problem concerning support for the webbing in the area framed by the curved ribs, which is relatively flat (Fig. 8b.2-4). It was resolved by reducing the section of the rib to a very thin tablet of stone, which provides the necessary support for the webbing while simultaneously interrupting the visual continuity of the lierne (Figs. 8b and 2b).

Secondly, a low wall was added to the haunch of the diagonal ribs in the central vaults (Fig. 14b) to create extra weight to counteract the oblique component of these thrusts.

This balance of stresses may also explain the presence of an abandoned voussoir above the keystone of some of the transverse arches (Fig. 14a.5). Gómez Martínez describes their possible origin as follows: "While the solidification of haunches is a widespread device, the counterweight placed on top of the central keystone is a much more selective procedure, associated with the most genuine notions of Gothic architecture." (1999, p. 166).

6. *Singular solutions due to classical formal approaches*

The church in Iznalloz was not an isolated example. Andalucian masters were aware of the different methods and traditions practised in the region at the time and innovated with them as they moved from one area to another. This awareness is revealed in the specific solutions that this experimental practice necessarily required.

Diego de Riaño, active at the same time as Siloé, was similarly characterised by a tendency to blend classical and Gothic elements in his constructions. Both were outstanding masters who built numerous Roman vaults during the first half of the sixteenth century. Their originality lies in the fact that they did so with their knowledge of ribs and webbing, which according to Palacios and Bravo represented a new type of vault: "crossing vault" (Palacios Gonzalo & Bravo 2013).

One example of this is the vault that Riaño designed for the antesacristy at the priory church in Carmona (1528–1525) (Fig. 16a), an unusual structure in which classical ribs, an oval and a quatrefoil of curved ribs are overlaid to form an interlocking grid system. This vault incorporates several formal elements from different ecosystems and experiments with new adaptive logics.

The design of these new vaults necessarily ushered in changes in building practices. For example, Riaño's vault contains misalignments in the geometry and construction elements that the master resolved with innovative solutions (Ampliato & Acosta 2020). Similarly, for the vault over the east end of the church of San Jerónimo in Granada the traditional technical procedures were even inverted (Salcedo Galera & Calvo López 2020, pp. 841–842).

Other masters like Alonso de Vandelvira also used their knowledge of traditional methods in their design of certain classical vaults, such as the "crossing octagon", the "round crossing chapel" and the "crossed chapel" (Ibáñez Fernández 2016, p. 61). Even in the treatise of Hernán Ruiz II, the only drawing for a ribbed vault evidences a non-traditional solution (Ibánez Fernánez 2016, p. 60).

Meanwhile, curved ribs around the central keystone and groups of tangent lines to circles were already being used in the Iberian Peninsula. This design can be found in earlier works, such as the carved backrest of a choir stall at Seville Cathedral (1479), and in vaults by masters like Juan Guas at Segovia Cathedral (1472-1491) (Fig. 16b) and Juan Gil de Hontañón at Palencia Cathedral (c. 1505) (Fig. 16c) (Gómez Martínez 1998, pp. 91, 99 and 154). Siloé may also have used this design for some of the vaults at Granada Cathedral (Fig. 16d) (Rosenthal 1990, pp. 53 and ff.), although these were executed after the Iznalloz vaults.

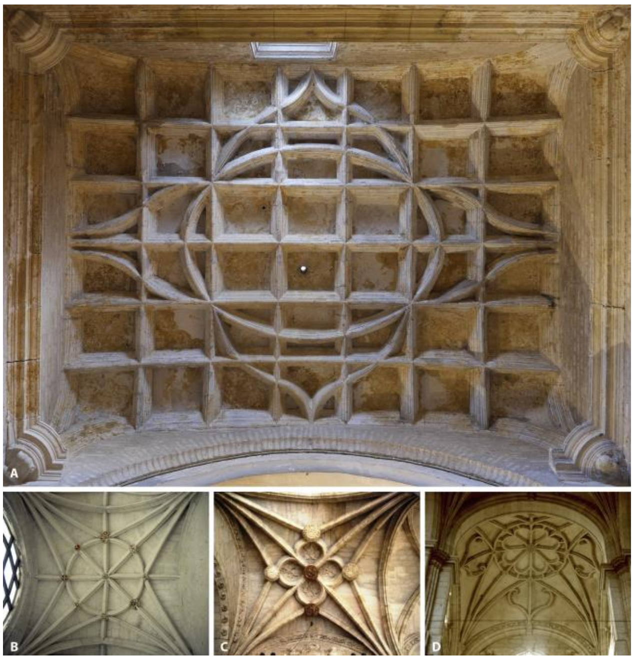

Fig. 16: (a) Vault of the antesacristy in Carmona, Diego de Riaño (1528–1535). Photograph by the authors. (b) Vault at Segovia Cathedral, Juan Guas (1472–1491) and (c) vault at Palencia Cathedral, Juan Gil de Hontañón (c. 1505). Photographs courtesy of (Departamento... 2011)

The ribbed vaults in Iznalloz were designed as crossing vaults with no keystones. A similar building solution can be found in certain vaults at the parish church of Santa María in Mediavilla, at the College of Santiago Alfeo and in the cloister at León Cathedral, all designed after 1530 (Gómez Martínez 1998, 95, 101 and 102).

Lastly, it is interesting to note that in the parish church of Priego in Cuenca (1531–1541), Pedro de Alviz also simplified the construction by using curved ribs resting on planes, as in the Iznalloz vaults (López-Mozo, Rabasa-Díaz & Alonso-Rodríguez 2020).

Conclusions

A detailed study of these vaults enables us to conclude that they display a combination of factors based on the established tradition in the Iberian Peninsula and others influenced by the new Renaissance practices. The Iznalloz ribbed vaults are an interesting architectural exercise because they were built in an alien formal context: an entire church in the Roman style. As with the palatial facade of the church, Siloé had no qualms in adapting the ribbed vaults to provide a solution that integrated with the classical discourse of the building.

This combination generated misalignments here and there whose resolution – the creation of a coherent whole out of two different syntaxes – demanded innovative solutions. This advanced approach was only possible because of the master's expert knowledge of the technique.

Lastly, we can also conclude that the ribbed vaults at the church in Iznalloz represent some of the most outstanding examples of the transition in form and building practices that occurred in Andalucia with the advent of Classicism. This church is therefore a testament to the cultural change that was taking place in Spanish architecture in the mid-sixteenth century.

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References

Acosta, E. (2022). *El proyecto de Diego Siloé para la iglesia parroquial de Iznalloz. Modelado digital y concepción arquitectónica* [Universidad de Sevilla]. Retrieved from https://hdl.handle.net/11441/138357

Acosta, E., Spettu, F., & Fiorillo, F. (2022). A procedure to import a complex geometry model of a heritage building into BIM for advanced architectural representations. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVI-2/W1-2022*, 9–16. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-9-2022

Adami, A., Fassi, F., Fregonese, L., & Piana, M. (2018). Image-based techniques for the survey of mosaics in the St Mark's Basilica in Venice. *Virtual Archaeology Review*, *9*(19), 1. https://doi.org/10.4995/var.2018.9087

Alonso Ruíz, B. (2009). El 'Arte de la Cantería' en Castilla durante el siglo XVI. In *El arte de la piedra. Teoría y práctica de la cantería* (pp. 157–172). CEU Ediciones.

Ampliato, A., & Acosta, E. (2020a). A Gothic-Renaissance Synthesis in a Diego de Riaño's Vault. *Nexus Network Journal*, *22*, 429–447. https://doi.org/10.1007/s00004-019-00471-2

Ampliato, A., & Acosta, E. (2022). Organismos duales: Una aproximación a la arquitectura de Diego Siloé a través de sus iglesias parroquiales. In *Antonio Luis Ampliato Briones, Rafael López Guzmán, Juan Clemente Rodríguez Estévez (coordinadores), Diego de Riaño, Diego Siloé y la arquitectura en la transición al Renacimiento*. Editorial Universidad de Sevilla.

Besl, P. J., & McKay, N. D. (1992). A Method for Registration of 3-D Shapes. *IEEE Trans. Pattern Anal. Mach. Intell.*, *XIV*(2), 239–256.

Calvo López, J., & Rabasa Díaz, E. (2016). Construcción, dibujo y geometría en la transición entre Gótico y Renacimiento. *Artigrama*, *31*, 67–86.

Cruz Isidoro, F. (2001). *Alonso de Vandelvira (1544-ca.1626/7), tratadista y arquitecto andaluz*. Editorial Universidad de Sevilla.

Departamento de Construcción y Tecnología Arquitectónicas. (2011). *Bovedas góticas de crucería. Escuela Técnica Superior de Arquitectura (Universidad Politécnica de Madrid)*. Retrieved from http://www.bovedasgoticasdecruceria.com/

García Ortega, A. J., & Ruíz de la Rosa, J. A. (2017). Geometría, proporción y trazado en Santa María de Carmona. In *La obra gótica de Santa María de Carmona: Arquitectura y ciudad en la transición a la Edad Moderna. Ampliato Briones, Antonio Luis, coord.; Rodríguez Estévez, Juan Clemente coord.* (pp. 213–236). Universidad de Sevilla.

Gómez Martínez, J. (1998). *El gótico español de la Edad Moderna: Bóvedas de crucería*. Secretariado de Publicaciones e Intercambio Científico, Universidad de Valladolid.

Gómez-Moreno, M. (1983). *Las aguilas del renacimiento español: Bartolomé Ordóñez, Diego Silóe, Pedro Machuca, Alonso Berruguete*. Xarait Ediciones.

Gómez-Moreno Calera, J. M. (1989). *Las Iglesias de las siete villas: Colomera, Guadahortuna, Illora, Iznalloz, Moclin, Montefrio, Montejicar* (Fundación Rodríguez Acosta).

Heyman, J. (1999). *Teoría, historia y restauración de estructuras de fábrica: Colección de ensayos*. Ministerio de Obras Públicas, Transportes y Medio Ambiente, Centro de Publicaciones.

Huerta Fernández, S. (2004). *Arcos, bóvedas y cúpulas geometría y equilibrio en el cálculo tradicional de estructuras de fábrica*. Instituto Juan de Herrera.

Ibáñez Fernández, J. (2016). Le radici bassomedievali della stereotomia spagnola del Cinquecento. *Lexicon. Storie e Architettura in Sicilia e Nel Mediterraneo*, *22–23*, 53–68.

López-Mozo, A., Rabasa-Díaz, E., & Alonso-Rodríguez, M. Á. (2020). Layout, Construction and Surveying of Curvilinear Ribs in Late Gothic Vaults. The Case of Priego. In L. Agustín-Hernández, A. Vallespín Muniesa, & A. Fernández-Morales (Eds.), *Graphical Heritage* (Vol. 5, pp. 247–258). Springer International Publishing. https://doi.org/10.1007/978-3-030-47979-4_22

Marías Franco, F. (1988). De iglesia a templo: Notas sobre la arquitectura religiosa del siglo XVI. In *Seminario sobre arquitectura imperial (1º. 1988. Granada); Rosenthal, Earl E. otros* (pp. 113–135). Universidad de Granada.

Mayer, C., Pereira, L. M. G., & Kersten, T. P. (2018). A Comprehensive Workflow to Process UAV Images for the Efficient Production of Accurate Geo-information. *IX CNCG: Conferência Nacional de Cartografia e Geodesia*, 1–8.

Palacios Gonzalo, J. C. (1990). *Trazas y cortes de cantería en el Renacimiento español*. Ministerio de Cultura, Instituto de conservación y restauración de bienes culturales.

Palacios Gonzalo, J. C., & Bravo, S. C. (2013). Diseño y construcción de las bóvedas por cruceros en España durante el siglo XVI. *Informes de La Construcción*, *65*(Extra-2), 81–94. https://doi.org/10.3989/ic.13.022

Rabasa Díaz, E. (1996). Técnicas góticas y renacentistas en el trazado y la talla de las bóvedas de crucería españolas del siglo XVI. In *Actas del Primer Congreso Nacional de Historia de la Construcción* (pp. 423–433). Instituto Juan de Herrera, SEHC.

Rabasa Díaz, E., & Alonso-Rodríguez, M. Á. (2017). Basas en la catedral de Girona. In *Obra congrua: Estudios sobre la construcción gótica peninsular y europea / Enrique Rabasa Díaz, Ana López Mozo y Miguel Ángel Alonso Rodríguez (eds.)* (pp. 309–318). Instituto Juan de Herrera.

Rosenthal, E. E. (1990). *La Catedral de Granada: Un estudio sobre el Renacimiento Español*. Editorial Universidad de Granada.

Ruíz de la Rosa, J. A. (2005). Fuentes para el estudio de la geometría fabrorum. Análisis de documentos. In *Actas del Cuarto Congreso Nacional de Historia de la Construcción* (pp. 1001–1008).

Salcedo Galera, M., & Calvo López, J. (2020). Las bóvedas de la cabecera de la iglesia del monasterio de San Jerónimo en Granada. Arquitectura y construcción en el primer quinientos hispánico. In *Da traça À EDIFICAÇÃO: A arquitetura dos séculos XV e XVI em Portugal e na Europa. Fernando Grilo, Joana Balsa de Pinho e Ricardo J. Nunes da Silva (Coord.)* (pp. 833–848). https://doi.org/10.51427/Iha.2021.0001

Vestartas, P., & Settimi, A. (2020). *Cockroach plugin for Rhino* (0.01). Retrieved from https://www.food4rhino.com/en/app/cockroach

Willis, R. (1910). *On the construction of the vaults of the middle ages*. Royal Institute of British Architects.