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Compound brick vaults by slices in written sources

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ABSTRACT: The vaults called "par tranches" by Auguste Choisy are those built by laying the bricks with their bed in a vertical or slightly sloped position. The form and process of executing these vaults have been scarcely studied, partly because it is difficult to define the hidden elements of the masonry. Until the 19th century there were no primary sources explaining these ways of building, which depend more on the skill of the masons than on the abstract knowledge of the designer. This article compares the technical proposals of French and Spanish texts from the late 19th century addressing construction works in Byzantium and Extremadura (Spain). The genesis of the system (designed for barrel vaults) is explained according to each author. The subsequent evolution of different types of compound vaults is analysed with special attention to the groin vault since the others are based on its layout and construction strategies.

1 INTRODUCTION

The vaults that Auguste Choisy (1876, 1883) calls "par tranches" are those that are built by laying the bricks with their bed in a vertical position (aligned with the directrix of the arch), or slightly pitched. The brick is supported without the help of any formwork due to the adhesion of the mortar and the slight inclination given to the pieces when lime or clay is used as a binder. The alternative use of plaster allows greater freedom in the laying of the bricks, which can sometimes be even capricious.

The oldest examples of this solution, originally used for the construction of barrel vaults, have been located in the Middle East and Egypt as of the 13th century BC (Besenval 1984). The Eastern Roman Empire used this technique profusely and brilliantly to elaborate compound forms (groin vaults, sail vaults and domes) and disseminated it throughout the Mediterranean. It also spread throughout the Islamic world (Galdieri 1981). Examples abound in the Iberian Peninsula, some of them prior to the 10th century (Almagro et al. 2013; Araguas 2003: 84). Since the Modern Age, in an area of Extremadura, Spain known as La Raya, a characteristic type is very abundant, also extending through the Alentejo in Portugal to reach Lisbon and the south of Salamanca (Spain). In addition, it travelled to the New World, where in Mexico it continues to be used – and in a very imaginative way (Rabasa, in press).

In Extremadura today they are called *bóvedas a rosca*, but they are actually vaults by slices. The authors of the 19th century also called them pitched vaults or vaults by slices according to the layers (Albarrán 1855: 49; Ger & Lóbez 1869: 253). More recently, some researchers have referred to them as "byzantine brick laying" or "tangential" vaults (Araguas 2003: 84), or vaults "a bofetón" (Almagro 2013). A careful study of these *de rosca* vaults would likely show that they were a much more common solution than it might seem.

2 THE SOLUTION IN THE TECHNICAL TEXTS OF THE 19TH CENTURY

The real shape and the execution process of these vaults have been little studied, partly due to the difficulties in defining the precise arrangement of their bricks, which are usually plastered. Unlike the timbrel vaults, it seems that this variant was not incorporated into construction techniques texts until the 19th century.

The first written references to vaults by slices are found in 19th-century texts by several Extremaduran authors. In this region of southwestern Spain, the peak popularity of this variant began in the 18th century (Paredes [ca. 1883]: 2004). In 1855, a short article by Francisco Javier Boguerín was published in the magazine *Obras Públicas* encouraging civil engineers to use this option because it was economical. Boguerín pointed out that, although they were not reported in the treatises, the masons of Extremadura used this method with great ease. The manuscript describes the

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execution of barrel vaults in sparse detail, although its author claims to have seen "vaults of all kinds and openings built in this way" (Boguerín 1855:136). Later, the article was cited by Espinosa (1859) in his *Manual de Construcciones de Albañilería*, though he does not mention the author.

The text by Florencio Ger y Lóbez (1869, 1898, 1915), which also echoed Boguerín's proposal, includes a greater number of variants. Ger y Lóbez explains and draws, for the first time and with greater precision, what he calls "shear vaults, without formwork" according to the traditional method of radial beds, down to the angle of slip and the link of their "cuts" or pitched slices (Ger & Lóbez 1869: Figs. 292–294).

In 1885, José Albarrán García-Marqués published another description of this technique in his article "Bóvedas de ladrillo que se ejecutan sin cimbra" ("Brick Vaults Executed without Formwork"). Relying on fairly precise drawings, he explains how to build barrel vaults, as well as the adaptation of this method for the formalization of "bóvedas cruzadas" and "bóvedas de pabellón". In particular, he also lists several real examples that follow the method (Albarrán 1855: 89).

But beyond these precocious incursions, the studies of two authors from the last quarter of the 19th century stand out from the rest since they describe the design and construction strategies of these vaults in a more detailed way. The French engineer Auguste Choisy (1841–1909) first published a paper in 1876 and subsequently his full investigation in 1883 in the book *L'art de bâtir chez les byzantins* (*The Art of Building in Byzantium*), where he analyses the construction processes of the eastern part of the Roman Empire, dedicating six chapters to the execution of brick vaults by slices.

The Extremaduran architect Vicente Paredes (1840–1916), who trained at the Madrid Special School of Architecture, wrote a manuscript entitled "Construcción sin cimbra de las bóvedas de ladrillo con toda clase de morteros" ("Construction of Brick Vaults without Formwork with All Kinds of Mortars") probably between 1883 and 1885 (Pizarro & Sánchez 2004: 14). In this book he details the technical design and the construction of Extremaduran vaults with bricks arranged by vertical or pitched slices.

Choisy's explanations are precise and methodical while Paredes's are more intuitive, although less didactic. The first arise from the analysis of a selection of real examples, which the author complements with the construction of a 3.40 m-span vault, with 22 × 11 × 5 cm bricks, to reinforce his hypotheses (Choisy 1876: 441). The latter are deduced from daily practice, although Paredes attempts to enrich them with some theoretical reflections of a geometric nature. However, both technicians describe systematic processes that allow the construction of a certain variety of vaults (groin vault, sail or star vaults) that are normally set as the composition or intersection of cylindrical fragments, whose execution is similar to that of a barrel vault.

The most elementary technical solutions in the form of a barrel vault in the texts by Choisy and Paredes have been studied by Rabasa et al. (2020). These authors suggest that Paredes may have known Choisy's work because his proposals have points in common, despite Paredes's proposal of an unprecedented configuration based on the definition of concave constructive cones for the formation of the slices of the vaults, which is the opposite of the convex cones proposed by the French author. As noted, Choisy bases his proposals on the study of Byzantine vaults while Paredes echoes the Extremaduran construction tradition (18th and 19th centuries). For this reason, it is reasonable to compare the technical proposals of these French and Spanish texts of the late 19th century.

This work analyses the design and construction strategies of the groin vaults defined by these five authors, based on the studies of Rabasa et al. (2020) for barrel vaults, and their adaptation to other variants of compound vaults, devoting especial attention to sail vaults (Figure 1).

3 TECHNICAL CONCEPTION OF THE SYSTEM

The vaults by slices arise from the necessity of building brick vaults without formwork in the absence of wood. It should be remembered that the formwork, in addition to serving as a support for the bricks while the lime mortar sets, permits control of the shape during the implementation process.

The absence of plaster as a binder forced many builders to look for assembly strategies and construction arrangements that would help to preserve the position of the pieces when the adherence of the lime or clay mortar was not sufficient. The bricks slide due to the action of the tangential component of their own weight. The force of friction, strengthened by the adherence of the mortar, opposes this sliding. Therefore, to increase the stability of the pieces during laying, it is advisable to use light bricks with wide beds in order to increase the contact surface and, therefore, the friction. Furthermore, it is necessary to take into consideration the possibility of laying the bricks with inclinations of less than 40^{o} to reduce the incidence of tangential force. This option can also be reinforced

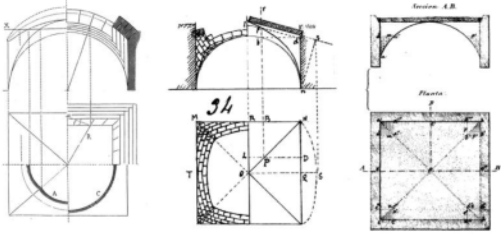

Figure 1. Tracing of the groin vaults in Choisy (1876: pl.21), Paredes (ca. 1883: pl.4) and Albarrán (1855: 86).

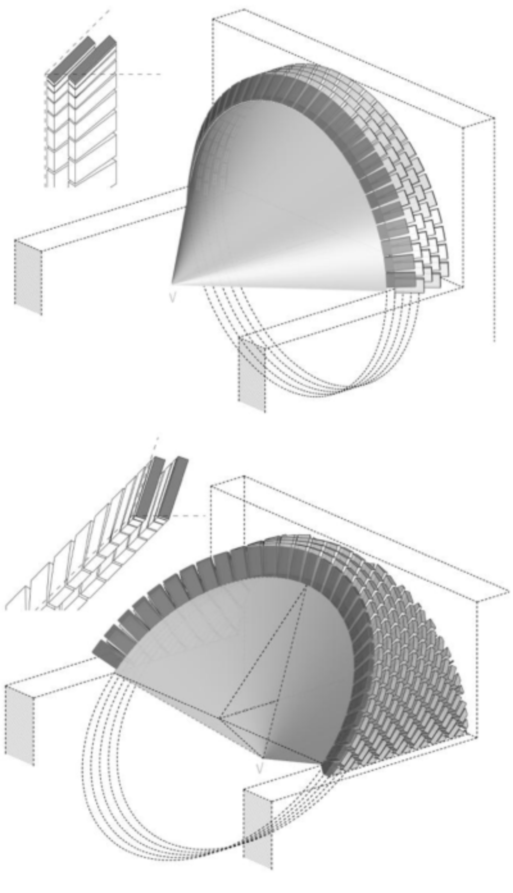

Figure 2. Above, convex cones vault (Choisy). Below, concave cone solution (Paredes).

by other additional means to improve the fastening, increasing friction and preventing parts from slipping, such as the formation of the pitched and conical beds so characteristic of vaults by slices.

Byzantine builders, for example, usually used large, thin bricks. According to Choisy, the smallest ones were 30 × 15 × 4 cm and to help their stability and prepare the correct seating plane of the next sheet, a thick layer of mortar, 4 to 5 cm thick, was laid on them just after their placement (Choisy 1883: 37). As will be seen later, this levelling layer is essential when the slices are inclined and conical. In Extremadura, Paredes (ca. 1883: 160) recommends using a small brick measuring 21 × 14 × 3.2 cm called a "trabuto" or "stool" because, when the vault is small, a larger size creates "too large openings for wedging in the back of the layers". However, in one of his examples he uses a 28 × 14 × 2.4 cm brick, which is quite close to the size of the bed proposed by Choisy and the Roman "later pedales" (López & López 2015: 995), although the thicknesses of the Extremaduran bricks seem to tend to be smaller and, therefore, so is their weight.

Regarding the tilt of the pieces, Choisy (1883: 31–37) explains four possible arrangements used by the Byzantines to ensure the stability of the bricks during the execution of a barrel vault by slices. These are the result of formalizing the vault by adding vertical or inclined slices up to a maximum of 45^o and, optionally, arranging the beds of the bricks to the directrix of the cone or with a slight inclination of about 20^o. Arguably as compensation, the most favourable settings for the stability of the pieces are those that acquire more complex shapes. In addition, the option of inclining the pieces relative to their directrix plane forms frusto-conical slices with their axis in horizontal position (coinciding with the axis of the vault) or slightly inclined (with their axis tilted). This creates difficulties in controlling the shape that led Choisy to offer his own solutions based on the use of ropes and belts.

As mentioned above, according to Paredes, in Extremaduran vaults the brick layers form concave cones (from the operator's working plane) and not convex ones, as described by Choisy in the Byzantine examples. In this case, the plane of the directrix is also inclined as in Choisy: the difference lies in the direction given to the inclination of the bricks with respect to the directrix plane (Figure 2). For Paredes, this peculiarity improves the resistance of the leaves and facilitates the implementation. The process has been explained by Rabasa et al. (2020: Fig. 17).

4 GROIN VAULTS

The groin vault has been treated in different depths by four of the five cited authors. Florencio Ger y Lóbez (1869: 255, 1898: 258, 1915: 202) describes these vaults as the result of the encounter between two-barrel vaults with their bricks arranged by inclined slices. Neither the graphics nor the text provide information on the exact arrangement of the slices. His recommendations are strictly constructive. In the 1869 edition, the author emphasizes the need to formalize both cylinders simultaneously, without the help of formwork, to ensure stability during execution and the formal control of the edges. For the definition of these edges, he briefly proposes the setting of diagonals using ropes and plumb or by the natural meeting between the brick slices of the two barrels, performing an ellipse in this case (Ger and Lóbez 1898: 258). During the laying of the bricks, they are mounted "one on top of the other", compressing each other "by their edge" (Ger & Lóbez 1915: 202).

In his texts, the Frenchman Choisy (1876: 443, 1883: 49) makes a conceptual abstraction of various real cases of groin vaults on a square and rectangular plan that proves a more practical understanding of the type. As stated above, his explanations address the control of the form and the problems of implementation in an orderly and exhaustive manner, based on plan and elevation drawings that refer to the examples studied during his travels.

During his fieldwork, Choisy identified two design variants in Byzantine groined vaults, but only one constructive arrangement for the bricks. He begins his exposition by explaining that the principles applied to barrel vaults "immediately resolve the question of groin vaults", understood as an intersection of two cylindrical surfaces formed by layers parallel to the perimeter arches (Choisy 1883: 49). In this case, its conception would be similar to that proposed by Ger and Lóbez, but with one caveat: in Byzantium the cylinders are formed by vertical frusto-conical slices and not by inclined flat courses (Choisy 1876: 444, pl. 21). He also points out that the underground vaults at Vatopedi, Athos and those of Zografos belong to this first group. But he immediately clarifies that those examples are, in fact, exceptional. According to the author – and this is his most important observation – the Byzantines preferably opted for another, much more interesting geometric construction method to form the groin vaults which facilitated the execution and produced less thrust. Moreover, it allowed the closure of rectangular plans and could be easily adapted to the construction of other compound vaults.

Something similar occurs in Paredes's text (ca. 1883), whose dissertation is not as systematic as Choisy's, perhaps because it is a rough draft, but offers some drawings that reveal great insight. The author states that this variant is one of the most important in construction due to its numerous applications, and his approach to these vaults is especially complex. Like Choisy, he first describes the groin vault as the meeting of two barrel vaults formed by cylinders of inclined slices with a frusto-conical section (Paredes ca. 1883: 130). But then, he offers various variants of increasing difficulty in which he progressively moves away from the initial constructive concept towards a purely formal typological classification of various compound vaults that only considers their edges and the shape of their panels.

Albarrán (1855: 85) pays little attention to the shape of the groin vaults, but offers interesting recommendations for the construction process of the solution by cylinders and some novelties on the formation of their springings. This author reports that the vault is initially built from the inside by four masons, one for each lunette, forming "curvilinear slices" (truncated cone courses), just like in barrel vaults. When the masons start to get in the way of each other, they continue the construction from the rear side.

Albarrán offers two enforcement procedures. For the first one, he uses two strings attached to the vertices of the opposite arches as a guide. The formation of the edges depends largely on the skill of the mason. For definition purposes it is supported by five plumb lines, four of them "close to the angles and on the diagonals" and a last one at their intersection. The plumb lines only determine the plane in which the cylinders are located, which is why he warns that "irregular edges are often seen that the mortars and plasters have to correct" (Albarrán 1855: 88).

Albarrán states that his second method had been inspired by the work of commander Don Carlos Vila, whom Ger y Lóbez also claims to follow when he sets out his constructive indications. According to

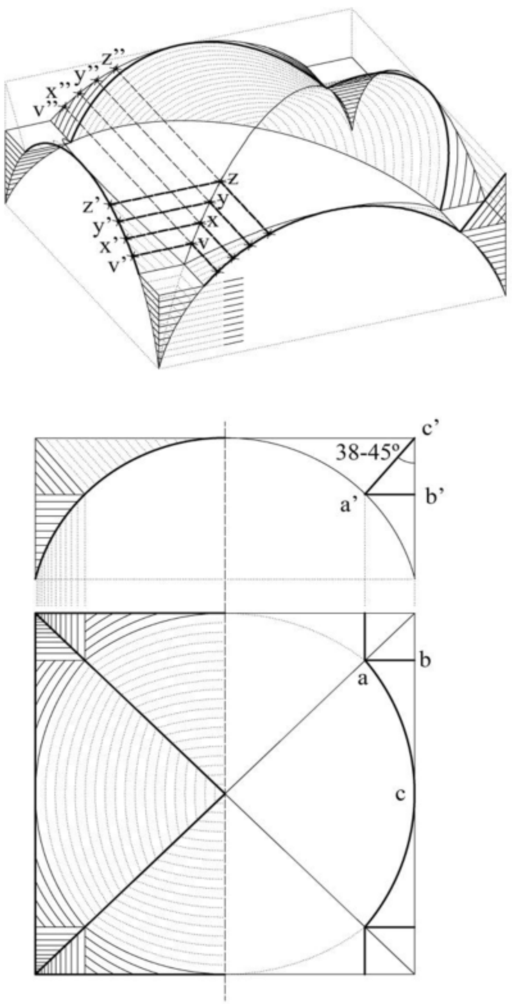

Figure 3. Trace of the Extremaduran groin vault according to Albarrán (1855: 86).

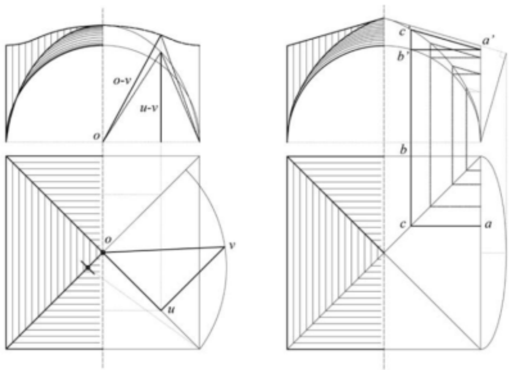

Figure 4. Trace of the Byzantine groin vault according to Choisy (1883: 55) and the Extremaduran pointed groin vault with "retumbo" proposed by Paredes (ca. 1883: plate 4).

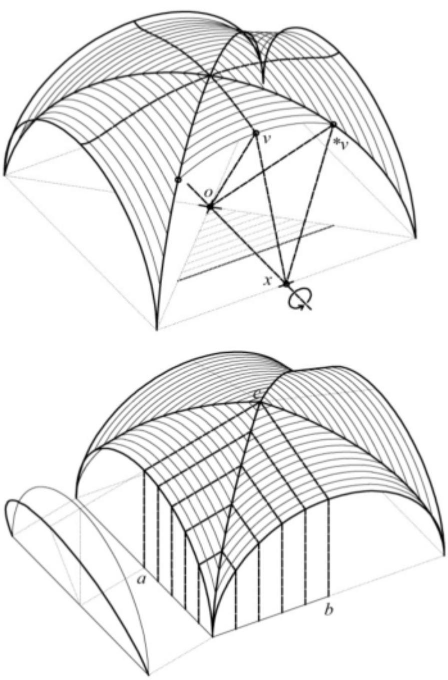

Figure 5. Comparison between the Byzantine groin vault (Choisy) and the Extremaduran pointed groin vault (Paredes).

Albarrán, this method makes it possible to make the edges "with bricklayers who had never built groin vaults as perfect as those performed by the most skilled masons". In this case, the four lateral arches are divided into the same number of parts, as if it were a subdivision into voussoirs. Each of these divisions is numbered and joined with its equivalent in the opposite arch by means of ropes (Figure 3). Thus, the intersections of these "tendeles" define in practice the points of control of the joins, since those lines match the generatrices of the cylinders. The greater the number of divisions of the arches, the greater the number of control points that will define them, and therefore, the more precise its definition will be (Albarrán 1855: 88).

5 FROM THE GROIN VAULT TO THE COMPOUND VAULT

According to Choisy, the Byzantines introduced an alternative design for the groin vaults to avoid the formation of elliptical curves at the diagonals and correct the height of the central point. This solution was suitable for both "elongated rectangular plans" and square ones and was generalized for the design of other variants of compound vaults.

The layout described by Choisy reverses the problem, giving the designer great freedom (Figures 4, 5). The diagonal arch is always an arc of circumference that sometimes has its centre under the line of imposts so as not to exceed the height of the perimeter arches. As a result, the four panels or lunettes of the vault always take the shape of a surface of revolution. The condition of a common centre of intersection for the axes of revolution of the four panels can also be breached. Optionally, those axes can be arranged at different heights. In addition, the control of the form during execution is simple and lies in two operations. The correct formation of the diagonal is controlled with a wooden ruler or a rope tied to its geometric centre; the same happens with the slices of the vaults. The latter are formed by circumferences of variable radius whose measures are obtained successively just by taking the rope to a point on the diagonal. Each measure defines the layout of the concurrent course at that point (Choisy 1883: 54–56). Logically, this graphic abstraction of the author is expected to suffer some deviations during the construction of the vault. Ger y Lobez's 1898 edition includes a proposal very similar to the previous one.

In this system, all the elements of the layout become independent of each other. A panel can be lowered; the next one can be lifted; the diagonal arch can be given the desired deflection and each lateral arch can assume the appropriate height. The resemblance of this layout to the Gothic ribbed vaults design is evident and highly advantageous because it allows the formation of different shapes, from cylinders to surfaces of revolution and even a perfect sphere (Choisy 1876: 444, pl. 21). Nevertheless, it sometimes also introduces some rather peculiar irregularities to the relief of the vaults. In the case of the groin vault, its edges are gradually lost in the upper part of the vault, which usually approximates a spherical shape. In addition, the curve of the cross section presents an inflection in the shape of a small counter-curve close to the perimeter arches or the walls that support the vault (Choisy 1883: 55).

The Byzantines sometimes chose to hide these defects and sometimes not. The author describes some techniques to correct them and also reports on the numerous licenses that these builders introduce to make the shapes of these vaults more flexible and adapt them to a wide variety of requirements. This also allows a more agile execution when it comes to covering secondary spaces – such as fortifications – where construction speed prevails and such irregularities of their vaults are less of a problem. Apparently, there are currently no graphic studies that support Choisy's hypotheses (Huerta 2009). The authors of this article are collaborating with a team of researchers to verify them.

Like Choisy, Paredes also addresses the execution of non-canonical groin vaults in chapter 2 of his manuscript. His proposal also affects the layout of the edges, although with a different strategy. He starts transforming the orthogonal cylinders by tilting their directrix. He then proposes other variants in which the vaults are made up of surfaces of revolution (toroids or ellipsoids). And, finally, he also shows the formation of pointed vaults and even starred vaults or compound by spherical sectors.

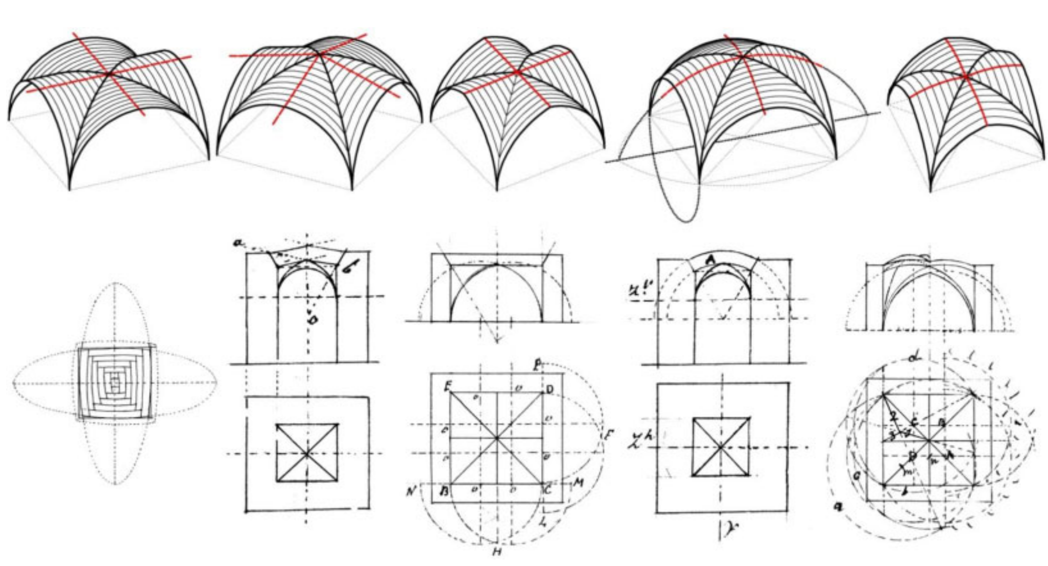

Figure 6. Variants of compound vaults according to Paredes (ca. 1883: plate 1, 2 & 3).

Paredes pays particular attention to the variant of inclined barrels on a square plan with semicircular arches because, according to him, this type has certain constructive and resistance advantages. He offers very specific instructions for controlling the shape during the construction process that can be adapted to other compound vaults such as the groin vault with spherical sectors, the star vault and the sail vault (Figure 6).

Paredes explains a practical way to raise the key during the execution process. For some authors, this "capialzado" (which is also known as an "arrepio", "resubido", "retumbo" or "empinamiento") is the raison d'être of the groin vaults without formwork and what the Roman vaults lack, transforming the cylindrical sections into the conical sections (López & López 2015: 996). The procedure consists of the laying of two ropes from the keys of the lateral arches and then raising the crossing point of both threads to a height of between 1/10 and 1/30 of the span, thus providing the barrels of the desired slope (Figures 4, 5). It also offers a practical method for defining some points of the diagonal ellipses in space, consisting of laying lines parallel to the directrix of the barrels and arranging a plumb line at its meeting point with the projection of the diagonal. Before that, he explains the geometric characteristics of the inclined slices, necessarily of an elliptical shape, that form the cylinders of these tilted vaults and also refers to the bricklaying to define those diagonal curves.

6 THE JOINS OF GROIN VAULTS IN EXTREMADURA

Paredes and Albarrán discuss this question in some depth. The first describes the aforementioned example of tilted barrels on a square ground plan, a method traditionally used in various countries. According to Paredes, in the springings of the vault the bricks must be "miter" cut so that they "form more perfection", at least until the vaults "interlock" (Figure 7). From that point, where the slices are forming an almost orthogonal angle, you can continue in the same way or choose to overlap some bricks with others, depending on whether the vault will be plastered. The author also proposes reducing the section of the vault in its upper part. In addition, he gives a brief overview of some particular cases, solving implementation problems such as the intersection of the vault with a non-orthogonal wall (Paredes ca. 1883: 154). The contributions of Albarrán (1855: 86 and 88) are much more interesting and closer to the actual construction in Extremadura. Albarán offers a solution for the formation of its joins dismissed in the previous texts and perhaps inspired by stonework. This consists of using an ordinary brickwork in several horizontal courses of bricks until the "slip angle" is reached; that is, until the bed planes of the bricks form angles of 38^{o} to 45^{o} with the horizontal. This option avoids the "miter" cuts proposed by Paredes for the springings (Figure 8). The issue has been analysed in a practical way by Wendland (2007).

A variant of the Albarrán proposal is widespread in Extremadura. Lowered vaults with this solution of the "pendentives" (or springings) supported by "dormido" and "spatillado" bricks are quite common. Thus, the courses are superimposed in a staggered manner along the entire edge up to the keystone, recalling the stonework of the ashlars of stone vaults. It seems that these vaults were built slowly, in sections, pausing for several days to allow the lime mortar to set before executing the next "pendentive" and its corresponding conical courses (López & López 2015: 997).

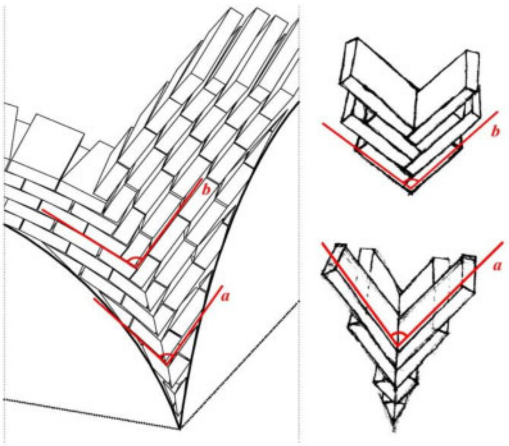

Figure 7. Explanation of the formation of the groins at the springings, according to Paredes (ca. 1883: plates 3 & 4).

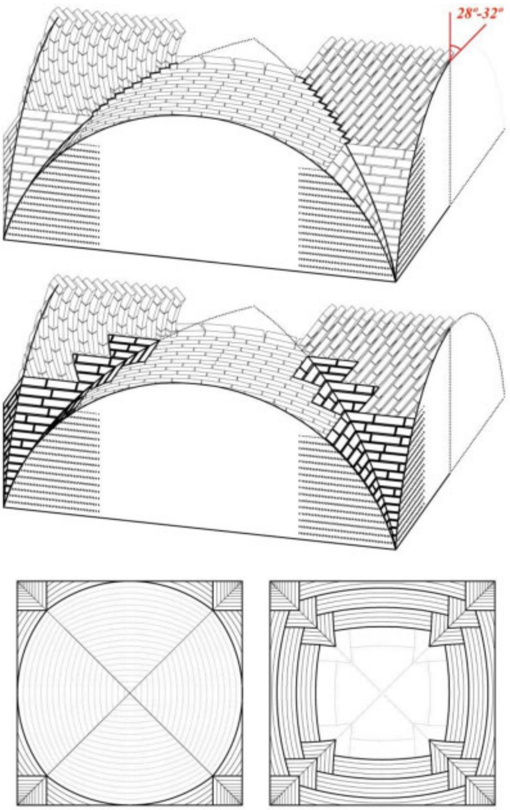

Figure 8. Scheme of the formation of the edges at the springings according to Albarrán (1855: 86) and in a real example of an Extremaduran vault.

These brickwork difficulties at the edges explain why many vaulted vaults both in Byzantium and in Spain have layers parallel to the planes of their diagonals. This way, the joints between vaults are

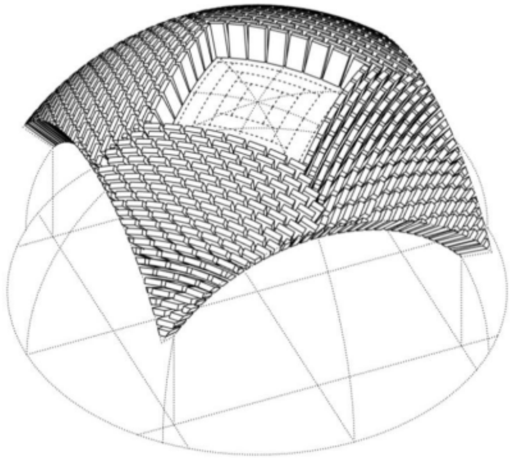

Figure 9. Formation of a sail vault by turned square courses. Thus, the joints between the slices occur at the quadrants.

produced on the quadrants, miter cut bricks are not necessary and the spans are shorter (Figure 9).

7 CONCLUSIONS

During the 19th century, several texts emerged in France and Spain that focused on the construction of vaults by slices, but it seems that they are not related to each other. The texts by Boguerín, Ger y Lóbez, Paredes and Albarrán are based on the authors' own professional experiences, while Choisy seems to support his hypotheses with visual analysis of some Byzantine vaults, although he claims that he carried out some practical experience to verify them.

The proposals do not show a direct connection. Extremadura seem to have developed independently, even while the texts undeniably share the Roman roots as a common origin. In his 1876 text, Choisy points out that, at that time, vaults by slices were being made in Mosul in the Byzantine manner, although the techniques differ in some aspects from those of Extremadura.

This article is limited to analysing and explaining the theoretical approaches offered by the manuscripts, without assessing their concordance with the preserved examples actually constructed, particularly in Spain. It is known that these types of texts sometimes provide a limited vision of the problem that only covers a few cases, usually the most elementary and descriptive of the technique. But this initial analysis is essential to any subsequent detailed study of surviving examples. In this new phase, the viability of these theories should be tested and other possible strategies not contemplated in the primary sources should be identified.

The authors are part of a team of researchers dedicated to the study of vaults by slices in the Iberian Peninsula and the eastern territories of the ancient Roman Empire. It is a complex task, because the most relevant data – such as the inclination of the bricks – can only be deduced from the visible surfaces of the vault (intrados and extrados). Therefore, some of the theories presented must be verified through the construction of scale models, with the support of the "experimental archaeology" that offers such good results in other analogous fields.

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João Mascarenhas-Mateus
and **Ana Paula Pires**

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