Compound brick vaults by slices in written sources

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ABSTRACT:
The vaults called "par tranches" by Auguste Choisy are those that are built by laying the bricks with their bed in a vertical or slightly sloped position. The form and the process of execution of these vaults have been scarcely studied so far, partly because it is difficult to figure out the true definition of the hidden elements of the masonry. Until the 19th century there were not primary sources that explain these ways of building, which depend more on the skill of the masons rather than on the abstract knowledge of the designer. This article compares the technical proposals of the French and Spanish texts from the late 19th century that address its construction works in Byzantium and Extremadura (Spain). The genesis of the system (designed for barrel vaults) is comparatively explained according to each author. Also, the subsequent evolution of different types of compound vaults is analyzed with special attention to the groin vault because 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 laying 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 since 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 spread 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 (Ara-guas 2003, 84; Almagro and Orihuela 2013). 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 (Portugal), reaching Lisbon and the south of Salamanca (Spain). In addition, it traveled to the New World, where in Mexico it continues in use, in a very imaginative way (Rabasa, in press).

In Extremadura they are called today "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 (Ger and Lóbez 1869, 253; Albarrán 1885, 49). More recently, some researchers have referred to them as "byzantine brick laying" or "tangential" vaults (Araguas 2003, 84) and "a bofetón" vaults (Almagro 2013). Probably a careful study of the so-called "de rosca" vaults would show that it was a much more common solution than it seems.

2. THE SOLUTION IN THE TECHNICAL TEXTS OF THE XIX 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 the construction techniques texts until the 19th century.

The first written references to vaults by slices are found in the texts from several 19th century Extremadura authors. In this region of southwestern Spain, this variant began its apogee in the 18th century (Paredes [ca. 1883] 2004). In 1855, a short article by Francisco Javier Boguerín was published in the magazine *Obras Públicas* encouraged civil engi-

neers to use this option because it was economical. Boguerín points out that, although they are not reported in the treatises, the masons of Extremadura use this method with great ease. The manuscript describes in little detail the execution of barrel vaults, although its author claims to have seen "vaults of all kinds and openings built in this way" (Boguerín 1855,136). Later, this article was collected by Espinosa (1859) in his «Manual de construcciones de albañilería», without mentioning the author.

The text by Florencio Ger y Lóbez (1869, 1898, 1915), which also echoed Boguerín's proposal, includes a greater number of variants. This author 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 and Lóbez 1869, fig. 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 that are 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". Particularly, he also lists several actual examples that follow this method (Albarrán 1885, 89).

But beyond these precocious incursions, the studies of two authors from the last quarter of the 19th century stand out, which detail describe in a more detailed way the design and construction strategies of these vaults. 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 analyzes 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), 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 project 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 meters-span vault, with 22x11x5 cm bricks, to reinforce his hypotheses (Choisy 1876, 441). The latter are deduced from daily practice, although Paredes tries 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 of the texts by Choisy and Paredes have been studied by Rabasa, López and Alonso (2020). These authors suggest that Paredes may have known Choisy's work because his proposals show points in common, despite the fact that the first proposes an unprecedented configuration, based on the definition of concave constructive cones for the formation of the slices of the vaults, opposite 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 the French and Spanish texts of the late nineteenth century.

This work analyzes the design and construction strategies of the groin vaults defined by these five authors, based on the studies of Rabasa et al. (2020) for the barrel vaults, and their adaptation to other variants of compound vaults, devoting especial attention to sail vaults (fig. 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, allows to control the shape during the implementation process.

The absence of plaster as a binder forced many builders to look for assembly strategies and construction arrangements, when the adherence of the lime or clay mortar was not sufficient, that would help to preserve the position of the pieces. The bricks slide due to the action of the tangential component of their own weight. The friction force, 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, friction. Furthermore, it is necessary to take into consideration the possibility of laying the bricks, with inclinations of less than 40º, to reduce the incidence of tangential force. This option can also be reinforced by other additional means to improve the fastening, increasing friction and preventing parts from slipping, such as the formation of pitching and conical beds, so characteristic of the vaults by slices.

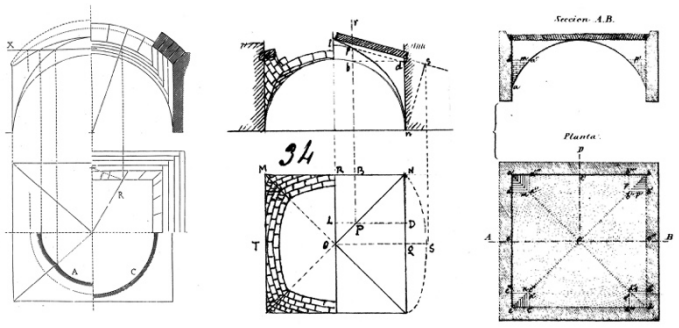

Figure 1. Tracing of the groin vaults in Choisy (1876, pl.21), Paredes (ca. 1883, plate 4) and Albarrán (1885, 86).

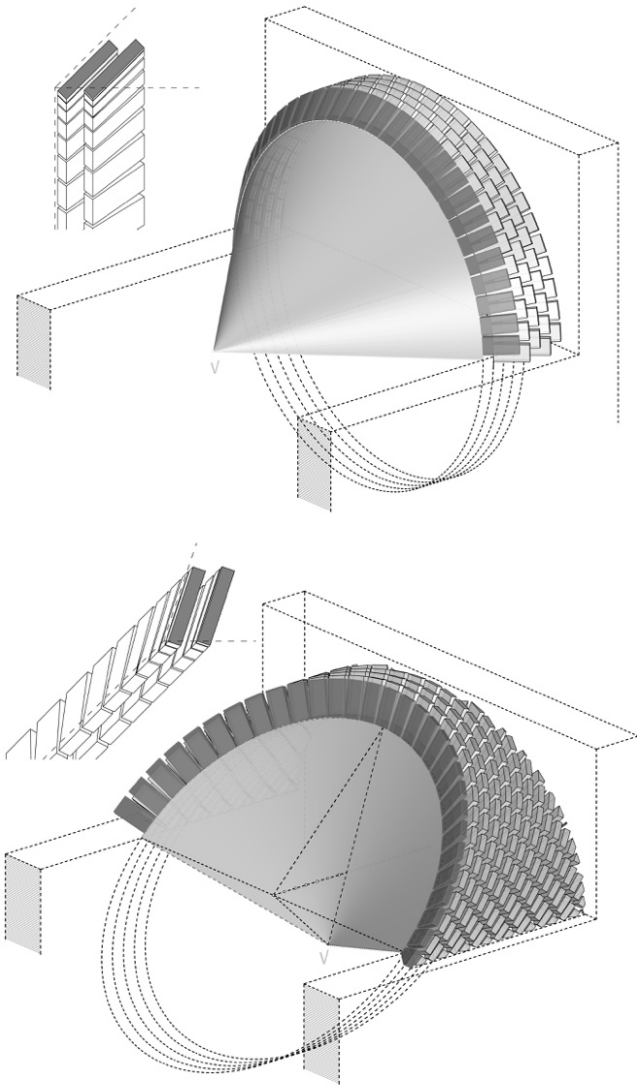

Figure 2. Above, convex cones vault (Choisy). Below, concave cone solution (Paredes).

Byzantine builders, for example, usually used large, thin bricks. According to Choisy, the smallest ones were 30x15x4 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 leveling layer is essential when the slices are inclined and conical. In Extremadura, Paredes (ca. 1883, 160) recommends using a small brick measuring 21x14x3.2 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 28x14x2.4 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 bricks Extremadura 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 45º, and optionally, arranging the beds of the bricks to the directrix of the cone or with a slight inclination of about 20º. Arguably as compensation, the most favorable 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 her own solutions based on the use of ropes and belts.

According to Paredes, as said, in Extremadura vaults the brick layers form concave cones (from the operator's working plane) and not convex, 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 (Fig. 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 and 1915, 202) describes these vault 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 either by the natural meeting between the brick slices of the two barrels, performing in this case an ellipse

(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 and Lóbez 1915, 202).

In his texts, the Frenchman Choisy (1876, 443 and 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 vaults of the undergrounds 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, on the other hand, facilitated the execution, produced less thrust and, 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 also first describes the groin vault as the meeting of two barrels vaults formed by cylinders of inclined slices with a frusto-conical section (Paredes ca. 1883, 130). But then, it 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 its panels.

Albarrán (1885, 85) on the other hand, pays little attention to the shape of the groin vaults, but offers interesting recommendations for the construction process of solution made by cylinders and some novelties on the formation of their springins. 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 backside.

Albarrán offers two enforcement procedures. For the first one, he use 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 1885, 88).

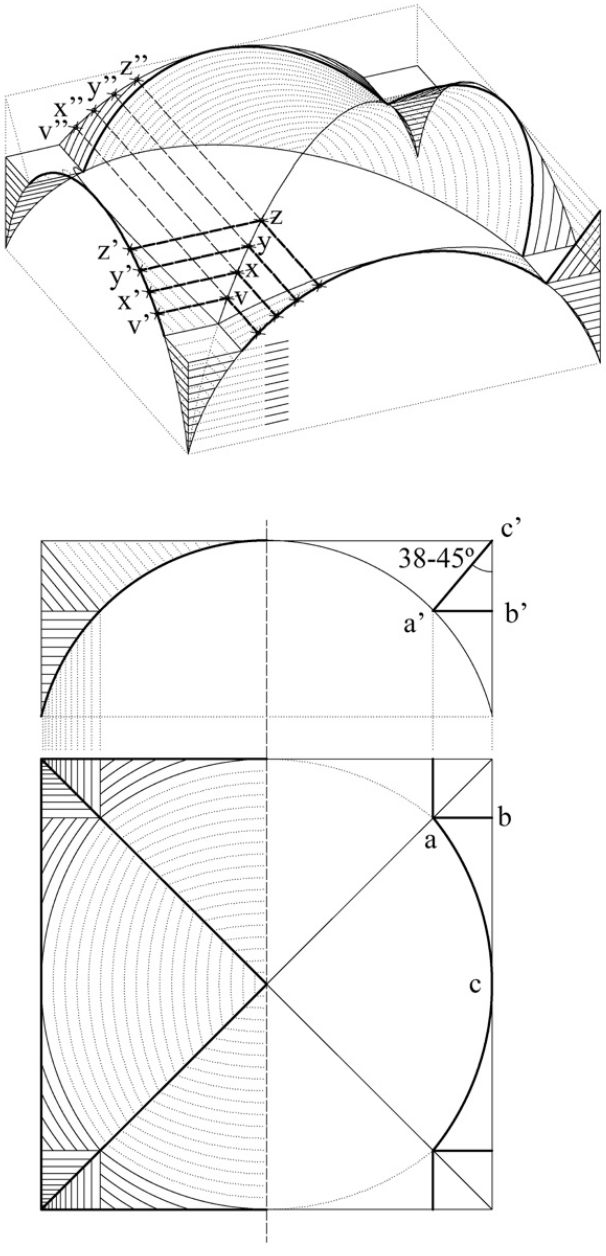

Figure 3. Trace of the Extremaduran groin vault according to Albarrán (1885, 86).

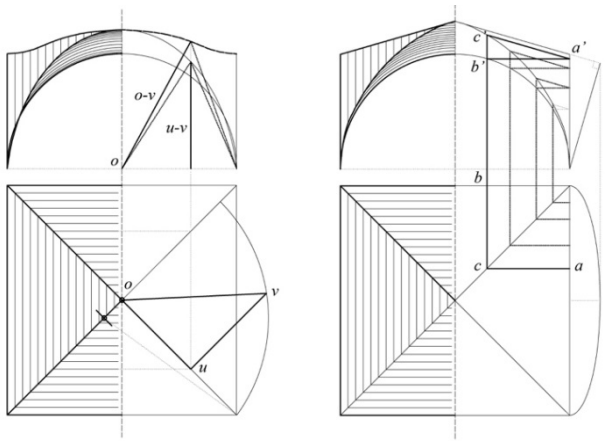

Figure 4. Trace of the Byzantine groin vault according to Choisy (1883, 55) and the Extremaduran pointed groin vault with "retumbo" proposed by Paredes (ca. 1883, plate 4).

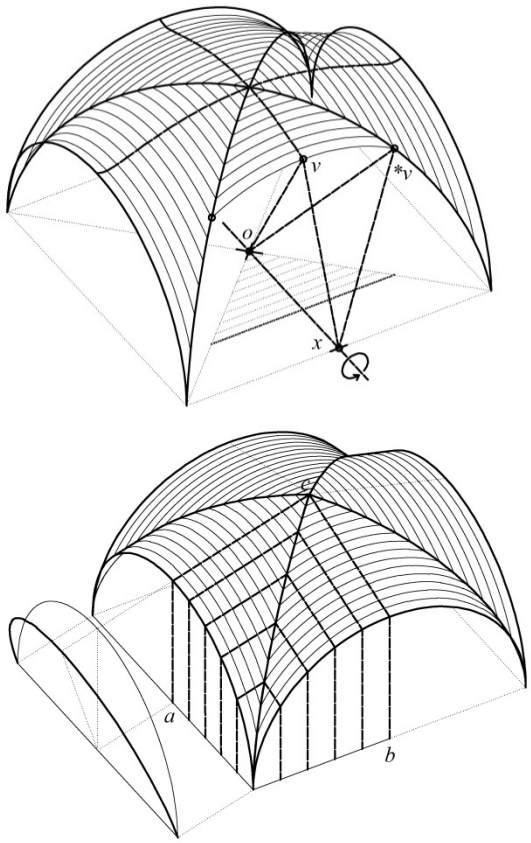

Figure 5. Comparison between the Byzantine groin vault (Choisy) and the Extremaduran pointed groin vault (Paredes).

Albarrán 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 presents his constructive indications. According to 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 (Fig. 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 1885, 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 to the designer a great freedom (Figs 4, 5). The diagonal arch is always an arc of circumference that sometimes has its center under the line of imposts so as not to exceed the height of the perimeter arches and 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 center 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 center and the same happens with the slices of the vaults. The latter are formed by circumferences of variable radius whose measures are obtained successively just 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). Logi-Logically, it is expected this graphic abstraction of the author 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 lift, the diagonal arch can be given the desired deflection each lateral arch the appropriate height. The resemblance of this layout to the Gothic ribbed vaults design is evident and highly advantageous because it allows to form different shapes, from cylinders to surfaces of revolution and even a perfect sphere (Choisy 1876, 444, pl. 21). But sometimes it also brings certain rather peculiar irregularities into 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 countercurve close to the perimeter arches or the walls that support the vault (Choisy 1883, 55).

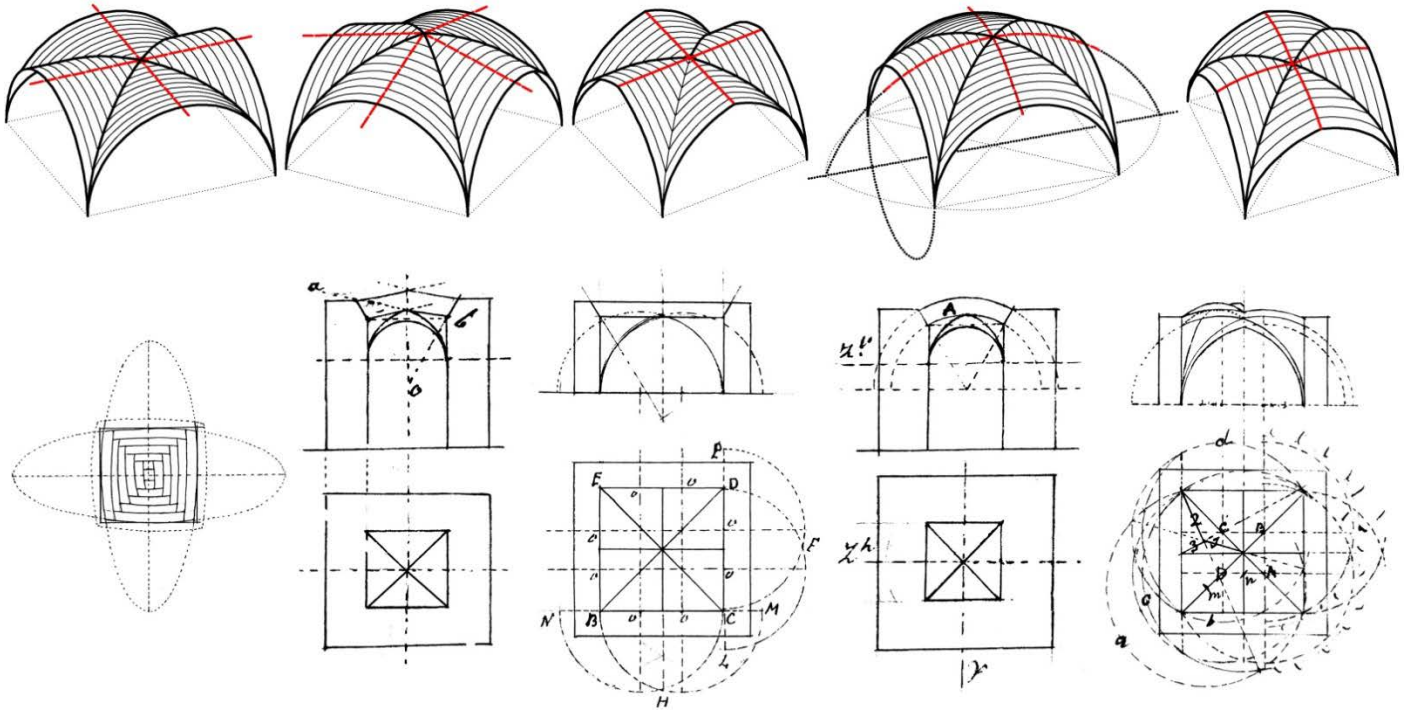

Figure 6. Variants of compound vaults according to Paredes (ca. 1883 plate 1, 2 & 3).

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, etc., where constructive 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 collaborate 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.

This author 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 for other compound vaults such as the groin vault with spherical sectors, the star vault and the sail vault (Fig. 6).

Paredes explains a practical way to raise the key during the execution process. For some authors, this capialzado, which is also called "arrepio", "resubido", "retumbo" or "empinamiento", is the raison d'être of the groin vaults without formwork and the Roman vaults lack, transforming the cylindrical sections of these into the conical of those (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 a height of between 1/10 and 1/30 of the span, thus providing the barrels of the desired slope (Figs 4, 5). It also offers a practical method to define some points of the diagonal ellipses in space, consisting of the laying of lines parallel to the directrix of the barrels and the arrangement of a plumb line at its meeting point with the projection of the diagonal. Before, 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 brick laying for the definition of those diagonal curves

6. THE JOINS OF GROIN VAULTS IN EXTREMADURA

Paredes and Albarrán discuss this question in a certain depth. The first one describes the previously mentioned example of tilted barrels on a square ground plan, a method traditionally used in different territories. According to Paredes, in the springings of the vault the bricks must be cut "miter" so that they "form more perfection", at least until the vaults "interlock" (Fig. 7). From that point, where the slices are forming an almost orthogonal angle, you can continue the same or choose to overlap some bricks

with others, depending on whether the vault will be plastered or not. The author also proposes to reduce the section of the vault in its upper part. In addition, he makes a brief review of certain 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 (1885, 86 and 88) are much more interesting and closer to the actual construction in Extremadura. It 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 of several horizontal courses of bricks until reaching the "slip angle", that is, until the bed planes of the bricks form angles of 38º to 45º with the horizontal. This option avoids the "miter" cuts proposed by Paredes for the springings of the vault (Fig. 8). The issue has been analysed in a practical way by Wendland (2007).

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

These brickwork difficulties at the edges explain why many vaulted vaults, both in Byzantium and in Spain, have their layers parallel to the planes of their diagonals. This way, the joints between vaults are produced on the quadrants, miter cut bricks are not necessary and the spans are shorter (Fig. 9).

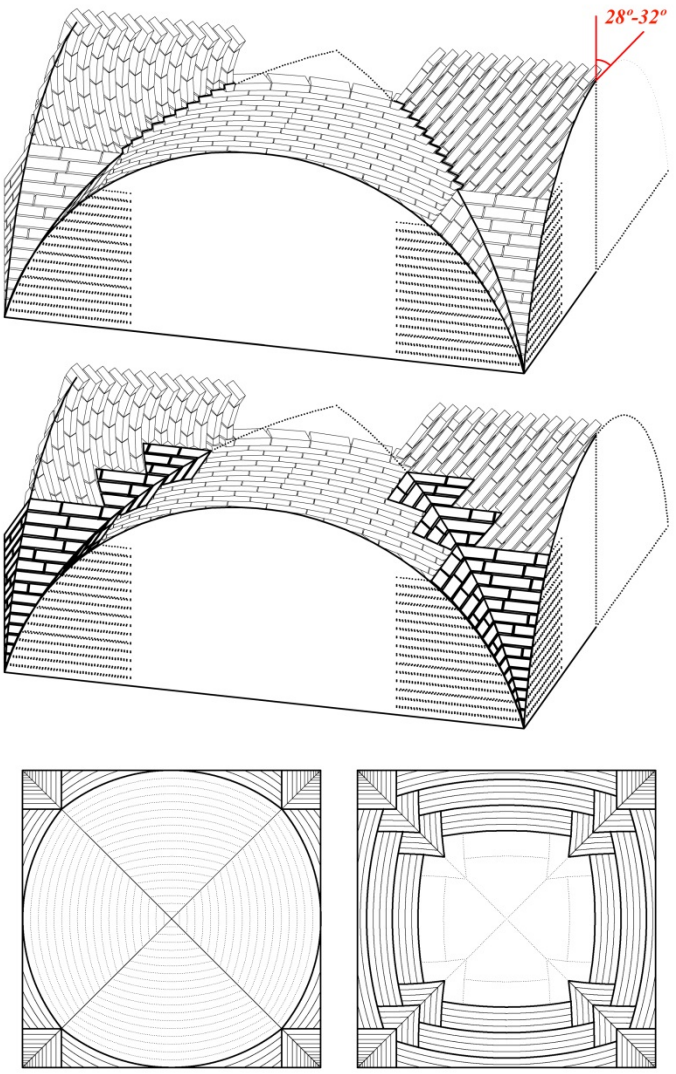

Figure 8. Scheme of the formation of the edges at the springings according to Albarrán (1885, 86) and in a real example of an Extremaduran vault.

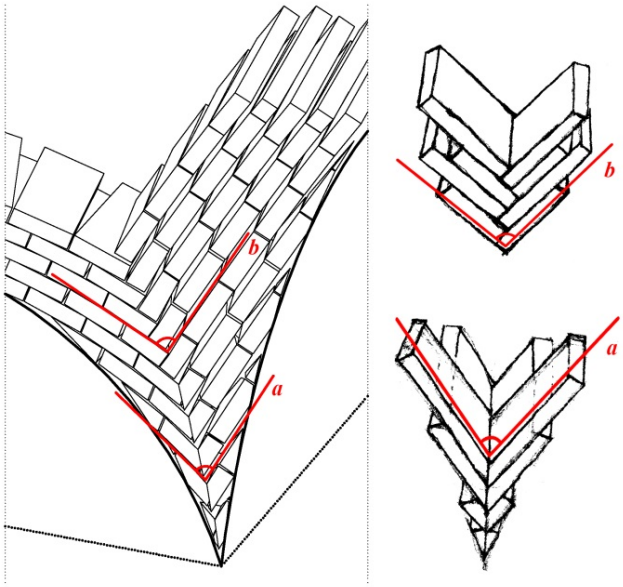

Figure 7. Explanation of the formation of the groins at the springings, according to Paredes (ca. 1883, plates 3 & 4).

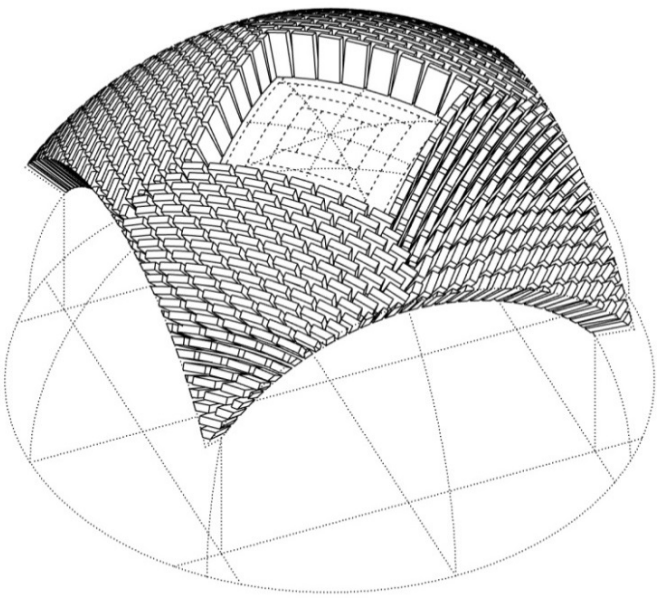

Figure 9. Formation of a sail vault by turned square courses. Thus, the joints between the slices occur at the quadrants.

7. CONCLUSIONS

During the 19th century, several texts appear in France and Spain that are interested in the construction of vaults by slices, but it seems that these are not related to each other. The texts by Boguerín, Ger y Lobez, Paredes and Albarrán are based on their own profesional experiences. Choisy seems to support his hypotheses in the visual analysis of some Byzantine vaults, although he claims that he carried out some practical experience to verify them.

The proposed traces do not show a direct connection between them. Extremadura solutions suggest an autonomous evolution, even if they share undeniably 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.

On the other hand, this article is limited to analyzing and explaining the theoretical approaches offered by the manuscripts, without assessing their concordance with the preserved examples, 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 for the subsequent detailed study of the preserved 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 will be 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 "experimental archeology", which offers such good results in other analogous fields.

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