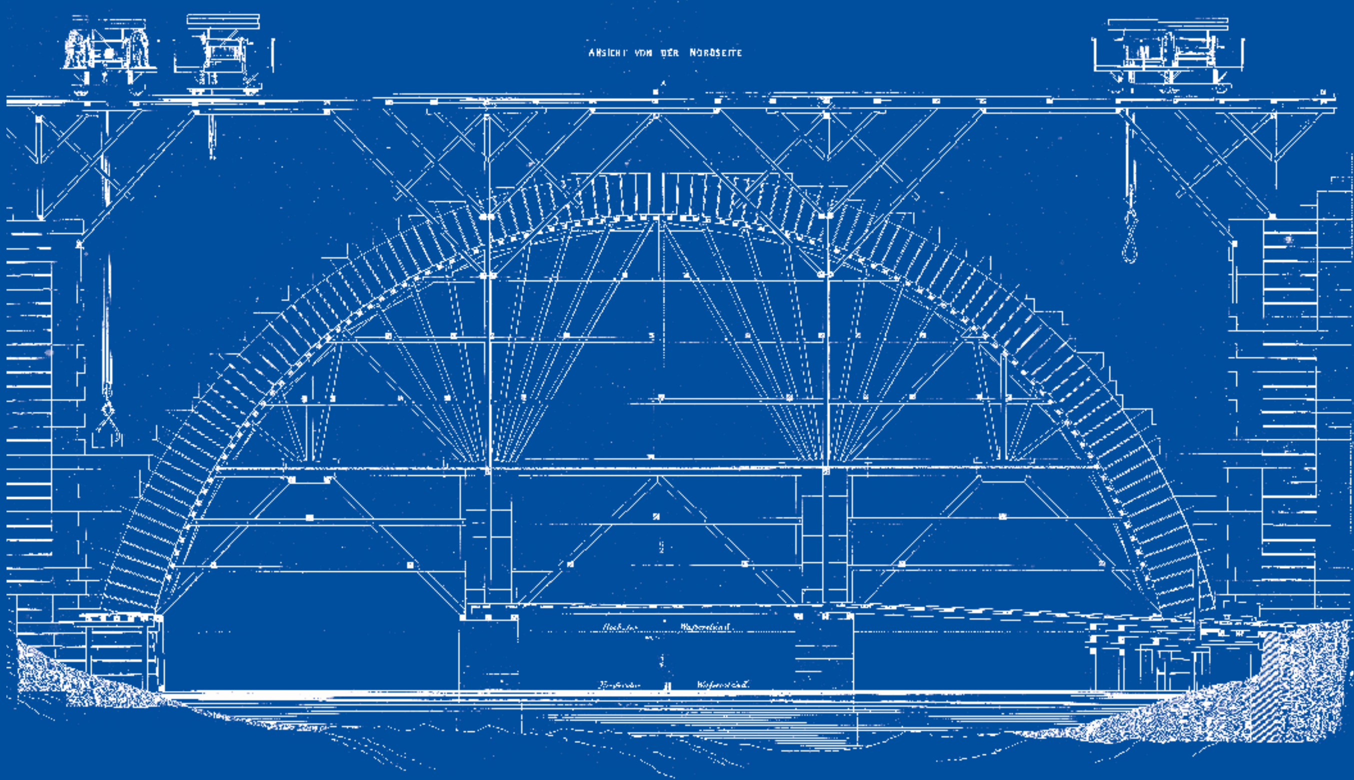
Proceedings of the 8th International Congress on Construction History

Stefan Holzer, Silke Langenberg, Clemens Knobling, Orkun Kasap (Eds.)



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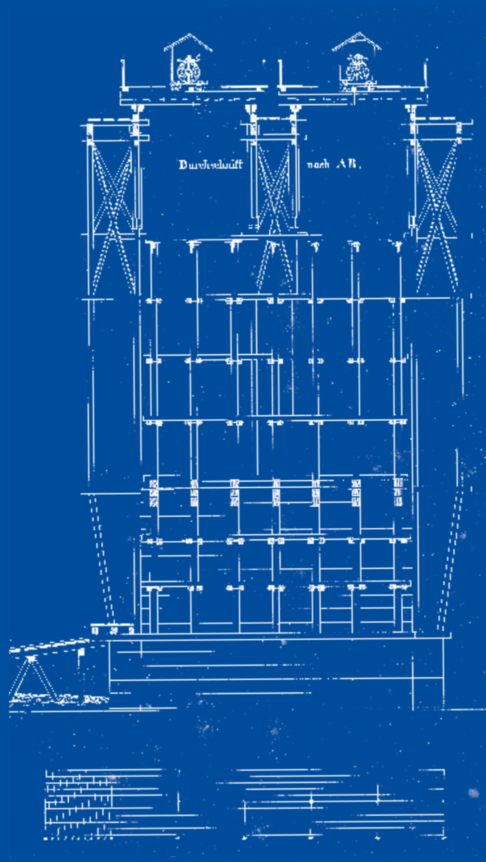

Matters

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Experimental assessment of existing ideas on brick vaults by slices building process

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Abstract: This paper deals with brick vaults by slices, that is, those built with no formwork, where the brick is vertical or inclined, held by the mortar adherence, and the courses form thin arches, which will finally show only their headers or stretchers on the intrados. Those vaults have been built in many different cultures and periods, in particular in Byzantium, in large areas in the Iberian Peninsula, especially in the Extremadura region and, more recently, in Mexico. The paper focuses on the material aspects of brick-and-mortar placement, the form of the slices, and the sequence of operations in the construction process. Original written sources will be critically analyzed, taking into account actual construction practice carried out by Mexican and Extremaduran bricklayers and physical models specifically prepared for this paper. This study reviews ideas of Spanish authors from the nineteenth century and statements of twenty-first century bricklayers, about the way in which the bricks should be placed, the mix ratio and use of mortar, the shape of the courses and the procedures that control the shape of the vault. Both historical sources and statements from practicing bricklayers, together with actual experimentation of the operating procedures, as well as the use of models, reinforce or deny traditional ideas.

Introduction

We call brick vaults by slices those built with no formwork when the brick is vertical or inclined, held by the mortar adherence, and the courses form thin arches which will finally show only heads or stretchers on the intrados.

Their presence in history has been constant, being especially relevant those built in Byzantium, in a large part of the Iberian Peninsula for centuries, especially in the region of Extremadura and, more recently, in Mexico. In the case of Byzantine vaults, Choisy (1876; 1883) explained that the slices can be placed vertically; however, to prevent deformations, they were frequently pitched, taking the shape of a plane or a conical surface—a cone frustum—convex from the operator's point of view.

The study of extant cases and written sources already carried out by our team has made clear the general form and brick arrangement of most important cases and types confirming or discarding some construction procedures (López-Mozo et al. 2021; Rabasa et al. 2022; Rabasa et al. 2023; López-Mozo et al. 2023). However, identifying the whole building process actually used in historical heritage is not so easy. The main contributions to related issues have been made by David Wendland (2007a; 2007b; 2007c) and some Mexican authors (Ramírez Ponce and Ramírez Meléndez 2012; Aguirre 2016).

The focus of this paper is not on the geometrical shape of the vaults, but on the material aspects of brick and mortar placement, the form of the slices, and construction process sequence. Original written sources will be critically analyzed taking into account actual vault building carried out by masons still familiar with this technique and physical models specifically prepared for this study.

The execution of vaults by slices with lime mortar was until recently common in Extremadura and is now common in Mexico; in these two places it is possible to find masons who can refer to a living tradition. That is why we have chosen masons from these places: the Mexican master Andrés Flores Castañeda, who constructed with us a "corner vault", widely used today in Mexico, and the Extremaduran master Máximo Portal Sánchez, who made a groin vault based on elliptical perimetral arches that is typical in Extremadura. Both vaults were built on a square plan with a span of 2.60 m, with bricks measuring 23.5 x 11.5 x 4.7 for the Mexican vault and 23.5 x 11.5 x 3.7 for the Extremaduran vault. (Fig. 1) As we have mentioned, the study of these types of vaults has already been done, and this paper seeks to provide information on the details of the execution with this technique.

1. On the brick laying

The fact that the bricks are laid one by one without formwork, just relying on the adherence of the mortar, may seem striking. Plaster used on the first layer of tile vaults hardens quickly. However, most vaults by slices are built with slow-setting lime mortar.

It is perfectly possible to place a brick vertically, held only by lime mortar, without risk of falling down. The precise reason why the bricks are held in place by lime mortar has not yet been clearly explained. In our test vaults, the Mexican master builder Andrés Flores began by bonding with mortar two bricks together, and then immediately held both bricks horizontally by grasping only the upper one. The authors of this paper have been able to reproduce this operation easily. (Fig. 2)

Figure 1. Vaults under construction, above by Andrés Flores, below by Máximo Portal. (Image by the authors).

Figure 2. Adherence between two bricks in horizontal position (Image by the authors).

The mortar adhesion cannot be attributed to a chemical reaction such as the curing process, since the laying is immediate, and the lime mortar may be exposed to air for a long time without reacting with the CO2 in the air. This fact can be explained taking into account that mortar immediately enters the pores of the brick and favours adhesion. It is well known that in this type of construction the bricks do not get soaked, as usual in other masonry building processes using ceramic materials. However, using dry bricks is not an absolute requirement. Both masons participating in our experiences agreed that it is possible, and advisable if the bricks are handcrafted, to wet them very quickly, to remove any dust. Slightly wet bricks cannot absorb the water from the paste immediately. Perhaps wetting the bricks just a little, without waterlogging them, allows the mortar water to be absorbed later, not immediately after laying. Also, may be that a thoroughly soaked brick is simply not advisable to avoid an increase in weight.

The fact that it is possible to hold a brick even in a horizontal position holding it from above suggests that a suction cup effect may be acting. The brick should be placed by hand and adjusted very quickly, with a few trowel strokes, but moving the piece to improve its position after the first three or four seconds should be avoided, especially if the piece oscillates in such a way that some part of it moves away from, rather than towards, the underlying bricks. This fact, and the wish of keeping the brick free from dust, are compatible with the explanation that alludes to the suction cup effect. On the other hand, the piece receives the pressure of the hand and some strokes (only in the central part, to avoid oscillation). This may suggest the action of some kind of rheopecty, which is an increase in viscosity of a non-Newtonian fluid when it is subjected to stress (Rodríguez Agudo and Rodríguez Navarro 2010). This phenomenon is very noticeable, for example, in gypsum paste and cornstarch paste; this would also explain the ease of sticking mortar on a wall when it is thrown from a distance with a trowel.

The brick can be laid either by placing the mortar on the piece or by throwing it on the underlying brick, indistinctly. We also know from the testimony of Choisy (1876, 441) that it is possible to place a layer of mortar over the whole of the previous course before laying the bricks. In the test vaults mentioned above, particular care was taken to record the proportions of lime and sand. Both masons recommended a mix ratio of 1:3. However, in both cases lime or water was added frequently taking into account the appearance and viscosity of the paste, assessed with the trowel. Neither too much sand nor too much water is desirable, but lime in excess does not harm.

Both masons recommended adding some Portland cement but made it clear that this was not essential, as shown by historical works. The advantage of adding cement is not completely clear; it seems that present-day masons, knowing the properties of this material, seek shorter setting times and greater mechanical resistance when finished.

Regarding the brick inclination, as we have already mentioned, the piece can be placed in a completely vertical position. Most of the arches and barrel vaults with completely vertical courses are to be found mainly in the Alhambra palace, in North Africa and in Iran. In these places, as far as we know, gypsum mortar is generally used.

In non-barrel vaults, brick inclination is related to other important factors, as explained by Wendland (2007c), such as the inclination of the intrados surface or the ease vault sections meeting. If these factors do not influence, as in barrel vaults, the brick can be placed in more or less inclined slices. Vicente Paredes (1883) explained in a manuscript that he carried out the experiment of placing several bricks, one on

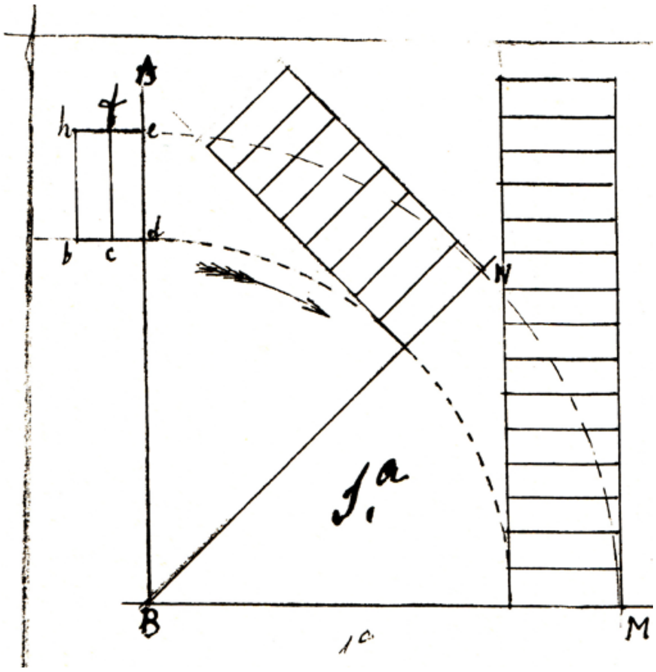

Figure 3. Assessment of bricks adherence in Paredes (1883).

top of the other, until collapse. (Fig. 3) It is evident that there is no limit in practice for bricks laying one in top of another; at forty-five degrees Paredes could lay up to eight pieces; however, using vertical courses he could place only two. This depends, of course, on the weight of the brick. The support of some courses on others in a barrel vault, as opposed to a succession of arches, improves the stability of the course and the behaviour of the ensemble while the mortar is fresh. The term used in Mexico, *recargado*, which has been roughly translated as "leaning brick" (Ramírez Ponce and Ramírez Meléndez 2012), suggests the resting of each course on the previous one.

The placement of bricks in each course starts at both ends, to avoid a long row of bricks before the arch is closed. Consequently, it is usually necessary to cut bricks in the central part. This detail that can also be seen in historical works, with exceptions as the vaults of the Fuente Grande de Ocaña, which have the bricks very perfectly ordered (Rabasa et al. 2023).

2. On the slices form

Wendland (2007a, 2007c) has studied in depth the relationship between the shape of the courses and the shape of the complete vault. He observed that the beds or the slices are generally placed on parallel planes in German gothic vaults, the changes in the slope of the intrados are achieved with the displacement of each course regarding the previous one and the inclination of the courses responds to the convenience of adapting as much as possible to the ascending slope of the vault. On the other hand, Wendland's studies show a close relationship between the method followed for the arrangement of bricks and courses and the resulting shape, for instance in the severies or caps. This is the consequence of a systematically followed procedure. In the studies we have carried out on Spanish vaults, we have been able to verify that the curvatures or the centers of the courses do not follow a systematic rule. We cannot yet confirm whether these Spanish traditions derive from the Byzantine ones, as this is a subject we are still studying.

In some vaults in Extremadura, the junction between sectors is not made by buttressing individual courses, but by inclined groups of courses. The explanation of this issue in nineteenth century authors, such as Ger y Lóbez (1869, 256) and Albarrán (1885, 88-89), is far from clear; they use the expression *tapa de coche*, that is, "car top". Wendland (2007c) has shown with models that this practice has the advantage of avoiding sharp cuts in the bricks that appear in vaults with vertical courses. The mentioned Extremaduran authors do not mention this advantage, which is not strange considering the ambiguity of their texts. Another type of vault from Extremadura, the one executed by Portal, which is similar to a groin vault, presents what are called pechinas (pendentives) or espigas (herringbone). These different arrangements in the groin seem to have the same purpose, to provide a correct support to the slices, in addition to reinforcing the diagonals. (López Mozo et al. 2023).

Wendland points out that the arrangement of inclined parallel flat slices is an alternative that improves the seams or encounters between sectors in vaults. Surveys of Spanish vaults of this type generally show course lines on parallel planes on the intrados. However, in some cases, the plane of the bed itself appears not to be flat; rather, it adopts the shape of a conical surface sector, as some collapsed vaults show nowadays in Toledo (López-Mozo et. al. 2021).

Choisy (1876, 1883) said that he observed an arrangement of frustum cone shaped courses in Byzantine vaults. The course or joint line visible in the intrados is flat; however, the bed surface of the course is a portion of a very open cone, with the convex side facing upwards, that is, to the operator. The manuscript by Paredes (1883)—which has the same date as Choisy's book on Byzantium—describes the opposite layout for Extremaduran vaults: the courses are portions of a cone, but is the concave side that faces upwards, to the operator. (Fig. 4)

According to Choisy, the purpose of the convex conical shape is to increase the inclination of the pieces. Paredes thought that the concave conical shape has mechanical advantages for the arch forming the course. Paredes' reasoning is as follows: a horizontal circular course, such as those of hemispherical vaults, is maintained without the need for formwork not only by adherence, but also by the compression of the ring. By inclining that course, taking only half of it, it becomes an arch that continues to take advantage of that compression to a certain extend to improve its stability. Rabasa Díaz, López-Mozo, and Alonso-Rodríguez (2020) show that the weight of a brick can be decomposed in the inclined course so that there is still that general compression that stabilizes.

Models have been built for this paper, comparing the mechanical behaviour of the layouts described by Paredes and Choisy. In our test, with 1:25 scale arches on boards that were slowly raised, it has been found that the concave course did not collapse under a certain load, and the convex course collapsed with half that load. (Fig. 5)

The surveys of historical vaults in Extremadura that we have carried out show brick layouts compatible with Paredes' descriptions. They are also incompatible with Choisy's convex cones, which are not possible above a certain inclination of the course. The courses of the groin vaults of Extremadura are

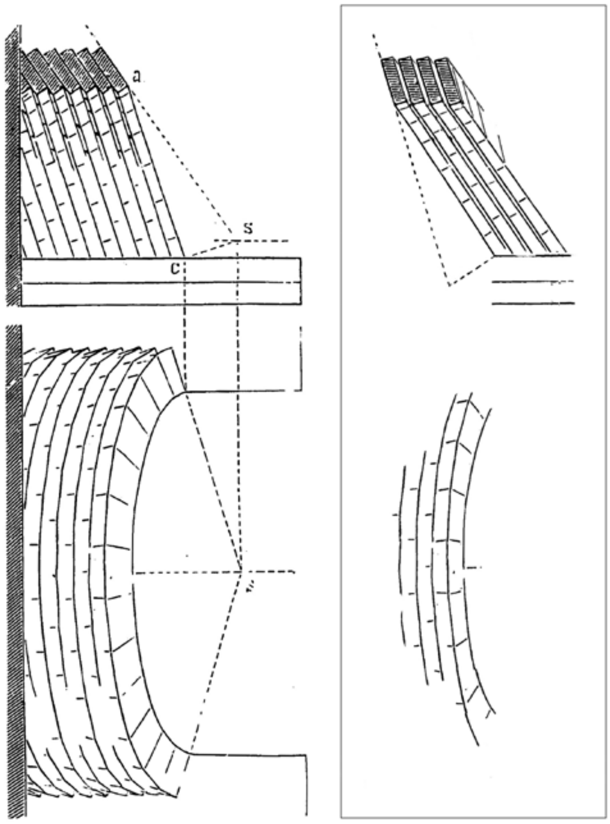

Figure 4. The convex cones in Choisy (1883) on the left, and the concave cones of Paredes drawn with the same graphism by the authors, on the right.

very horizontal, which makes even a flat course arrangement impossible. In the vault made by the Extremaduran Maximo Portal, this concave shape of the beds was not noticeable, probably because the size was small.

As for the Mexican vault, we have been able to verify that the shape of the bed is not flat. The author, Andrés Flores, explained that he tried to give a slightly greater verticality to the bricks in the central part of the course, in order to

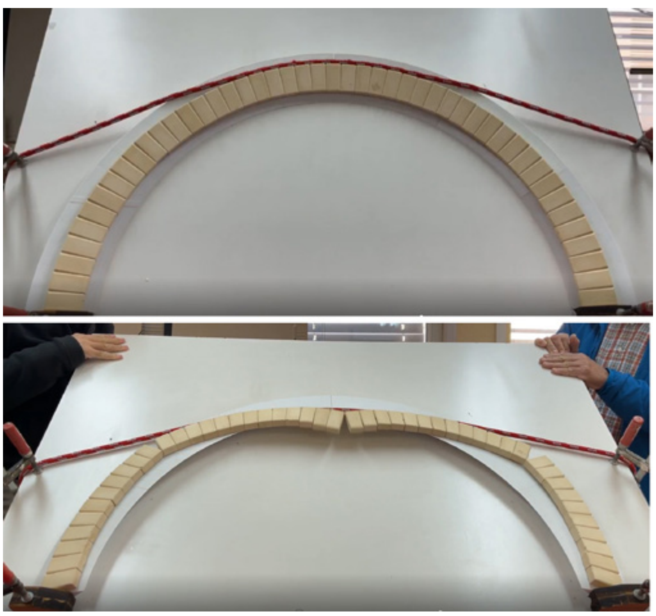

Figure 5. Above, load on a concave cone shaped course, below half of that load on a convex cone shaped course (Image by the authors).

Figure 6. Photogrammetric survey of a course of the vault built by Andrés Flores, positioned in such a way that the central area is on edge (Image by the authors).

reach the center of the vault with almost vertical bricks; a photogrammetric survey has proved this assertion. (Fig. 6)

In any case, the apparent course lines in the intrados of a vault cannot lie on planes converging on an axis, since this would require mortar joints with variable thickness, with a maximum at the center, which is not visible in the surveys and would be difficult for the mason to control (Wendland 2007c, 329).

Nevertheless, the cone shaped courses of Choisy and Paredes, in the case of barrel vaults with inclined and sufficiently long courses, would also make it necessary to adopt a variable thickness of mortar. Indeed, if the cone frustums are repeated in the direction of the axis of the barrel, those with vertical directrix can be parallel surfaces, but those with inclined directrix cannot. The thickness of the mortar would decrease (in convex cones, Fig. 7) or increase (in concave cones) from the springings to the keystone. The difference is small, and under normal conditions these barrels do not have completely semicircular courses; in fact, they are noticeably surbased, so the issue is imperceptible. The operator does not have to be concerned about the thickness of the mortar in each piece, as its position in the course and the continuity of the barrel would naturally cause the variation.

When the Extremaduran master Portal was asked about the possibility of laying completely flat and vertical courses, he replied that they would not be very stable and that in that case it would be advisable to bring forward the start of the following courses to form advances that act as buttresses. We can see the same idea in Nubian vault building. (Fig. 8) While building the vault, Portal advanced the perpendicular courses with a brick when finishing some courses. (Fig. 1 below) We have observed that it has the advantage of clearly defining the direction of that course not yet begun. This is relevant for maintaining a seam with the correct alternation of courses.

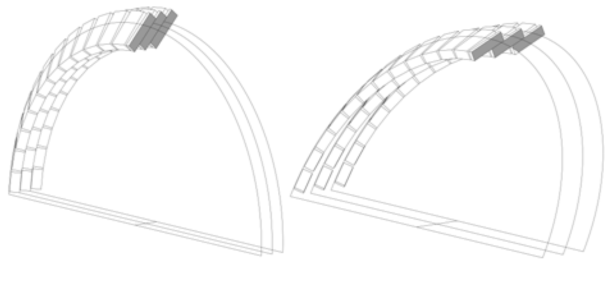

Figure 7. Variable distance between conical courses (Image by the authors).

Figure 8. Advances that act as buttresses in https://www.archinea.ch/cites-voutes..

3. On the material control of the vault form

Paredes (1883) shows in a drawing the arrangement of ropes that allow formal control of the course progress in an Extremaduran vault. (Fig. 9) Current bricklayers have confirmed the use of similar methods. Paredes' central vertical string is used to control the correct position of the seams between the four sectors by means of visuals; it is possible to estimate very accurately whether the seam is in the correct plane by placing an eye so that the corner of the vault coincides with the vertical string. Some masons have told us about the use of quince sticks, and Portal used curved metal rods. Since in many of the historical vaults studied the edges do not converge in the centre of the vault, it does not seem that these procedures have been universally used. In any case, the verticality of the seams must have been truly relevant for some constructors, since there are texts from the nineteenth century that mention other methods to control it (Rabasa et al. 2022, 941).

The ropes going from the center of the vault to the keystones of the perimetral arches in Paredes' drawing serve as a guide to lay the sectors with a slope that reaches the central point, which is higher. But many of the Extremaduran vaults show a non-straight cross section, but rather curved. This is what happened in the vault executed by Portal; the ropes were only used as an approximate reference. Although this master gave some importance to these references, it is possible that the final shape resulted from maintaining the curvature of the courses and their beginning from the diagonal lines.

The Mexican master Flores controlled the advance of the courses guided only by his intuition and visual control with very precise movements of his body. In fact, he noted that two masters of different heights working in sectors of the same vault often have coordination problems. There was no material reference to control the shape of his vault. Flores knew from experience the inclination that he should give to the first bricks and the aforementioned warping of the course.

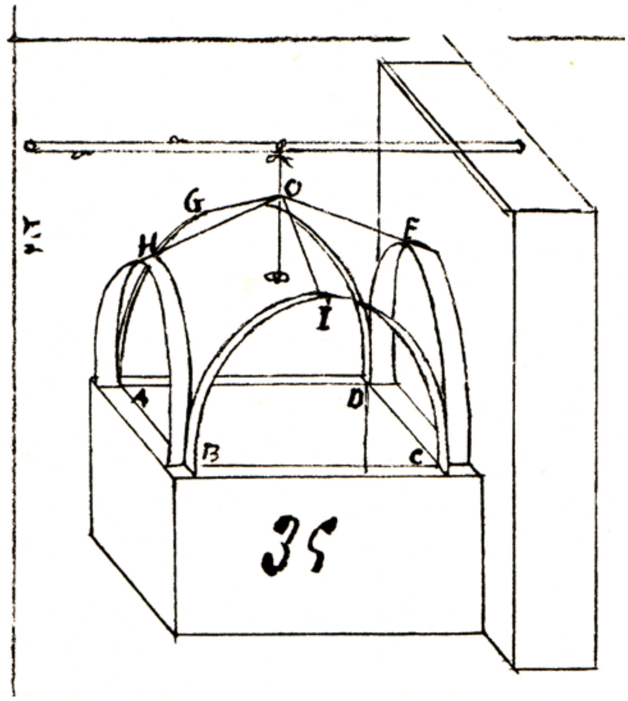

Figure 9. Ropes for work control in Paredes (1883).

Conclusion

The statements that we have collected from expert operators in these constructions tend to give great importance to intuition for the correct location of the bricks, for making the mixture, placing the brick, and controlling the general shape. On the other hand, nineteenth century texts dealing with vaults by slices in Spain make statements that tend to conceive the explanations of the processes and forms in a strongly idealized way, and often confusing. Consequently, direct experimentation is necessary to confirm the ways of doing things and their possible variants. On the other hand, we cannot conceive this construction system as immutable, since each detail of the process admits variants that can easily change over time.

Building brick vaults by slices has given us the opportunity to verify details of the laying process. For instance, when placing a brick, movements parallel to the previous slice must be done in the initial tree or four seconds and then only perpendicular strokes should be made.

The vaults built in central Europe present greater regularity in execution and greater uniformity than the Spanish and Mexican ones, and the possible influence of Byzantine construction in the Mediterranean area remains to be studied.

Acknowledgements

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