Geometry and Actual Construction in Brick Vaults by Slices: The Case of Carranque in Spain

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Abstract
This paper deals with the study of a rectangular plan sail vault built by brick slices in the Roman villa of Carranque in Spain in the fifth century, in the context of a research project on the constructive configuration of Mediterranean vaults of this kind. The project aims to identify technical links to trace their expansion and examine the possibilities of using this technique in present-day building practice. The case at Carranque confirms the arrival of this vaulting technique to the Iberian Peninsula prior to a possible diffusion through the Arab world. The analysis of a 3d photogrammetric model of the remains allows posing that the solution used to solve the slices meeting at the diagonal is different from Byzantine ones: the large perimetral arches were lowered, almost matching the height of the small ones, and a vertical area was placed, being arranged as if it were part of the vault itself. With this design, it is not easy to notice the rectangular form of the vault.

Keywords Brick vaults · Pitched brick vaults · Vaults by slices · Roman villa of Carranque · Construction history

Introduction

There are three main ways of arranging bricks in a barrel vault: radial brick, with beds radially aligned with the vault axis; tile vaults, with beds facing the intrados, and vertical or pitched brick, with beds vertical or slightly pitched (Fig. 1).1 This paper deals with the third one, which is a traditional technique. There is not an English single word to name the system, so in this paper the term by slices is used, as a direct translation of the French and Spanish terms per tranches and por hojas, to refer to the whole technique. During construction, each new element is supported

1 Tile vaults are also known as timbrel vaults and in folio vaults. The Spanish term for this technique is bóvedas tabicadas.

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by the adhesion of mortar and brick, aided in the pitched cases by the inclination of the previous slice, and no formwork is needed.

The oldest examples of vaults by slices, made with adobe, are documented in the Middle East and Egypt from the thirteenth century BCE on, and most frequently they correspond to barrel vaults with inclined adobe slices. The Eastern Roman Empire used this technique with brick profusely and spread it throughout the rest of the Mediterranean basin, but it was also disseminated across the Arab world (Almagro 2001, 2022). From Spain and Portugal, it moved to the New World, and this tradition is still alive today, especially in Mexico. A number of cases of brick vaults by slices are known, but their possible connections remain unstudied (Rabasa et al. 2021).

The present work is part of a research project about the historical construction technique of brick vaults by slices. It focuses on analysing the constructive configuration of the existing cases to identify technical links and trace their dissemination. At the same time, it aims to assess the possibilities of including this technique in current building practice. The system reached its zenith in the Byzantine vaults, which show a great variety of shapes and brick arrangements and might be the result of a simple and powerful construction system, probably with no formwork. That’s why they are the project starting point. The formal and constructive configuration of Byzantine vaults has been studied by Choisy (1876, 1883), Lancaster (2009, 2010, 2015), Huerta (2009), Karydis (2012) and Vitti (2014, 2016), but an in-depth analysis based on precise surveys of the preserved examples is still pending.

This paper studies a rectangular plan sail vault of brick slices existing in Spain in the Roman villa of Carranque (Toledo), in the context of other known examples of this type (Fig. 2). The original layout of both general shape and brick arrangement has been determined, in order to later be able to link case studies. The analysis methodology is based on a rigorous data collection of the preserved remains by automated photogrammetry, specifically carried out for this paper, to generate a precise three-dimensional model allowing a study of the formal and constructive configuration of the vault. The survey was carried out using Metashape V-1.6 for automated photogrammetry and Rhinoceros V-6 for postprocessing. 159 photographs were used for a model representing the front wall and 29 images for the vault details. In order to orient and scale these digital models, 6 reference points on the perimeter of the front wall were taken, gathering coordinates with a total station with a nominal precision for distance measurements of 2 mm + 2 ppm. When assigning the coordinates to the reference points Metashape adjusts them by least
squares; the average error in this operation was 0.0049 m for the model of the front wall and 0.0035 m for the one of the vault details. Since the reference points are located on the perimeter, the positional error of a point is estimated to be below 0.0049 m in all cases.

Since the lower walls are preserved, the form of the plan can be safely determined. In addition, one of the small arches is also standing as well as the springing of the vault, including part of one of the large arches. With these data, a hypothesis on the vault general form has been posed. Regarding constructive configuration, the intrados of the preserved slices has furnished fundamental information. Furthermore, because of the previous collapse of a large part of the vault, the ruins partially show the internal configuration of the slices and studying the bed directions has been possible.

**Brick Arrangements in Sail Vaults by Slices**

Brick vaults by slices in complex forms, rather than barrel vaults, were mainly used in the eastern part of the Roman Empire, and specially to build sail vaults – that is, vaults with spherical intrados on polygonal plan – that appeared exactly in that
area. The earliest known sail brick vault was built with circular horizontal courses of mud brick in one of the houses of Soknopaiu Nesos in Egypt at the end of the first century CE. There are also cases in Karanis, Epidaurus and Ephesus in the second century CE, Thessaloniki and Gamzigrad in the third, Side at the early fifth or Hagia Sophia Cistern in the sixth (Lancaster 2015, WebCat4). However, in the western part of the Empire, the vault at Carranque is so far the only documented example prior to the middle of the fifth century (García Entero et al. 2017: 150).

Most frequently, brick arrangements forming these early sail vaults feature courses according to vertical arches parallel to the plan sides (Karanis, Epidaurus, Istanbul, as well as Carranque) (Fig. 3). But there are also cases with brick slices parallel to the diagonals, or a mixture of both systems (Ephesus, Terrace Houses 2 and 1, Lancaster 2015, 82 and 79). Focusing on the first type, and according to Choisy, bricks in each slice align their beds with the centre of the vault, forming cones that become more open and flattened as they approach the upper part of the vault (Choisy 1883). An arrangement of the slices according to horizontal circles of the sphere could be framed in this system, but also in the radial one.

If the sail vault plan is not square but rectangular, the vault is not symmetrical about the diagonal, and perimetral arches have different spans (Fig. 4). If the course width, including brick row and mortar, is fixed in two facing sectors of the four defined by diagonal planes, the perfect geometric solution gives a different width for the remaining two. As a consequence, given that brick size cannot be varied, either the mortar width or the brick arrangement must solve the problem (Fig. 5).

Four different solutions have been identified in built examples solving the sectors meeting when the plan is rectangular (López-Mozo et al. 2021). If the plan proportion is not too far from a square, the problem may be solved by adjusting

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Fig. 3 Sail brick vault by slices parallel to the plan sides in Basilica Cistern, Istanbul, sixth century CE. (Photograph by the authors, 2015)
**Fig. 4** Sail vaults on square and rectangular plan. (Image: authors)

**Fig. 5** Different courses width in a rectangular plan sail vault arrangement by courses parallel to the plan sides. (Image: authors)
the mortar joint’s width. Focusing on more general solutions, a first option to solve the problem is to counterbalance the courses by matching two or three from one side, to one from the other. This solution may be appreciated in Basilica Cistern (sixth century) or in the Mezquita de las Tornerías in Toledo (twelveth century). This arrangement constrains the meeting of the courses, which can deviate from the diagonal (Fig. 6a). Another option is to build slices parallel to the plan sides, that meet along a line forming 45° in plan projection with the perimeter and are crowned with a rectangular “keystone” (Puerta del Sol in Toledo, fourteenth century). The meeting line deviates from the plan bisector, as the courses coming from the short side of the plan are placed in the sphere at a lower position than the ones they meet (Fig. 6b). However, the solutions to this problem found in Byzantine vaults frequently show a different alternative. They often have two side stripes with a single direction of slices, which leave a central square area that is easily built with four equal sectors. This solution is present in the cisterns at St Demetrius in Thessaloniki (third century) or in Haghia Irene in Istanbul (sixth century) (Choisy 1883) (Fig. 6c). There are also cases where two of these options are merged: in the palace of Galiana in Toledo (fourteenth century), courses are counterbalanced and, also, side stripes are placed, although they do not reach the point that would leave a central square.

The Vault at Carranque

A fragment of a sail vault on rectangular plan built by brick slices parallel to the perimeter is preserved in the Roman villa of Carranque in Spain. Archaeological dating ensures that it was built before the middle of the fifth century CE (García Entero et al. 2017: 150). No other vaults of this type from the Roman era are so far
documented in the Iberian Peninsula, but there are a many later cases in the southern two thirds since the ninth century CE, especially in Toledo since the twelfth century (López-Mozo et al. 2021), in Extremadura and the Portuguese Alentejo from the fourteenth to the nineteenth century, being still extant there in the twentieth century (Sánchez Leal 2000), and there are also a lot of cases in the area of Ciudad Real (Molero-García et al. 2022) and Murcia (Natividad-Vivó et al. 2021).

The available archaeological studies and the specifical survey carried out for this paper give a rectangular plan for the vault preserved at the Palace ruins (García Entero and Vidal Álvarez 2012: 137). The analysis of the three-dimensional data of the preserved remains allows confirming that there are differences between the theoretical sail vault on this rectangular plan and the actual built vault. The general form matches the theoretical one, but the large arch located on the long side of the plan is lower than it should be, and the vault presents a vertical area, between the actual springing of the vault, which is at a higher level, and the arch below (Fig. 7). The contour lines of the vault clearly show that vertical part of the vault (Fig. 8). The general form is then made of a vertical area between a lower arch and the canonical one, which is arranged as if it were part of the vault itself, and a spherical intrados (Fig. 9).

Regarding the brick bonding, a careful execution may be appreciated since bricks at the diagonals have been cut to match the adjacent course (Fig. 10). The general arrangement shows two different areas. In the vertical part bricks in each course

Fig. 7 Three-dimensional data from the photogrammetric model, together with the main lines of the sail vault shape. Theoretical sail vault perimetral arcs are drawn in red colour. (Image: authors)
form cylinders (what might be described as a “hidden tile vault”). In the vault itself brick beds seem to match Choisy’s hypothesis, forming revolution cones. In order to check the existence and configuration of these cones, on the three-dimensional model the best-preserved areas of the brick beds have been chosen, selecting surveying points on them. Then the planes best fitting these points have been traced and extended until meeting the horizontal plane at the centre of the vault. It has turned out that 90% of these planes are less than 20 cm away from the centre of the rectangle of the vault springing. As a consequence, it can be confirmed that the vault is formed by slices following revolution cones with their vertex near the centre of the plan (Fig. 11).

The problem of the sectors meeting derived from the rectangular form of the plan had to be solved in a specific way in Carranque. The solution of counterbalancing the courses by adjusting two from one side to one from the other, is not present in the preserved remains. The option of building rectangular courses meeting at a line forming 45° in plan is neither used. Attending to each
sector, joints width seems to be slightly different: they feature an average value of 2.6 cm at the short sector and of 2.2 at the large one. This difference helps to solve the rectangular plan problem. Moreover, vertical slices on the large side of the plan, which are coordinated with the first slices on the short arch, also help to solve the rectangular plan. These first slices on the short arch would be a kind of side stripes that can hardly be appreciated, as they are coordinated with the slices of the vertical part. It might be the reason for the position of the meeting of courses at the diagonal, which seems to be moved forward, and it is not actually matching the diagonal plane of the rectangular plan, drawn in red colour in Fig. 12. Most likely, the first three slices on the short arch, which have been highlighted in white colour in Fig. 12, reach the vertical plan on the large arch.
matching the corresponding first three slices in that part, which are highlighted in light grey-colour in Fig. 12. Subsequent vertical slices on the large side of the vault pass the “sail vault” perimetral arc and get into the spherical part, adapting their form from a plane to a sphere. Consequently, the slices of this area are not parallel to the long side of the plan; they have been highlighted in black colour in Fig. 12. These slices would form a third zone in the brick arrangement that would reach up to the keystone of the large arch.

Front stone wall and double radial brick arch would be first built. Then, the first three slices in both sides – the right ones vertical – would be built. The three left slices match the vertical area; they do not stop at the diagonal but are extended until reaching the vertical plane. From the fourth course on, vertical
slices on the large side of the vault pass the arc that limits the “sail vault” and get into the spherical part, adapting their form from a plane to a sphere (Fig. 12).

**Conclusion**

The vault at Carranque shows formal and constructive solutions that address real construction problems that geometrically pure solutions are unable to solve, especially those derived from irregular boundary conditions, among which the existence of a rectangular plan must be included. The architects at Carranque might have made specific decisions regarding the configuration of perimetral arches. A sail vault with a rectangular plan features semicircular perimetral arches reaching different heights; although they start from the equatorial plane, their diameters equal the different lengths of the plan sides. The solution used at Carranque to solve the rectangular plan might have been starting the vault on the long sides on an arch placed at a lower level, and then following a vertical plane. This strategy allows matching those vertical slices on the long side with the first slices on the short side, and it is not easy to appreciate the rectangular form of the plan, which is evident in the other three ways of solving the problem. It may be noticed that the actual sectors meeting is moved forward because of this arrangement and does not match the diagonal plane (Fig. 12). The arch placed lower, almost matching the height of the small arch, also helps to conceal the rectangular form of the plan, because both arches looking so similar make the vault to be perceived as if it were built on a regular square plan. This strategy of raising the small arch or lowering the large one in a rectangular plan sail vault has been found by the authors in other cases and might be encouraged by the idea of simulating a square plan (López Mozo et al. 2011: 745–746). A slight difference in mortar width, thicker on the short vault sector, would also have helped to solve the plan rectangular form at Carranque vault.

The presence of this vault in a Roman villa of the fifth century in Spain confirms the arrival of this vaulting technique to the Iberian Peninsula before a possible diffusion through the Arab world. Furthermore, its constructive arrangement with conical beds directed towards the centre of the vault is clearly Byzantine. In contrast, the solution used to solve the rectangular plan is different from those existing in the examples of the eastern part of the Empire. In addition, brick bonding seems to be not so carefully done in Byzantine vaults as in Carranque, where there is a complex conception of the vault – with a perfectly integrated vertical part – and a very careful execution, since the bricks at the diagonal have been cut to match the adjacent course (Fig. 13). The relative size of brick and mortar is also different from Byzantium vaults. This careful construction process at Carranque is especially relevant if it is considered that Roman vaults and walls were usually plastered. In any case, checking formal and constructive configuration of Byzantine vaults demands a specific survey that is intended to be carried out in future research.
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