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RESEARCH

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The Singular Brick Vault by Slices in Tower J17 from the Aurelian Walls in Rome

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Abstract
The lower chamber of tower J17 from the Aurelian Walls in Rome is covered by a singular brick vault by slices that is almost completely preserved. This kind of vault is unusual in a Roman context and specifically in Aurelian Walls. Brick vaults by slices were extensively studied by the French engineer Auguste Choisy, who mainly scrutinized their ease of construction that doesn't require formwork and can adapt to different plans to achieve lowered vaults. The best-known examples are in Byzantium and generally in the Eastern Roman Empire, while we don't know many cases dating from late Roman antiquity on the Italian peninsula. Based on a rigorous photogrammetric survey and thorough data management, a detailed analysis of this vault allows us to establish a hypothesis about its construction process and to deepen the knowledge of this type of structure.

Keywords Brick vault by Slices · Aurelian walls · Geometrical analysis · History of construction · Hypothetical model

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Introduction

Brick vaults by slices derive from a specific construction technique, directly related to their geometry. The bed or main plane of bricks is not arranged in a radial position but perpendicular to the vault axis. Each brick slice is built at one time, and it becomes self-supporting, as bricks are held by the adhesion of mortar to the previous slice. This technique makes it possible to carry out the entire construction without formwork and to adapt the vault to different shapes. Scientific terminology identifies this type of vault in different ways, always referring to the brick arrangement by slices (Fig. 1).

The earliest examples of brick vaults by slices date back to 13th century BC and were built in the Middle East and Egypt, whence the technique later spread through the Mediterranean Basin. There are several examples from the 4th century AD in the area later belonging to the Eastern Roman Empire (Lancaster 2015). In the Western Roman Empire, and specifically the Italian Peninsula, only a few examples of brick vaults by slices can be found, whereas cases in Spain and Portugal exist that date back to the 12th and 13th centuries (Rabasa et al. 2021; López-Mozo et al. 2021).

This work is part of a larger research project on brick vaults by slices aimed at studying historical examples to establish possible current uses of this specific construction technique. In this context, we analyzed a singular case of brick vault by slices from the Aurelian Walls in Rome (Aliberti et al. 2023). The study is based on the direct observation of the vault and an accurate survey carried out through automated photogrammetry. We had the opportunity to visit the vault thanks to the collaboration and the availability of the Capitoline Superintendency of Cultural Heritage of Rome.

The methodology used to manage the survey data is directed to analyze the geometry of the vault by studying both the 3D model and the derived products like section lines, orthoimages, contour lines. By working on curves and points critically extracted from the surface, we could approach the analysis of the general shape and the brick arrangement, that is essential to study and try to understand geometrical and constructive issues. Finally, this analysis aims to determine the geometry of the

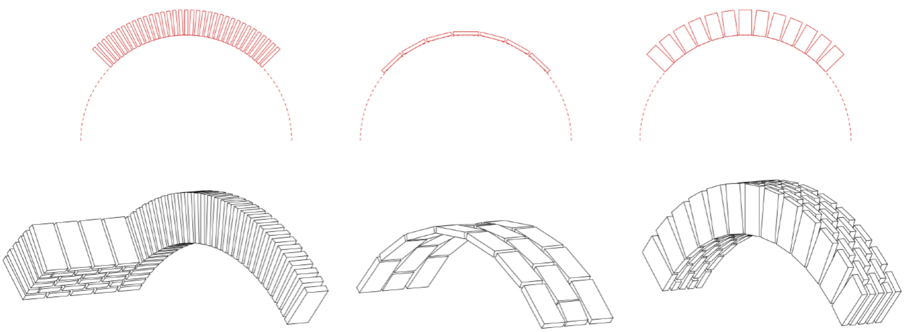

Fig. 1 Example of brick barrel vault in different building systems: (**a**) radial bricks; (**b**) timbrel vaults (or tile vaults); (**c**) brick vault by slices (*par tranches*, *por hojas*, *pitched bricks*, *a mattoni affiancati*). Image: authors

vault through the reconstruction of a hypothetical model and its comparison with the theoretical model of brick groin vault by slices.

The Roman Context

The research focuses on a singular example of a brick vault by slices in the Roman context that belongs to the extensive circuit of the Aurelian Walls in Rome. This enormous intervention had different building phases. In 271–275 AD Aurelian ordered the construction of the first circuit with an almost 19 km long wall and around 400 towers. Later minor interventions were carried out by Maxentius during his reign (306–312 AD), while a major restoration was undertaken by Honorius between 401 and 404 AD (Cozza 1987: 47; Dey 2017: 13). The present case study is a vault in a tower marked J17, following Richmond's classification (Richmond 1930: 269), in the section from Porta Metronia to Porta Latina of the Aurelian Walls (Fig. 2). It is difficult to establish the exact construction date of the vault, as it seems to be a specific restauration of the preexisting structure. However, it can probably be dated later than Honorius' works that aimed at elevating the artillery firing platform and transforming the towers to obtain two stacked chambers, generally connected by an internal staircase. The thickness of the wall was almost doubled and the original height of approximately 7–8 m was increased by almost 6 m, creating a new covered gallery with a system of barrel vaults (Dey 2017: 16). The new towers had two covered levels with an eight-sided pyramidal vault in the upper chamber and a barrel vault in the lower chamber (Cozza 1987: 39; Esposito et al. 2017: 127). All these vaults were built in Roman concrete, a technique that allowed for easy and fast construction. The

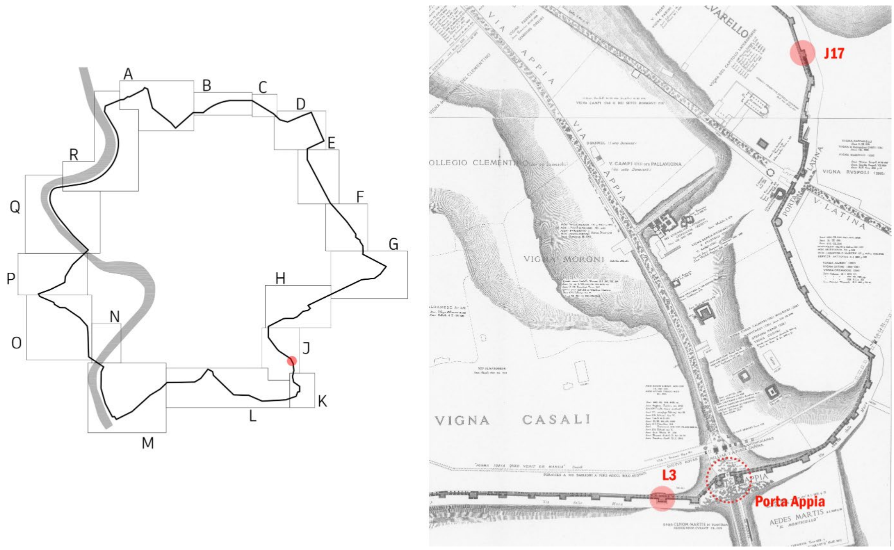

Fig. 2 (**a**) Circuit of Aurelian Walls based on Richmond's classification and Mendri's graphic restitution. Image: Richmond 1930: 269; Medri et al. 2016; (**b**) tower J17, tower L3 and Porta Appia reported in the *Forma Urbis Romae*. Image: Lanciani 1893-1901: Tav. 42

need to carry out this large-scale military construction in a short timeframe led to the choice of traditional and well-tested building techniques. Only the two examples of the vaults in the lower chambers of towers J17 and L3 are different, and they were probably built by Aegean builders with expertise in constructing brick vaults by slices (Cozza 1987: 43; Vitti 2013: 110).

After Honorius' works, other interventions were carried out by Valentinian III, probably after the 442 AD earthquake, and by Teodorico in 500 and 507–511 AD in Porta Appia (Mendri et Pallottino 2015: 11), that is located between sector L and K. It would be useful to establish any relationships between these interventions and the construction of the brick vaults by slices of towers J17 and L3, but so far, insufficient data exists.

The L3 tower contains a brick groin vault by slices of considerable size but in a poor state of preservation, whereas the vault of the tower J17 is almost entirely preserved (Figs. 3 and 4). Its geometry is similar to a groin vault, which was unusual in Roman buildings, as the sail vault was the most common type built with this technique (Lancaster 2015: 71–72). An example of Roman brick sail vault by slices is preserved in Spain in the villa of Carranque. The remaining fragments of the vault provide enough data to reconstruct its general shape and specific brick arrangement, aimed at adjusting the sail vault to a rectangular plan (López-Mozo et al. 2022).

The vault of tower J17 can be related to the type named by Choisy (1876: 443; 1883: 49) as a groin vault by slices (*per tranches*) (Fig. 5). In this theoretical model the springing arches on the sidewalls and the diagonal lines are circular-based. This kind of vault is suitable for both square and rectangular plans, unlike the classic groin vault which fits square plans and has elliptical curves on the diagonals. Moreover, this construction system allows low vaults. In this specific case, the tower J17 is located at a change of ground level (Fig. 3), therefore the possibility of creating a vault much lower than the barrel vaults is an evident advantage, probably aimed at obtaining the two chambers found in the rest of the towers of the Aurelian Wall. Brick constructions without formwork can adapt to complex geometries by adjusting the arrange-

Fig. 3 Views of the tower J17 from the exterior (**a**) and interior (**b**) side of the Walls; (**c**) Section of the vault with reconstruction of the tower based on Vitti hypothesis. Image: authors based on Vitti 2013: 140

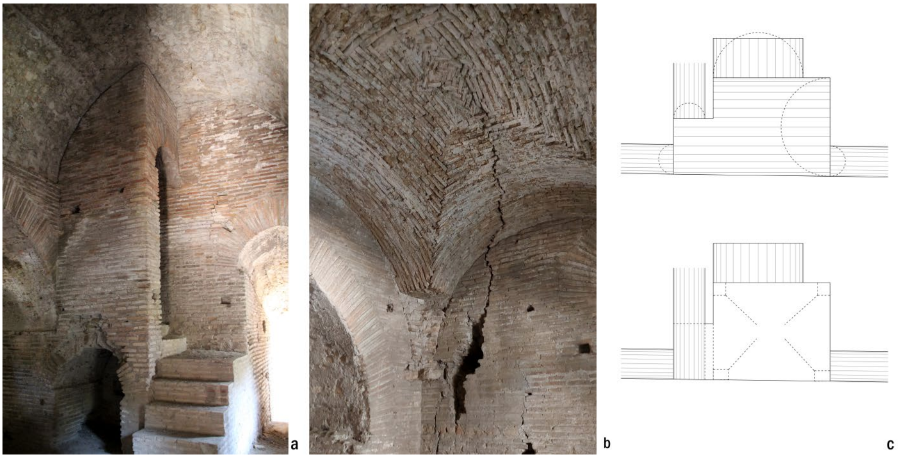

Fig. 4 (**a**) Lower chamber of tower J16 with typical concrete barrel vault; (**b**) Lower chamber of tower J17 with groin brick vault by slices; (**c**) comparison diagram between the standard solution like J16 tower (**a**) and the different vault of the tower J17 (**b**). Image: authors

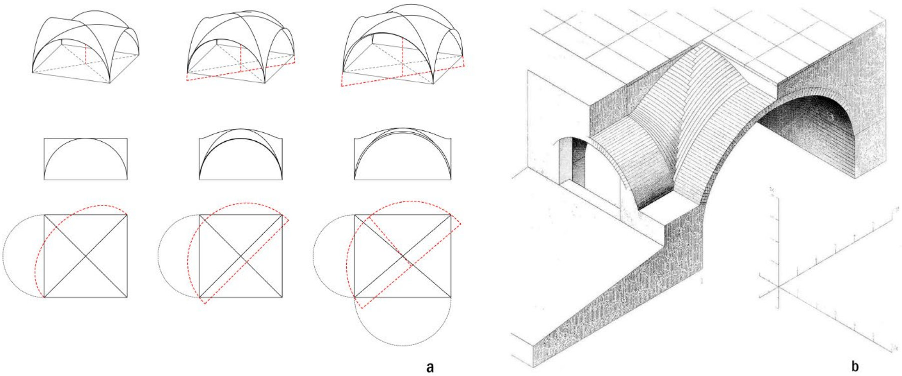

Fig. 5 (**a**) Diagonal layout in classical and Byzantine groin vault on square and rectangular plan (drawings by the authors); (**b**) Groin vault by slices in the Narthex of Hagia Sophia at Istanbul, 537 AD. Image: Choisy 1883: pl. XI.1

ment of the bricks and mortar wedges, in contrast to ashlar masonry, where the form of individual pieces determines the general shape (Calvo-López 2020: 2–3). We find examples of brick groin vaults by slices on rectangular plan dating back to the 4th century AD in the narthexes of Hagia Irene and Hagia Sophia in Istanbul. They both cover rectangular plans, and they are shaped like groin vaults with a rounded closure (Choisy 1883: pl. XI.1; Vitti 2013: 109).

Geometrical Analysis of the Vault

General Shape

The vault of tower J17 covers an essentially rectangular space measuring 4.16×3.5 m, or approximately 14×12 Roman feet (ft). The conversion of measures is based on the Roman foot value of 0,296 m (Lugli 1957: 189), making a minor under-approximation of 0,003% (14,05 to 14) on the long side and a slightly larger over-approximation of 0,015% (11,82 to 12) on the short side of the room. These dimensions refer to the main axes centered on the rectangular layout, as the actual plan is not exactly rectangular. Three of the sides are orthogonal to each other, and the fourth side has a slight deviation (0,76°) aligning with the direction of the connection path between the towers (Fig. 6).

The vault had impost blocks at the corners, consisting of marble plates set into the walls and resting on a brick base, likewise set into the masonry wall (Vitti 2013: 103). They have different shapes to adapt to specific conditions: while the two ones on the external side of the tower are square, the other two ones are rectangular so as not to obstruct the passage along the path connecting one tower to the other. If we consider the distances between these blocks, it results in a better approximation of Roman ft values: 11 in the long side with an under-approximation of 0,003%

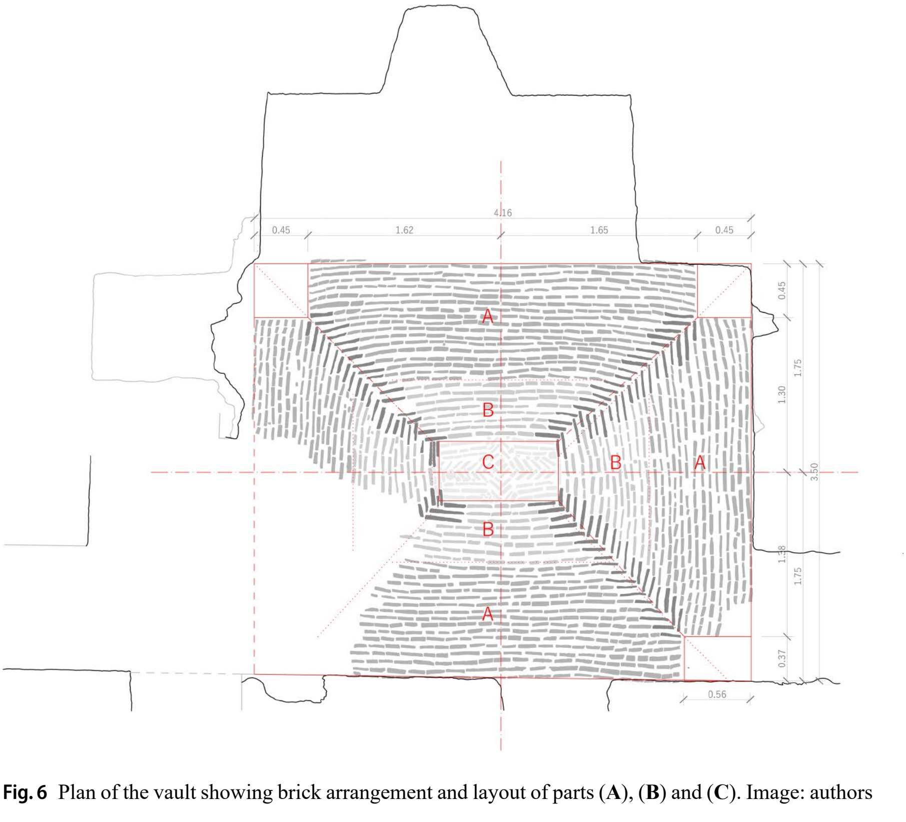

Fig. 6 Plan of the vault showing brick arrangement and layout of parts (**A**), (**B**) and (**C**). Image: authors

(3,27 m = 11,04 Roman ft) and 9 in the short side with an under-approximation of 0,005% (2,68 m = 9,05 Roman ft). Moreover, the side of the square blocks measures 0,45 m, which approximately corresponds to 1 ½ Roman ft (1 ½ pedes = 1 cubitus), while the rectangular ones seem to adapt to the dimensions of the long and short side of the vault. This suggests that the builders applied design principles to somehow control the irregularities of the room in the construction of the new vault.

The impost marble blocks were lost without substantial damage to three of the vault side arches. At the fourth side, the vault started from a segmental rampant arch that is currently collapsed along with that part of the vault. That arch separated the brick vault from the Roman concrete barrel vault that covered the flight of stairs leading to the upper chamber and was probably a weak point of the structure.

The general shape of the vault relates to the theoretical model of Byzantine groin vault by slices described by Choisy (1883: 49–58). Byzantine builders avoided the elliptical curves on the diagonals and generated revolution surfaces in the four sectors fixing a common center for the axes of revolution. This construction process leads to the progressive loss of the diagonal edges when approaching the central part while forming an inflection in the cross sections close to the perimetral arches. The vault of the tower J17 shows many similitudes to this theoretical model. The three remaining diagonal lines of the vault fit to circumferential arcs with an average radius of 3,06 m, 2,76 m, and 3,15 m, measured from the corners of the impost blocks to the corners of the rectangle in the central part. This is an important element of similarity with the theoretical model of Byzantine brick groin vaults by slices, although the vault does not exactly match the type described by Choisy. The curves in the cross sections don't present the characteristic inflection of the theoretical model of Byzantine groin vaults, as the first part of the vault must here be adapted to the design of the corner blocks. Indeed, the surfaces of the three remaining sectors aren't revolution surfaces, but they show a more complex geometry.

The studies carried out by the authors led to the identification of three segments of the general shape. The first one (A), near the side arches from which the vault was built, shows a cylindrical geometry. The second one (B) is a transition segment that connects to the central part (C) which has a distinct shape that can be described as rounded, although it does not exactly fit a spherical surface. The analyses were based on the layout of the springing curves, diagonal curves, transverse sections, and longitudinal sections of the vault, drawn from automated photogrammetry model data (Fig. 7). Partially collapsed sectors were excluded from the study of the general shape, as they may have undergone displacements and deformations. On the other hand, this zone of the vault has been very useful for the detailed study of brick arrangements.

In Part A of the vault, during the first meter from each side of the rectangle, the vault sectors describe upward cylinders. The springing curves are circumferential arcs with an average radius of 1,55 m on the conserved short side of the vault, 1,89 m on the long external side and 1,69 m on the long internal side. The radii and height of centers of these circumferences adapt to the design principles fixed by the corner blocks. The cylinders' slopes are very similar in both directions (8.4° – 8.9°). There is a difference of 12 cm between the rise of the perimetral arches of the short and long sectors, probably designed to reach the same level using the same slope. The first

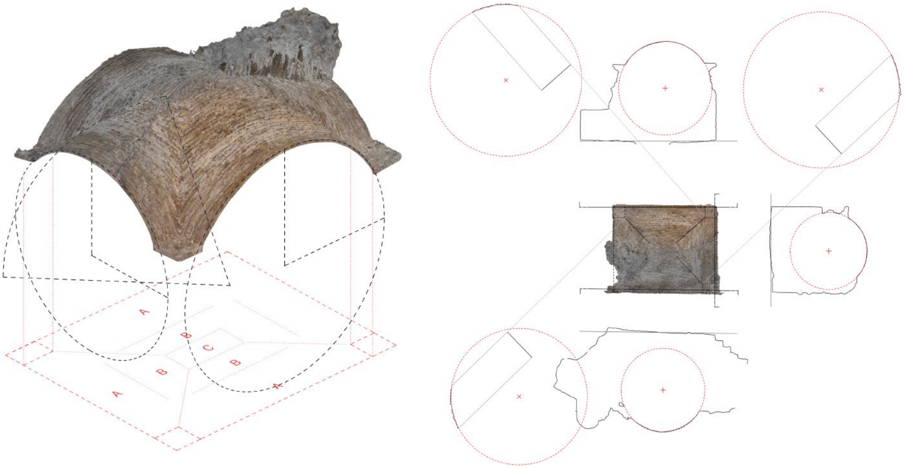

Fig. 7 Photogrammetric model with circular-based springing arches and diagonal lines and layout of the springing arches and diagonal sections. Image: authors

slices of the upward cylinders have the bricks at the ends slightly turned to adapt to the horizontal plane of the impost blocks.

The central closing of the vault, previously named Part C, has a clearly defined shape, and while not spherical, resembles a rounded vault on four segmental circular-based arcs. This part has a higher level than the crowns of the perimetral arches, as in the Byzantine groin vault described by Choisy (1883: 54), and can be related to 'pitched-brick dominical groin vaults' described by Karydis (2011: 168). Part C covers a 2:1 rectangle of 1,02 × 0,5 m and meets the diagonals that start from the impost blocks. Its perimeter contains four arcs whose radii and upper points are clearly linked. The radii of the cross and longitudinal sections measure 1,22 m and 0,59 m, showing a ratio of approximately 2:1. This confirms that the surface is not spherical. Moreover, the central part shows a different arrangement of the bricks, very similar to the central solutions of the rectangular vaults in the narthex of Hagia Sophia at Istanbul. Therefore, it was probably a predefined design or a common model for the builders. In addition, the center of the main arc is noticeably set on the same horizontal plane as the spring line of the diagonal arcs of the vault, which points out a purpose to relate the design of the vault to the pre-existing structure (Fig. 8).

There is a transition area between these two well-defined parts, previously named Part B. It starts tangent to the cylinders of Part A and rises in elevation with a curvature opposite to that of Part C, for an extension of ca. 0.50 m on the short sides and 0.76 m on the long side. The brick slices maintain their conical shape and radii similar to those previously built, but instead of forming a cylinder, they become increasingly tilted to gently join the central part.

Brick Arrangement

Concerning the analysis of the bricks, a certain variety of sizes can be observed throughout the rest of the vault. According to Vitti (2013: 103), the bricks used were

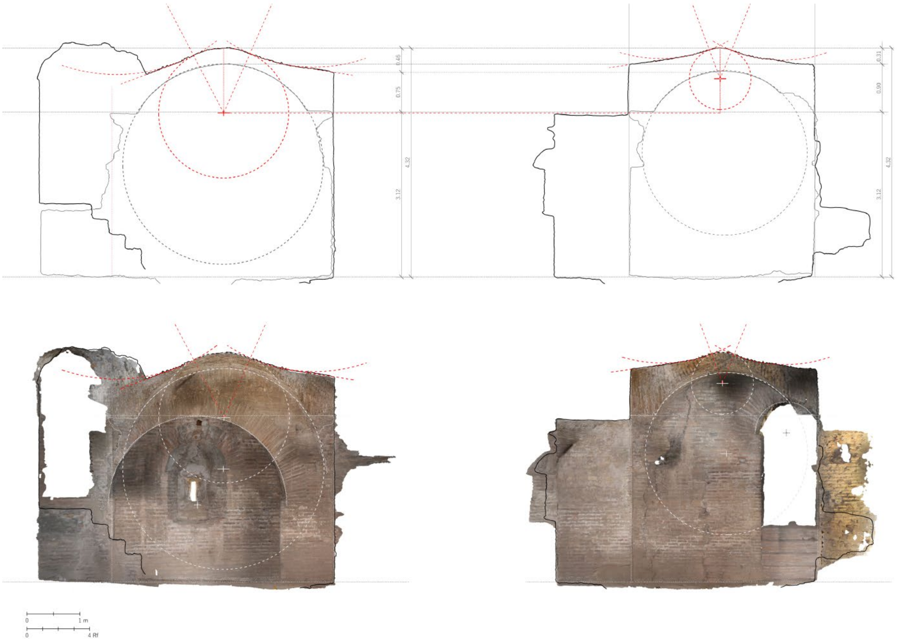

Fig. 8 Transverse and longitudinal sections with geometrical analysis of the general shape of the vault. Image: authors

newly produced *pedales* cut in half. The side dimension of this kind of square brick was 1 Roman foot, 29,6 cm, and they were usually cut along the diagonal lines with a small loss of material in the cutting process (Lugli 1957: 585). In this case the bricks are cut in half along one of the axes to create two rectangular pieces of approximately 1/2 by 1 Roman ft in size. Calculations of brick dimensions based on the photogrammetric model corroborate this hypothesis to some extent. We registered the exposed faces and thick dimensions of 135 bricks, classified belonging to parts A, B and C, with special attention to the three diagonals conserved, and we calculate the average values. The thickness of the bricks is close to 3 cm, while the length of the exposed faces ranges from ca. 14 to 32 cm. That suggests some of the bricks have their header face exposed and others their stretcher face. It has been verified that those near the diagonals, particularly in the first segment (A), were laid with their stretcher face downward. That eases the encounter between sectors, as the shorter the depth is, the less that must be cut off from the encountering pieces.

The observation of brick arrangement provides useful information to understand the construction process of the vault. For this purpose, the plan projection of the brick courses has been analyzed, checking for straight or curved lines. This suggests two possibilities: the courses are contained in a vertical plane and may fit into a straight cone, or the courses belong to an inclined plane and may fit into a concave or convex oblique cone. Moreover, we traced the average circumferences that join the points of the lower line of each brick course. The study of the alignment of the centers of these circumferences shows the possibility that some tool would have been used for formal control, such as a tense string or a rigid ruler that could ensure the layout of the revolution surface. In zone A the courses projected in plan are tendentially rectilinear and fit to average circumferences of approximately constant radius whose centers are aligned in a line slightly inclined to follow the direction of the vault profile (Fig. 9). At the ends the courses present a slight curvature necessary to adapt the oblique cylindrical surface to the contact with the corner impost blocks. In Part B the brick arrangement is similar to that of the models described by Choisy (Choisy 1876: 444, pl. 21; Rabasa et al. 2020). Each slice is conically shaped with its concave side downward where its plan projection is slightly curved. In Part C the rectangle that gathers the end points of the diagonal lines shows a specific design following a herringbone pattern that shows similarities with the Hagia Sophia mentioned above. It clearly seems to be a pre-established design for the closure of the vault in which the construction by conical courses is no longer followed.

Another important element is the analysis of the pitch of the bricks in each course and how it changes in the different parts of the vault. This specific study was made possible due to the partial collapse of the vault, exposing some of the brick courses that have been documented in detail by photogrammetric restitution. The pitch of the bricks can be observed in the remaining edges near the collapsed zone, where they appear uncovered. The angles measured along the central line of the vault are approximately 15° from a vertical reference plane during the first meter near the walls and become greater as they get closer to the central part. The angles measured from a reference plane containing the circle defined by the lower rim of each slice are noticeably constant (Fig. 10).

Comparison with the Hypothetical Model

Based on these studies, we can propose a hypothetical model that fits the data. First, we tried to apply the exact theoretical model of Choisy to the vault. We traced a revolution surface fixing its axis in the average line marked by the centers of the circumferences related to the brick courses. This model didn't exactly fit the survey model. The specific conditions given by the introduction of the corner blocks make it rather difficult to apply the theoretical model that Choisy describes for square or rectangular vaults. Moreover, the crowns of the perimetral arches are at different

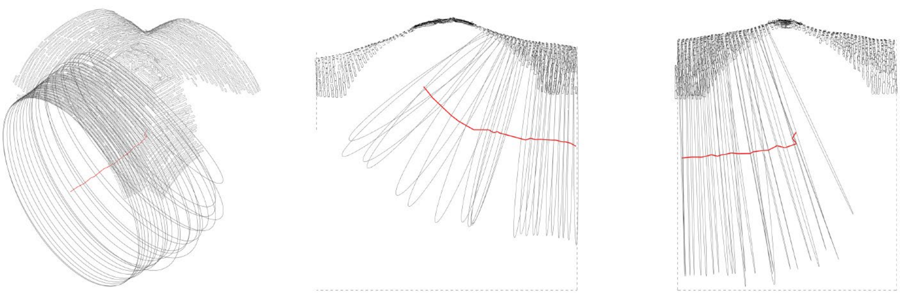

Fig. 9 Analysis of brick slices: average circumferences defined by the lower rim of each slice with constant slope angle in the first sector and continuous line connecting the centers of the circles (possible use of a control tool during construction). Image: authors

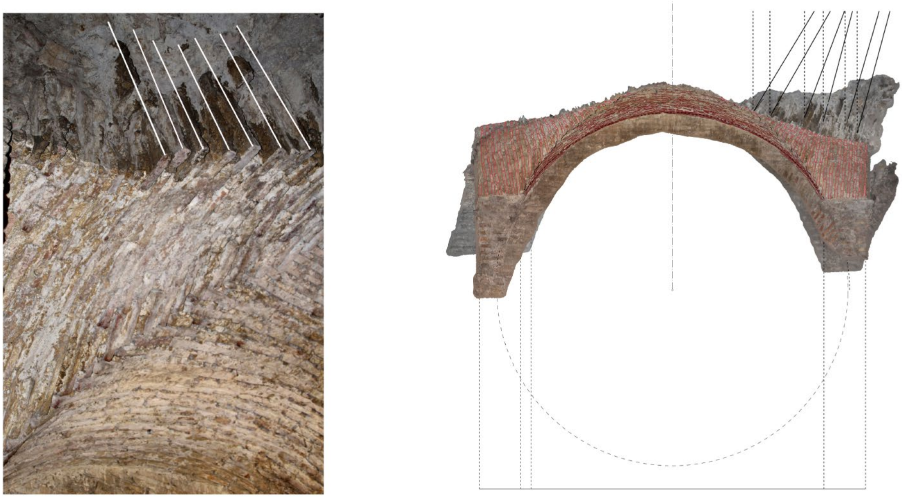

Fig. 10 Brick angles measured along the central line of the vault and photo of exposed bricks in the collapsed zone

heights. Although the difference is just 15 cm, it is significant as the vault is very low. Indeed, the total height between the highest point of the vault and the crown of the major arch is only 46 cm. The differences between the long and short vault sections and the diversification of the conditioning factors make it difficult to fully match the theorical model of the Byzantine groin vault by slices.

On the other hand, the surface can be studied from the curves and points that presumably acted as reference elements during its construction. First, we can state that the starting perimeter arches are circular-based arches, as are the diagonals. The transverse and longitudinal sections are both composed of a straight line and two linked circular arcs, which correspond to the three different parts of the vault. The height of the impost aligns with the crown of the existing arch separating the vaulted space from the tower extension to the outside of the walls. The layout of the arches that rules the vault design is carried out by determining the reference points: the impost blocks and the crowns of the perimetral arches; the diagonals as circular arcs from the corner impost blocks to the central rectangular part; and the upper point of the vault (Fig. 11).

The brick arrangement of the hypothetical model was fixed based on the analysis of the photogrammetric model. In Part A the hypothetical brick courses angle from a vertical reference plane is 15° and then it becomes gradually greater in Part B. In Part C it is difficult to establish the inclination of the bricks, although they seem to become approximately orthogonal to the rounded surface.

The hypothetical model based on these data matches the photogrammetric model. The main curves and the reference points directly coincide, and the direction of brick courses studied in cross sections is very similar (Fig. 12). The contour lines of the surface are very similar in both models, while they differ from the theoretical groin vault model of Choisy (1883: 54–56), which proposes a revolution surface between the circles of the diagonal arcs (Fig. 13).

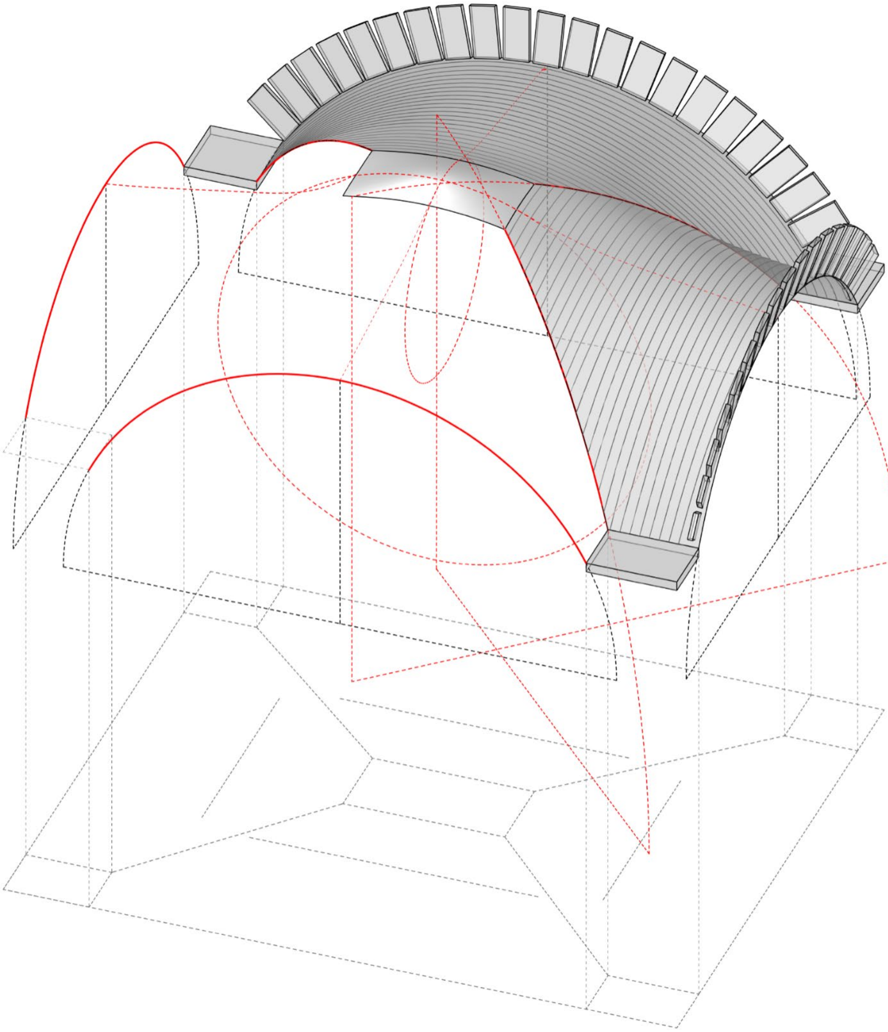

Fig. 11 Hypothetical model based on main curves and reference points with reconstruction of brick arrangement. Image: authors

The hypothetical model shows an easy tracing of the principal curves but a complex surface adjusting to these conditions. The adaptability of the layout of the brick courses without the use of formwork allows the construction of this kind of surface. This singular experimentation with brick vaults by slices in the Roman context shows a direct connection to the specific setting of the vault.

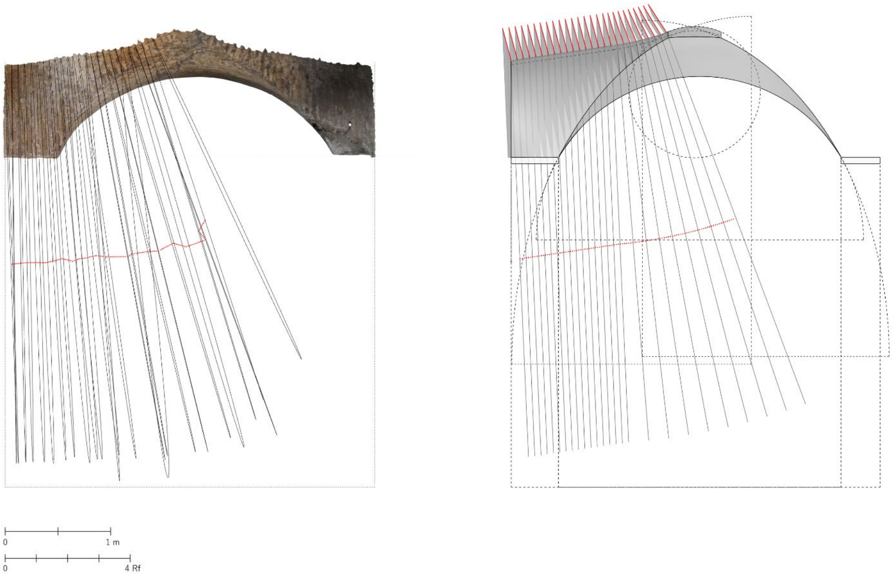

Fig. 12 Comparison of brick slices in the photogrammetric model of the existing vault and in its hypothetical model. Image: authors

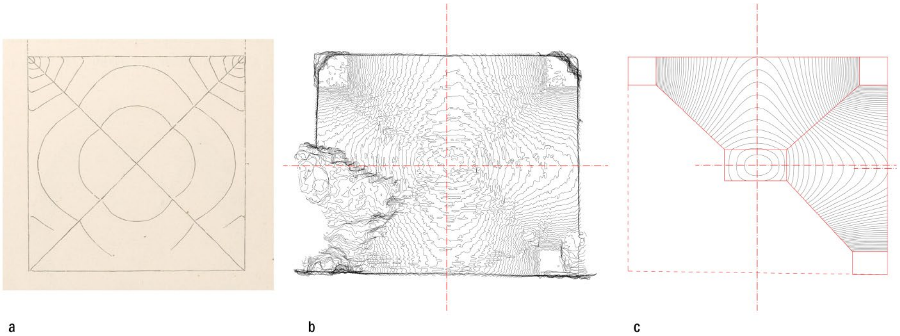

Fig. 13 Comparison of brick slices in the photogrammetric model of the existing vault and in its hypothetical model. Image: authors

Conclusion

Considering the similarities with the Byzantine brick vaults by slices described by Choisy and the uniqueness of the vault of tower J17 in the Roman context of the Aurelian Walls, this study corroborates the already existing hypothesis about the possible intervention of expert Aegean workers in its construction. The execution of the vault was presumably an intervention for restoring or adapting the existing structure and subsequent to the works undertaken by Honorius. If the vault dates to the 5th century, it would be contemporary with some references in Constantinople described by Choisy.

Although it does not accurately match any of the types described by the French engineer, the studied vault features some of its key characteristics, such as the conical-shaped slices and circular-based diagonal arcs. However, the centers of the slices follow an upward line, and the vault shows three different parts: being cylindrical near the springing, round in the center, and with a transition segment between them. The detailed study of the relationship of the surface with its spatial constraints explains the discrepancies from the theoretical model of groin brick vault by slices. The hypothetical model is based on constructive constraints. Builders may have employed some tools for formal control, like a stiff ruler or a tightened string, to follow the circumference arc in the diagonals of the vault and to fix the relationship between the curvature along the short and long axis in the central part. Moreover, in the first part of the vault, the centers of average circumferences described by brick courses are approximately aligned, so we can argue that its builders may have used some tool to adjust brick courses to the pseudo-cylindrical surface.

Starting from simple elements such as arcs of circumferences and reference points, we aimed to discern a building process that enabled the generation of a complex surface with reduced total height and supposedly without formwork. This indicates the adaptability of the system and makes this case even more singular within the Roman and Italian regions.

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Consent to Participate Not applicable.

Consent for Publication Not applicable.

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