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Geometrical Analysis of a Brick Vault by Slices from the Aurelian Walls in Rome

Licinia Aliberti[1] · **Manuel de-Miguel-Sánchez**[2] · **Ana González-Uriel**[1]

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Abstract

This work focuses on the analysis of a singular case of brick vault by slices from the Aurelian Walls in Rome. The study is based on an accurate survey carried out through automated photogrammetry. This analysis aims to determine the geometry of the vault and compare it with the theoretical model of its type.

Keywords Aurelian walls · Brick vault by slices · Brick arrangement design · Geometrical analysis · Hypothetical model

Introduction

Brick vaults by slices originated in the Near East and then spread throughout the Mediterranean basin. However, there are very few examples of this type of vault in the Italian Peninsula, where builders experimented almost exclusively with traditional construction techniques until the end of the late Roman period. This work presents the study of a singular case of a brick groin vault from the Aurelian Walls in Rome. Considering its state of preservation, we can carry out an analysis of the shape of the vault and a detailed study of brick arrangement, as they appear uncovered in a collapsed zone. The geometry of brick vaults by slices is closely linked to their brick layout and intended to optimize the construction process and avoid the need for formwork. The study is based on an accurate survey carried out through automated photogrammetry. This analysis aims to determine the geometry of the vault and compare it with the theoretical model of its type.

✉ Licinia Aliberti
licinia.aliberti@upm.es

[1] School of Architecture, Polytechnic University of Madrid, Madrid, Spain

[2] School of Architecture, University of Alcalá, Alcala de Henares, Spain

The Research

The case study is located 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 in Rome. The vault can probably be dated later than Honorius' works on the Aurelian Walls carried out between 401 and 404 (Cozza 1987: 47). Those works aimed at elevating the artillery firing platform and transforming the towers to obtain two stacked chambers. The new upper vaults of the towers were pyramidal, while the lower vaults were barrel vaults (Esposito et al. 2017: 127). Both forms are easily and quickly built with Roman concrete. Only the two examples of towers J17 and L3 are different, and they were probably built by Aegean builder experts in brick vault by slices construction (Cozza 1987: 43; Vitti 2013: 110).

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 J17 tower is almost entirely preserved. Its geometry is similar to a groin vault, which was unusual in Roman buildings, as the most commonly built type using this construction technique was the sail vault (Lancaster 2015: 71–72).

The analyzed vault can be related to the type named by Choisy (1876: 443; 1883: 49) as a groin vault by slices (*per tranches*) on a rectangular layout, such as those in the narthex of Hagia Sophia at Istanbul (Choisy 1883: pl. XI.1). The springing arches on the sidewalls are circular-based, and the diagonal lines also follow circular arcs. Brick constructions without formwork can adapt to complex geometry by adjusting the arrangement 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). However, the vault of the J17 tower does not exactly match the type described by Choisy. The studies carried out by the authors led to the identification of three segments. The first one (A), near the side arches from which the vault was built, shows a cylindrical geometry. The central part (C) has a distinct shape that can be described as rounded, although it does not exactly fit a spherical surface. There is a transition segment (B) between these two well-defined parts. 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. Partially collapsed sectors were excluded from the study, as they may have undergone displacements and deformations (Figs. 1, 2).

The vault covers an essentially rectangular space measuring 4.16×3.5 m, or approximately 14×12 Roman feet. 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. The main axes of the vault are centered on the rectangular layout, although supports at the corners have different shapes (Fig. 3).

The vault had impost blocks at the corners, marble plates set into the walls and resting on a brick base, likewise set into the masonry wall (Vitti 2013: 103). Those impost blocks were lost without substantial damage to three of the vault

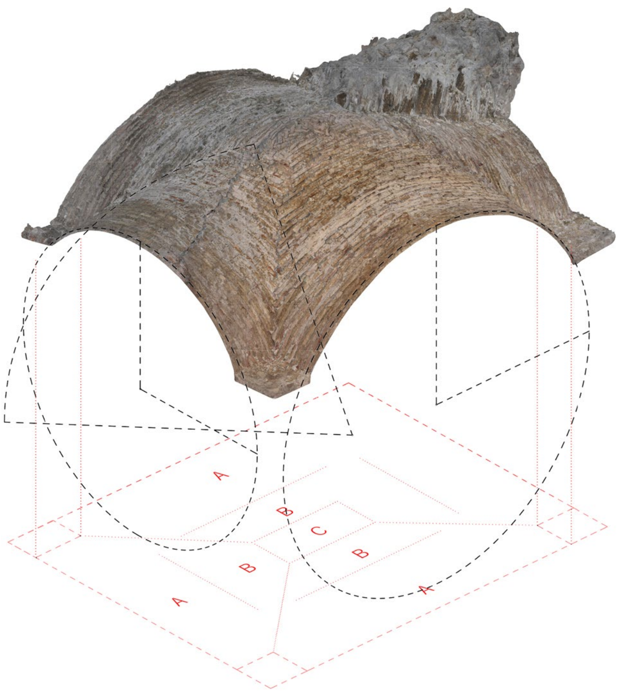

Fig. 1 Photogrammetric model with circular-based springing arches and diagonal lines

side arches. At the fourth side, the vault started from a segmental rampant arch and currently collapsed along with that part of the vault. The 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 (Fig. 4).

In Part A of the vault, during the first meter from each side of the rectangle, the vault sectors describe upward cylinders. Their 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 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, also has a clearly defined shape, not spherical but similar to a rounded vault on four segmental circular-based arcs. This part has a higher level than the crowns of the perimetral arches, so the vault can be related to "pitched-brick dominical groin vaults" described by Karydis (2011: 168). Part C covers a 2:1 rectangle 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 have a ratio of approximately 2:1. Moreover, the central part shows a different arrangement of the bricks. Therefore, it was probably a predefined

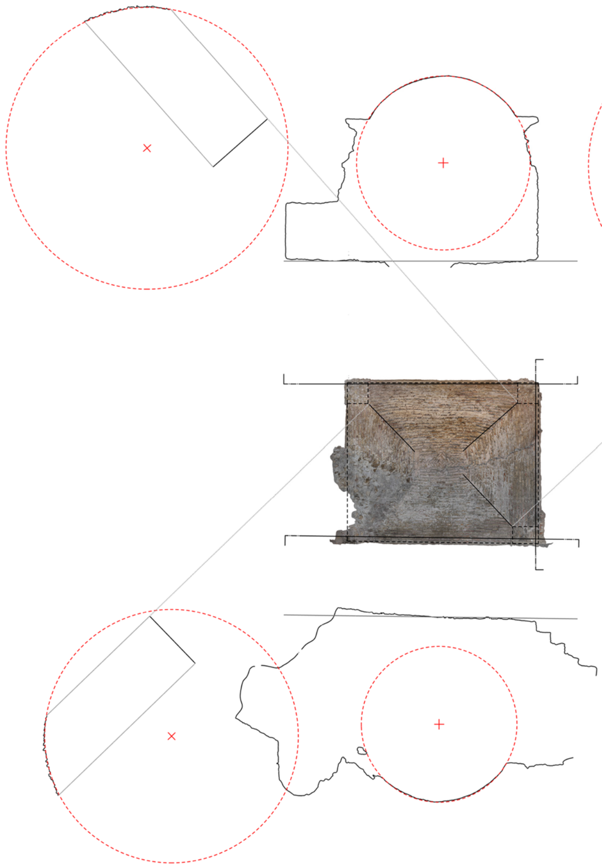

Fig. 2 Layout of the springing arches and diagonal sections

design or a common workaround 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.

There is a transition area between these two well-defined parts, previously named Part B. The brick slices maintain their cone shape and radii similar to those previously built, but instead of forming a cylinder, they become increasingly tilted to gently join the central part.

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 newly produced *pedales* cut in half. Calculations of brick dimensions based on the photogrammetric model corroborate this hypothesis to some extent. 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

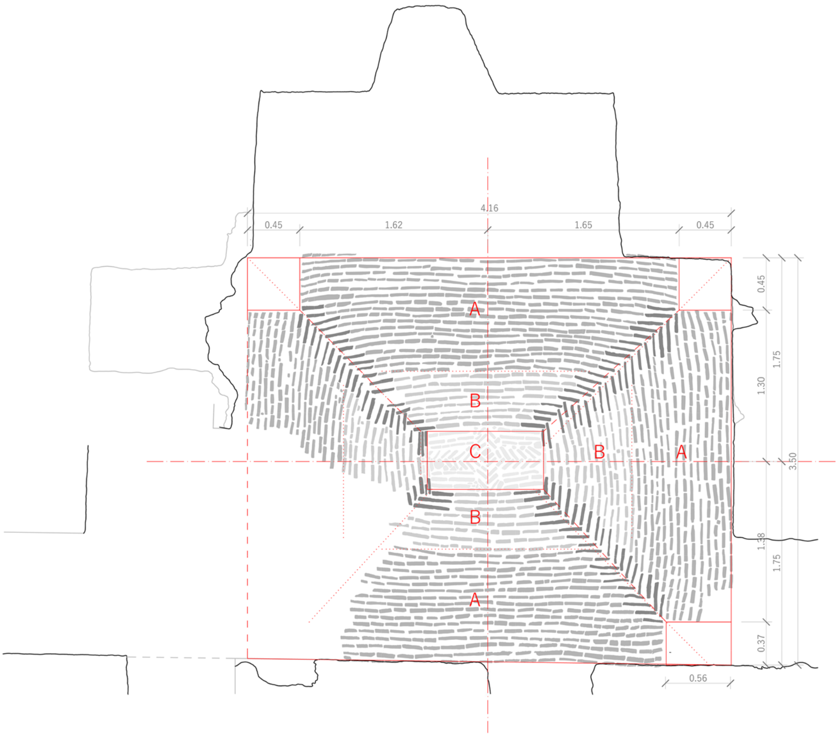

Fig. 3 Plan of the vault showing brick arrangement and layout of segments A, B and C

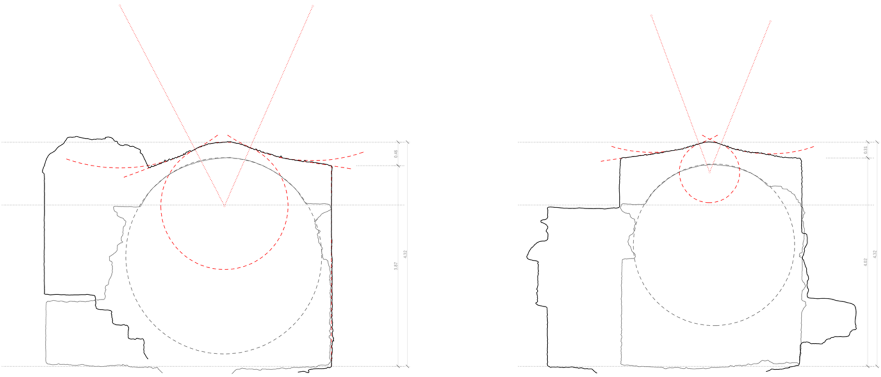

Fig. 4 Transverse and longitudinal sections with geometrical analysis of the general shape of the vault

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 brick arrangement is similar to that of the models described by Choisy (Choisy 1876: 444, pl. 21; Rabasa et al. 2020). Each slice is cone shaped with its concave side downward. 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.

Based on these studies, we can propose a hypothetical model that fits the data. 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 circle 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 devise the vault design is carried out by determining the reference points: the impost blocks and the crowns of the perimetral arches; the diagonals as circle arcs from the corners impost blocks to the central rectangular part; and the upper point of the vault. The hypothetical model based on these data matches the photogrammetric model. The main curves and the reference points directly coincide, and the contour lines of the surface are very similar in both models, while they differ from the groin vault theoretical model of Choisy (1883: 54–56), which proposes a revolution surface between the circles of the diagonal arcs.

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

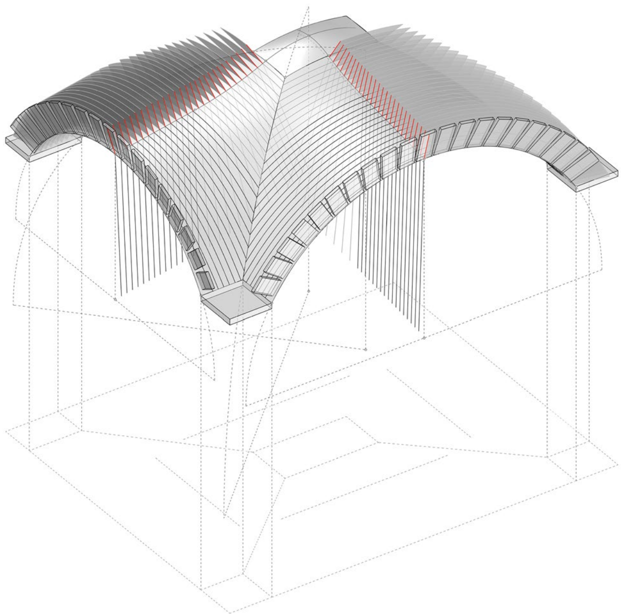

Fig. 5 Hypothetical model based on main curves and reference points with reconstruction of brick arrangement

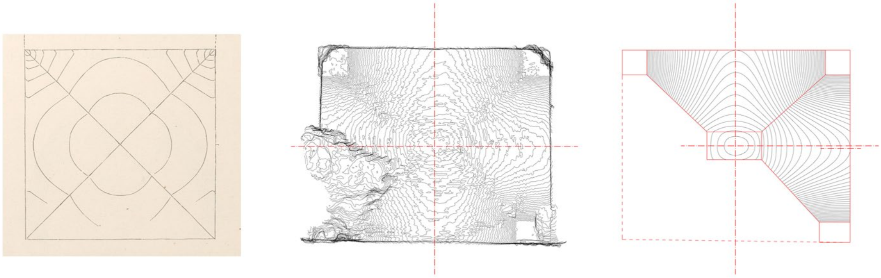

Fig. 6 Comparison of contour lines in the groin vault theoretical model of Choisy (1883: 56), photogrammetric model of the existing vault and its hypothetical model

of surface. This singular experimentation with brick vault by slices in the Roman context shows a direct connection to the specific setting of the vault (Figs. 5, 6).

Conclusion

The studied vault belongs to the building technique named by Choisy as Byzantine, vaults built by slices without formwork. Although it does not accurately match any of the types described by the French engineer, it features some of its key characteristics, such as 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: cylindrical near the springing, round in the center, and a transition segment between them. This indicates the adaptability of the system and makes this case even more singular within the Roman and Italian areas.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Licinia Aliberti is an architect from Roma Tre University and PhD from the Polytechnic University of Madrid. Her dissertation on geometry and construction of Pantheon and Roman domes received a mention in the UPM Extraordinary PhD Awards. She teaches geometry and architectural drawing at the Polytechnic University of Madrid. She has also been a lecturer at the European University and at the School of Design, Innovation and Technology of the Camilo José Cela University. Her research focuses on geometrical analysis of architectural heritage and on contemporary metric restitution techniques. She has carried on several surveys of historical buildings. She has been involved in projects promoted by the Spanish Institute of Cultural Heritage and other public institutions, working on studies and graphical restitution of the ancient walls of Ávila, Belver de los Montes, Calatayud and Santo Domingo de la Calzada in Spain. Member of the research group "Historic Building and Shape" of the Polytechnic University of Madrid, she participates in seminars and research activities, and she has written studies for national and international publications.

Manuel de Miguel Sánchez has a Ph.D. in architecture by the University of Alcala, he is an Architect by the Polytechnic University of Madrid since 1996 and has a Master of Architectural Restoration from the Polytechnic University of Madrid (2001). His research is related to analytical studies of historical and contemporary architecture, architectural heritage, architectural geometry, construction, and sustainability. He also works on the relationship between mathematics and architecture, teaching, and innovation. Manuel is a Professor of Architectural Graphic Expression at the Department of Architecture of the University of Alcalá since 2004. He has taught at several universities and hold research stays at foreign centers such as the University of California Berkeley (CA, USA) the Institute of Urbanism of Paris (France), the Polytechnic of Turin (Italy) or the University of Novi Sad (Serbia). He has published his work as part of the research group "Intervention in Architectural heritage and Sustainable Architecture" (CCTE2.006/R34) in numerous scientific journals and international conferences (https://www.uah.es/es/estudios/profesor/Manuel-de-Miguel-Sanchez/). Manuel has participated in numerous projects in collaboration with researchers from various Spanish and foreign universities. Currently he is principal researcher of a project about wooden structures of the Spanish Renaissance (2020-2021).

Ana González-Uriel PhD, is an architect and associate professor at the Polytechnic University of Madrid. Member of the educational innovation group "Computer Graphic Geometry", her teaching includes Geometry and Architectural Drawing, Digital Imaging and Geometrical Modelling. Her research includes

architectural heritage geometric and constructive studies. Member of the research group "Historic Building and Shape" of the Polytechnic University of Madrid, she is currently involved in two research projects, one related to historical uses and updating of brick vaulting by slices techniques, and another one related to historic Castilian wooden structures.