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Brick vaults by slices in Turin in the 19th century. A new approach to the building process

Licinia Aliberti [a,*], Ana López-Mozo [a], Ana González-Uriel [a], Manuel de-Miguel-Sánchez [b], José Calvo-López [c]

[a] Universidad Politécnica de Madrid, Escuela Técnica Superior de Arquitectura de Madrid, Av. Juan de Herrera 4, 28040, Madrid, Spain
[b] Universidad de Alcalá, Escuela de Arquitectura, C. Sta. Úrsula, 8, Alcalá de Henares, Madrid, 28801, Spain
[c] Universidad Politécnica de Cartagena, Escuela Técnica Superior de Arquitectura y Edificación, C. Real, 3, Cartagena, Murcia, 30201, Spain

1. Introduction

Vaults by slices feature bricks arranged with their beds vertical or slightly pitched, forming self-supporting arches usually parallel to the plan sides. The system allows construction with no falsework[1] or other supporting elements, as bricks are individually held by adhesion and each slice becomes a self-supporting arch as soon as the mortar sets. Tools such as rulers, ropes or laths are sometimes used to control the shape of the intrados. Analysing historical examples, both in their general form and in the details of the brickwork, can provide information on the construction process and the principles behind the brick vault by slices construction system.

The earliest examples of brick vaults by slices are documented in Egypt, dating back to around 2900 BC. (Emery, 1958, 98). The technique was widely used in the Byzantine empire between the 4th and 6th centuries (Choisy, 1883; Lancaster, 2015), and then spread to the Mediterranean basin. Numerous cases are found in the Iberian Peninsula, especially in Toledo between the 12th and 16th centuries and in south-west between the 15th and 18th centuries (Rabasa-Díaz et al., 2021; López-Mozo et al., 2023, 2024). In the specific context of the Italian peninsula, few examples from the Late Antique period are located in the central south (Vitti, 2013; Aliberti et al., 2024), where traditional Roman concrete vaulting techniques on falsework are more common. On the other hand, we find many cases in northern Italy, especially around Turin, in the second half of the 19th century, a period of great development of the city. Brick vaults by slices are constructed in a modern and systematic way, seeking an efficient method that is applicable to a large number of buildings and adaptable to different conditions (Fig. 1). Vaults by slices can be observed in some of the many porticoes built throughout the historic centre in different periods from the late 17th century onwards (Fig. 2). A significant example of the use of vaults by slices can be found in the Mole Antonelliana. This building, an emblem of late 19th century technological development in Turin, uses brick in the supporting structure and the main vault. Antonelli experimented with a new system using traditional materials in both representative and residential buildings and became a fundamental reference model for architects of the time (Rosso, 1977; Re, 2003: 1710; Wendland, 2021: 48–49).

Considering these particular conditions, it can be understood that in the case of Turin, brick vaults by slices present certain characteristic elements that clearly distinguish them: the generally very low form, their presence also in the upper floors of the buildings, the use of diagonal or concentric brickwork, and the existence of metal ties embedded in the vaults or in the arches that separate them (Fig. 1). A comparison of written sources from the time raises another peculiarity of the Turin context. Paredes (1883) in Spain clearly indicates how the construction of brick vaults by slices is carried out without falsework, highlighting the advantages of this system, as does Choisy (1883) in France, analysing examples from the Byzantine period. On the other hand, in Turin, Musso and Copperi (1890 [1885]) are the authors of a reference treatise that was fundamental for architects and engineers up until the early 20th century, in which they point out the need to use falsework and formwork with rigour and accuracy to control the shape of the vault intrados, while pointing out the constructive advantages of laying brick courses by slices. It remains to be established whether these guidelines correspond to actual construction practice. The extensive use of brick vaults is evident even in the upper floors in most buildings in Turin and is confirmed by written sources from the time (Curioni, 1969:

* Corresponding author.
E-mail addresses: licinia.aliberti@upm.es (L. Aliberti), ana.lopez.mozo@upm.es (A. López-Mozo), ana.g.uriel@upm.es (A. González-Uriel), manuel.miguel@uah.es (M. de-Miguel-Sánchez), Jose.Calvo@upct.es (J. Calvo-López).

[1] Falsework can be defined as the ensemble of the provisional structures used to support a vault under construction: a) formwork, that is, a surface following the shape of the vault b) centering, that is, a structure supporting the vault and the formwork during construction and c) shoring or underpinning, a structure transmitting the weight of the vault, the formwork and the centering to the ground or finished parts of the construction.

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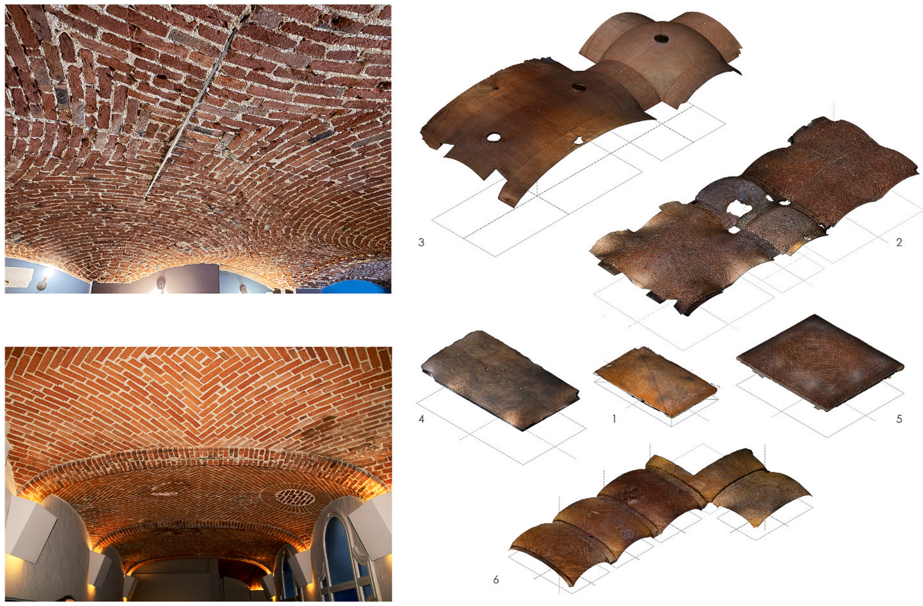

Fig. 1. Examples of low brick vaults by slices in Turin with concentric brickwork, metal tie rods and diagonal brickwork.

189–191; Musso and Copperi, 1890 [1885]: 113) and from the immediately succeeding period (Chevalley, 1923).

2. Materials and methods

Within the framework of a research project about historical technique of constructing brick vaults by slices,[2] this paper aims to consider the constructive configuration of the vaults built in Turin at the end of the 19th century, by studying a series of built examples and written sources published in the city at that time. The aim of the research is to identify the general form, the details of the brickwork and to deduce aspects of the construction process, especially to confirm or disprove the use of falsework. The vaults have been studied using a new graphical methodology based in the analysis of a 3 d model obtained by automated photogrammetry, scaled and levelled with data from a LIDAR scanner, bringing up new data on the general shape and brickwork which allow proposing some hypotheses about the constructive attributes of these structures. General form is analysed with a working methodology that includes determining the height/span ratio of the vaults of the vaults, or the span-development in height ratio, obtaining contour lines, which in a single drawing provide a great deal of information, and the layout of axial, diagonal and perimeter sections to document the shape of the vaults in the main directions and the shape of the perimeter arches. To study the brickwork, the courses were drawn on the three-dimensional model to analyse their circular outline and to see if the position of their centres indicates great regularity. This could be due to construction with falsework or at least with a platform and the use of laths. On the other hand, the three-dimensional volume of the bricks along relevant sections has been constructed by extruding a rectangle with three vertices in the 3D model of the vault, in order to obtain more information on the constructed brickwork. Comparison with previous examples reveals possible similarities in terms of the dimensions, form, type of brickwork and height/span ratio of the vaults analysed. Characteristics that are common to the examples analysed may also indicate some guidelines in the intensive and modern construction of this type of vault in the city of Turin.

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3. Results and discussion

3.1. Case studies

The examples studied include 6 buildings located in the historic centre of the city, specifically in the expansion areas built in the period of unification immediately following the creation of the Italian state, regulated by the master plan 1850–52 and the expansion plans of 1868 (Comoli, 1986: 67), continuing with the 1886 plan for the restoration of the historic centre. Apart from the singular case of the Mole Antonelliana, the vaults analysed are in residential buildings. In the absence of a detailed historical study of each case, the approximate date of their construction is deduced from the graphic documentation of the master and expansion plans.

Specifically, thirteen vaults were observed and analysed: four in the building at Corso Moncalieri 33 (1886), four in Via Giuseppe Pomba 14 (1870), one in Via Andrea Doria 5 (1870), one in Corso Stati Uniti 11 (1873), one in Via Silvio Pellico 2bis (1876), and finally two on the ground floor of the Mole Antonelliana (1863). There are also brick vaults by slices in the porticoes on Via Po at the corner of Via Accademia (1720), near Porta Nuova Station on Via Paolo Sacchi at the corner of Via Assietta (1884–1905) and in Piazza Vittorio Veneto at the corner of Via della Vanchiglia (1820–25). However, a complete survey of the portico vaults has not been carried out as most of the surface is covered with plaster, leaving part of the brick structure visible only in areas where the plaster is deteriorated. In the case of the groin vaults of the portico on Via Po, a photograph of damage caused by bombing during World War II shows part of the structure where the layout of the bricks by slices with diagonal brickwork can be seen (ASCT, 1942: UPA 3065, 9D03-22). However, it is worth noting the fact that the porticoes cover a significant amount of the public space in the historic centre and that such widespread use of the brick-by-slices technique during different periods indicates its relevance and continued use in the local building tradition.

The case studies are located on the ground floor of the buildings although, as we have seen, this type of vault can also be found on lower and upper floors. Building regulations exercised direct control over city development in the second half of the 19th century, starting with the ordinances of 1843, successively modified in 1862 (Comoli, 1986). The use of vaults at different levels in residential buildings implies the search for very low forms in order to comply with municipal by-laws. In his

Fig. 2. Brick vaults with diagonal brickwork in the porticoes of Via Po at the corner of Via Accademia, in Via Paolo Sacchi at the corner of Via Assietta and in Piazza Vittorio Veneto at the corner of Via della Vanchiglia.

treatise on the theory and practice of building, Curioni (1869: 189–191) indicates that very low brick vaults are usually built in Turin and that some builders calculate the rise at the various levels of 1/10, 1/9, 1/8 and 1/7 of the main span of spaces to be covered, depending on whether it is the ground, first, second or third floor respectively, in some cases going as far as 1/11, 1/10, 1/9 and 1/8. In the context of this paper, we can compare the ground floor vaults as a common reference value.

A decisive requirement when selecting the examples was that the vault had no cladding so that the brickwork could be studied. Table 1 summarises the general data of the case studies, identified by their numbering.

3.2. Analysis of the general form

In the first stage, the form of the vaults was analysed in relation to the floor plan. Results indicate that most of the vaults analysed are developed on a rectangular plan, with the Mole being the only example with vaults that are approximately vaulted on exact square plans. The proportion of the rectangles is varied, and there are also examples with obvious irregularities, as in case 2, with rounded vaults on parallelogram-shaped plans. The variety of these conditions and the use of similar solutions in different contexts confirm the adaptability of the system (Fig. 3).

The first relevant characteristic of the vaults analysed is their extremely low form, which is analysed by calculating the ratio between the rise and the length of the longest side. The results indicate that most of the examples, including pavilion,[3] rounded and fan-shaped vaults, have a value of 0.1 or even lower in some cases. These results fully meet the guidelines set out in Curioni's treatise (1869: 189–191) mentioned above for the control of the rise-to-span ratio of brick vaults in civil buildings, in our case specifically for the ground floors. The rounded vaults on a rectangular plan in case 6 reach a value of 0.16, making a slight difference with respect to standardised constructions, but always

[3] We identify as pavilion vault a derivate of the cloister vault built on a rectangular or extended plan, which normally has a flat ending. In Turin we also find a similar form that we could identify as squinch vault. Lancaster (2015: 71) describes it as a vault that "sprang from all four walls of a square or rectangular space without any intersecting groins".

Table 1
Numbering and identification of case studies with summary of data that are significant for the research.

No. Case	building	date approx.	No. Vault	plan				form			lenght [m]	width [m]	rise [m]	rise/ span	visible ties	visible courses [plan view]	
				square	rect.	trap.	parallel.	rounded	fan	trought						straight	curves
1	Via Silvio Pellico 2bis	1876	1		1					1	5.00	3.05	0.42	0.14		1	
2	Corso Moncalieri 33	1886	1				1	1			2.72	2.62			x		1
			2				1	1			2.73	2.68	0.30	0.11	x		1
			3				1		1		6.00	5.90	0.57	0.10	x		1
			4				1		1		5.92	5.90	0.62	0.11	x		1
3	Mole Antonelliana	1863	1	1				1			4.12	4.10	1.25	0.30	x		1
			2		1			1			9.50	4.10	1.24	0.13	x	1	1
4	Corso Stati Uniti 11	1873	1		1					1	6.87	4.06	0.37	0.09		1	
5	Via Andrea Doria 5	1870	1			1				1	5.87	4.96	0.47	0.09			1
6	Via Giuseppe Pomba 14	1870	1		1			1			4.12	2.43	0.62	0.15	x	1	
			2		1			1			4.11	2.43	0.63	0.15	x	1	
			3		1			1			4.12	2.67	0.62	0.15	x	1	
			4		1			1			3.70	2.50	0.61	0.16	x	1	
	TOTAL		**13**	**1**	**7**	**1**	**4**	**8**	**2**	**3**				**0.14**		**7**	**7**

maintaining a limited height in relation to the proportions of the floor plan. In the particular example of the Mole, the value is 0.3 in square plan vaults and 0.13 in rectangular plan vaults, a limit value for this type of structure if we consider its remarkable size of 9.5 by 4.1 m. The perimeter arches containing the Mole's vaults feature metal ties embedded in the structure itself, which are also present in two of the other cases, a detail that probably contributes to the construction of such low structures.

The shapes identified in the case studies are mainly pavilion and rounded, generally not perfectly spherical. Curioni (1869: 187–189) indicates that the most commonly used vaults for residential buildings are barrel vaults, cloister vaults and pavilion vaults. According to the study, we find three pavilion vaults on a rectangular plan, one of which has a flat ending. The perimeter lines are horizontal, except for a few small irregularities. Observation of the contour lines shows how the diagonals are well marked in the first section of the vault and are lost as the height increases in the vaults in cases 5 and 4. However, in case 1, sharp edges can be seen on the diagonals until they meet, defining the encounter between two roughly cylindrical surfaces of the same radius.

In the rounded vaults on the square plan of the Mole (case 3), the four perimeter arches are comparable to circles of a very similar radius, as well as the transversal and longitudinal sections. The centres of the perimeter arches are not aligned with the centre of the axial sections and the diagonal sections are not circular arcs, indicating that the surface is not perfectly spherical (Fig. 4). Similar characteristics can be found in the two small vaults in case 2, with axial sections and perimeter arches similar to circular arcs. This type of structure can be identified with a non-spherical, lowered vault and is defined primarily by perimeter and axial arches, which for this reason could be the elements of the falsework used in its construction.

The large rectangular plan vault of the Mole (case 3) has cross-sections that fit circles of very different radii and with noticeable variations in the height of their centres, which indicates that the surface is neither perfectly spherical nor cylindrical. The longitudinal perimeter arches are also circles while the axial longitudinal section could be composed of a circular arc in the central section and straight lines in the end sections, beyond the lateral oculi. Rounded rectangular plan vaults are also found in case 6, in which the axial sections are similar to circular arcs of different radii whereas the perimeter arches fit flattened ellipses (Fig. 4).

Of note are the large vaults in case 2, with two consecutive perimeter circular arches on each side, which entail the alternation of concave and convex surfaces in a similar way to fan vaults. Transverse and longitudinal sections are extremely low and consist of circular arcs in the springing area and a flat part in the central area in which metal ties are visible in both directions. This is an unusual case where, in addition to the articulation of the surfaces, the vaults are continuous with each other, as also occurs in case 6, according to the system that Antonelli experimented with.

The succession of different vaults is achieved by constructing arches that rest on the supports and form the lateral edges of the adjoining vaults. Written sources from the time advise that arches be introduced when the spaces to be covered are wide, indicating that they should not exceed a span of 8 m in order to have vaults of ordinary span (Curioni, 1869: 191). Various types of vaults can be created between the arches, such as the rounded rectangular plan vaults in case 6, or the succession of rounded rectangular plan vaults in the Mole Antonelliana (case 3). The system of distributing loads to the vertical supports, *fulcri*, by means of brick arches makes it possible to free up large spaces, based on a more versatile vision that Antonelli pursues by experimenting with the construction of a modern structure (Rosso, 1975; Rosso, 1977: 4–5). The concern with redirecting stresses to point supports and optimising structures to free up space is a characteristic trend of the 19th century, the result of developments in construction brought about during the industrial revolution through the use of steel and concrete. Industrialisation reached Italy later than the rest of Europe. This means that architecture lacked the conditions to make full use of the new techniques and materials. Antonelli's work in pursuit of novel experimentation pushes the possibilities of traditional materials to the limit, specifically local brick, which the architect uses in many of his works combined with metal ties (Leva Pistoi, 1969: 67; Wendland, 2021: 48–49). His disciple Caselli used a very similar system in the *Ospizio di Carità* in Turin in 1887, where we observe the same system of brick vaults with metal ties and brick arches that distribute loads on the point supports, completely freeing up the space (Re, 2003: 1711).

3.3. Brick distribution and course analysis

The study of brick distribution and the form of the resulting courses can provide important data on the construction technique used, both to understand structure behaviour and construction processes (Fig. 5). The vaults analysed in this paper have two basic types of brickwork: courses perpendicular to the diagonals in plan and curved and concentric courses starting from the corners.

The treatise by Musso and Copperi (1890 [1885]: 120) describes the different possibilities for course arrangement in relation to their structural behaviour, having previously clarified the need to build with timber falsework that reproduces the exact shape of the intrados. According to the authors, when the formwork is removed, the structure usually subsides slightly due to the thrust of the materials pressing

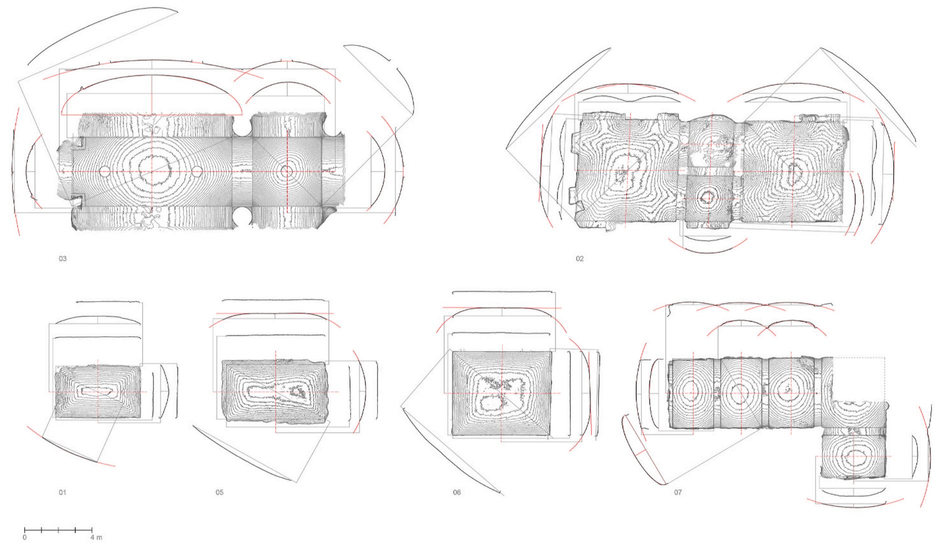

Fig. 3. Survey of the general form, contour lines every 3 cm and cross, longitudinal and diagonal sections with hypothesised overlapping design.

Fig. 4. Study of lines. A: Circular arcs in perimeter and axial sections of case 3 (Mole Antonelliana). B: Circular arcs in axial sections and lowered ellipses in perimeter arches of case 6.

strongly against the mortar joints and causing minimal movement. If the courses are orthogonal to the directrix, this movement is greater due to the many joints along the line of the arch that can be subject to deformation. In the case of courses parallel to the directrix, sag when removing the formwork is significantly lower and in the case of diagonal courses it will have an intermediate value. This would suggest that it is advisable to build vaults by slices even when using falsework, which on the other hand can be lighter as it does not have to bear the loads of the entire structure during construction. Moreover, Chevalley (1923: 210) highlights that this technique allows to execute the vaults in successive segments and that with skilled workers it is possible to build it without fixed falseworks, especially when the bricks are pitched.

Considering the specific and differential characteristics of the two main types of brickwork, this research examines the diagonal course arrangement on one hand, and the concentric course arrangement on the other, looking for common features and relevant data in each case.

3.3.1. *Diagonal-course brickwork*

One of the most common brick vault designs in Turin is the diagonal-course brickwork, generally orthogonal at the bisectors of the angles of the plan to be covered. Diagonal courses may be linked in some way with the webbing of certain Central European ribbed vaults, which are documented in written sources (Wendland, 2007). Northern Italy's cultural links with Central Europe, especially as far as Turin is concerned, may have facilitated such influences. Some isolated cases of diagonal brickwork are also found in Spain, including the vaults of the Palacio de Riofrío in Segovia, built in 1752 on a project designed by Italian-trained architect Vigilio Rabaglio, which have ties embedded in the arches as in some cases in Turin (López-Mozo et al., 2024). In northern Italy, diagonal courses are common practice in groin vaults, as in the cloister of Novara cathedral, which dates back to the 15th century (Wendland, 2021).

Hybrid construction with radial courses parallel to the starting walls in the first part of the vault and then by slices, according to Choisy (1883: 36) is the most common example of Byzantine barrel vaulting. The author indicates that radial-course construction is carried out up to the permitted point without the use of falsework, and then moves on to construction by slices, which also does not require supporting structures. Lancaster (2015: 60), however, notes that the radial bricks in some of these vaults make up a significant portion that is difficult to build without supports, and sometimes the holes to shore the falsework are still preserved. In such a case, the change of brickwork could indicate the builders' intention to create a structure that was intuitively stronger in the terminal zone of the vault, even though the construction was also built on formwork. Cases from the Byzantine period are generally barrel vaults in which, after the section of courses parallel to the axis, the vertical bricks are arranged parallel to the directrix. The examples analysed in Turin include pavilion vaults and feature diagonal courses in

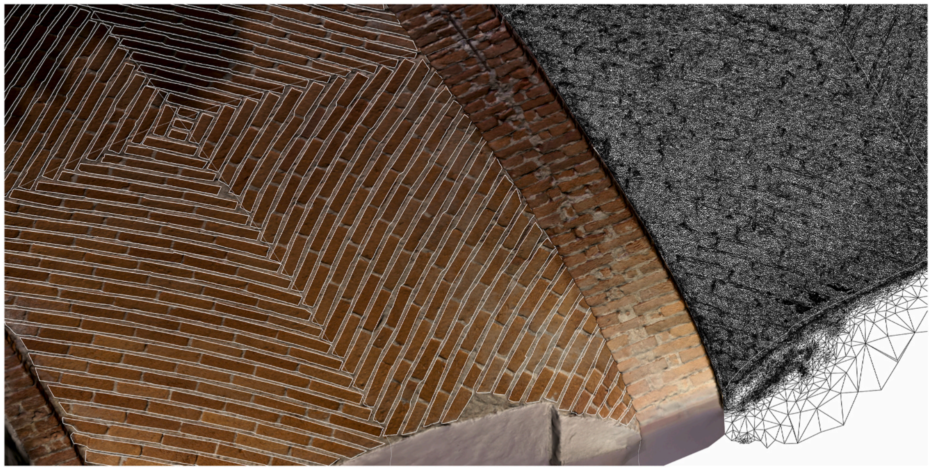

Fig. 5. Method of graphical analysis of brick distribution by tracing courses from the mesh surface obtained by photogrammetric survey.

the central zone, very similar to the types described in Musso and Copperi's treatise on barrel vaults (1912 [1885]: tav. XX) (Fig. 6).

As for the specific case studies in this paper, diagonal courses can be found in both the rounded vaults of case 6 and in the pavilion vault of case 5. Pavilion vaults of cases 4 and 1 feature courses that are parallel to the walls and successively diagonal (Fig. 7).

In order to study the layout of the brick slices, the lower edges of the courses are analysed to look for any possible correspondence with controllable geometric layouts in the construction phase. Firstly, from observing the plan view we can deduce that the visible courses are approximately straight and vertical (Fig. 7). The bricks modelled in the upper part of the sections appear to be orthogonal on the surface, without staggering, as though they were supported on the formwork.

In the cases studied, course direction is similar to perpendicular at the bisectors of the angles of the rectangular plan to be covered, but it does not fit exactly at 45°. The four panels meet with a certain regularity along the transverse and longitudinal axes of the vaults, and the termination zone is generally centred.

Course lines do not fit any clearly defined circular arcs or curves in the two vaults that have a first section of courses parallel to the walls.

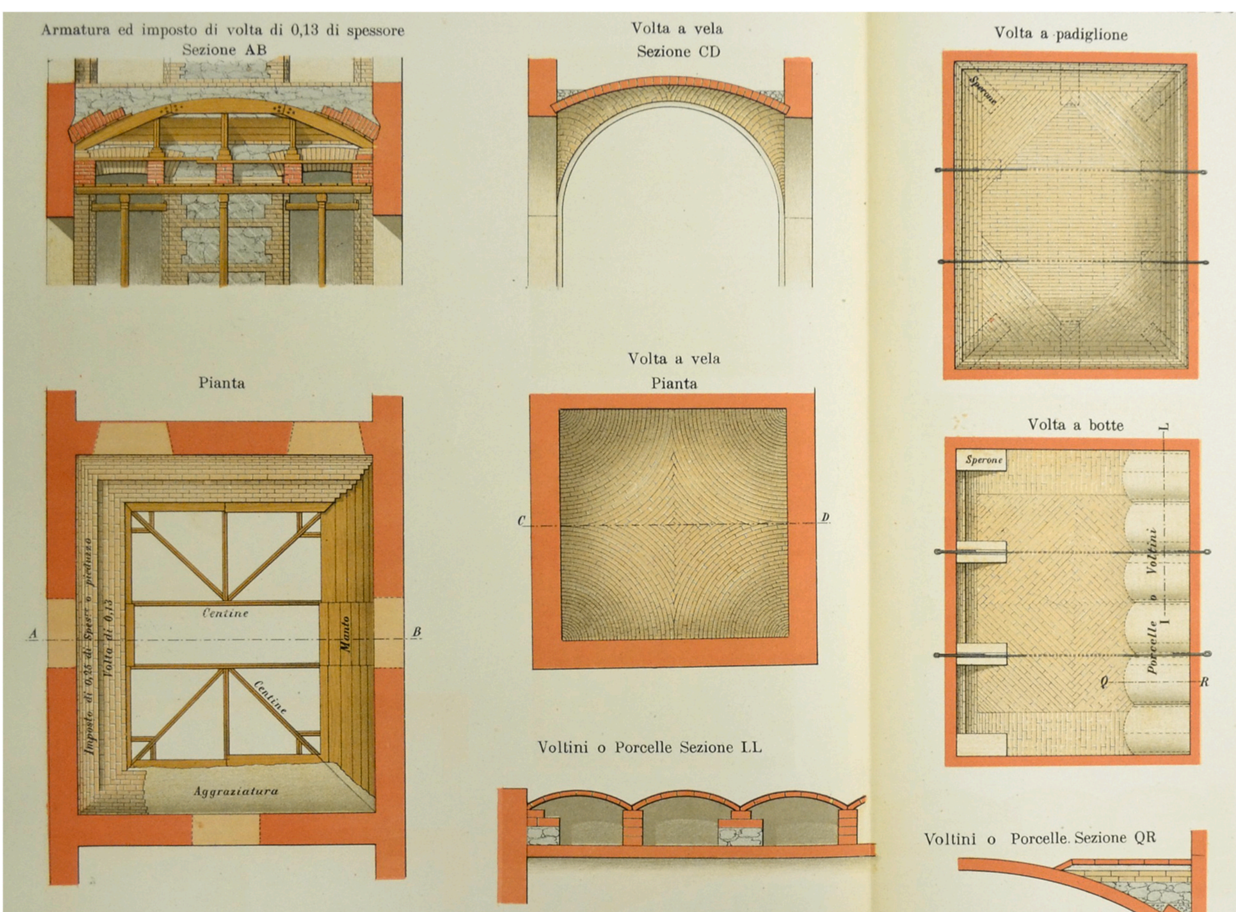

Fig. 6. Brick vaults in the Musso and Copperi treatise with details of brickwork types, vault shape and falsework (Musso and Copperi (1912 [1885]: tav. XX).

Their projection on a frontal plane shows a succession of pointed and approximately symmetrical curves, which do not correspond to geometric lines (Fig. 7). This could indicate that course development is controlled solely on the basis of the shape of a shoring system for a cylindrical pavilion vault, which is probably arranged partly along the diagonals and partly orthogonally to the perimeter straight lines. This is a traditional form of falsework construction for pavilion vaults or groined vaults, which requires a reliable system of formal control in order to mark the diagonals (Musso and Copperi, 1912 [1885]: tav. XX). The use of centring just for diagonal lines with some additional arches entails lower construction costs compared to full formwork (Wendland, 2021: 51) and, considering there is a degree of irregularity in the surfaces analysed, it could be a solution used in these cases.

On the other hand, in vaults with diagonal brickwork directly from the corners, course lines can be somewhat comparable to circular arcs. In the rounded vaults in case 6, the course lines are approximate to circular arcs of the same radius. In the pavilion vault in case 5, the course lines are equivalent to concentric circle arches of a progressively larger radius up to the central zone, where the surface tends to be flat and the lines are difficult to define. The intrados surface of this last example shows some irregularity, which could indicate construction with no formwork. Likewise, the traceability of circular arcs in correspondence with the apparent courses indicates that they could have been made using a lath or a ruler to control their shape without necessarily using formwork during the construction phase.

3.3.2. Brickwork with curved and concentric courses

The curved and concentric courses starting from the corners are considered in scientific literature to be an invention designed by Antonelli specifically for the Mole, and the solution was almost immediately incorporated into building treatises and disseminated until the early 20th century (Rosso, 1977: 13). The need to obtain absolute structural continuity led the architect to propose this special brickwork with the intention of evenly distributing thrusts and anchoring the vault to the

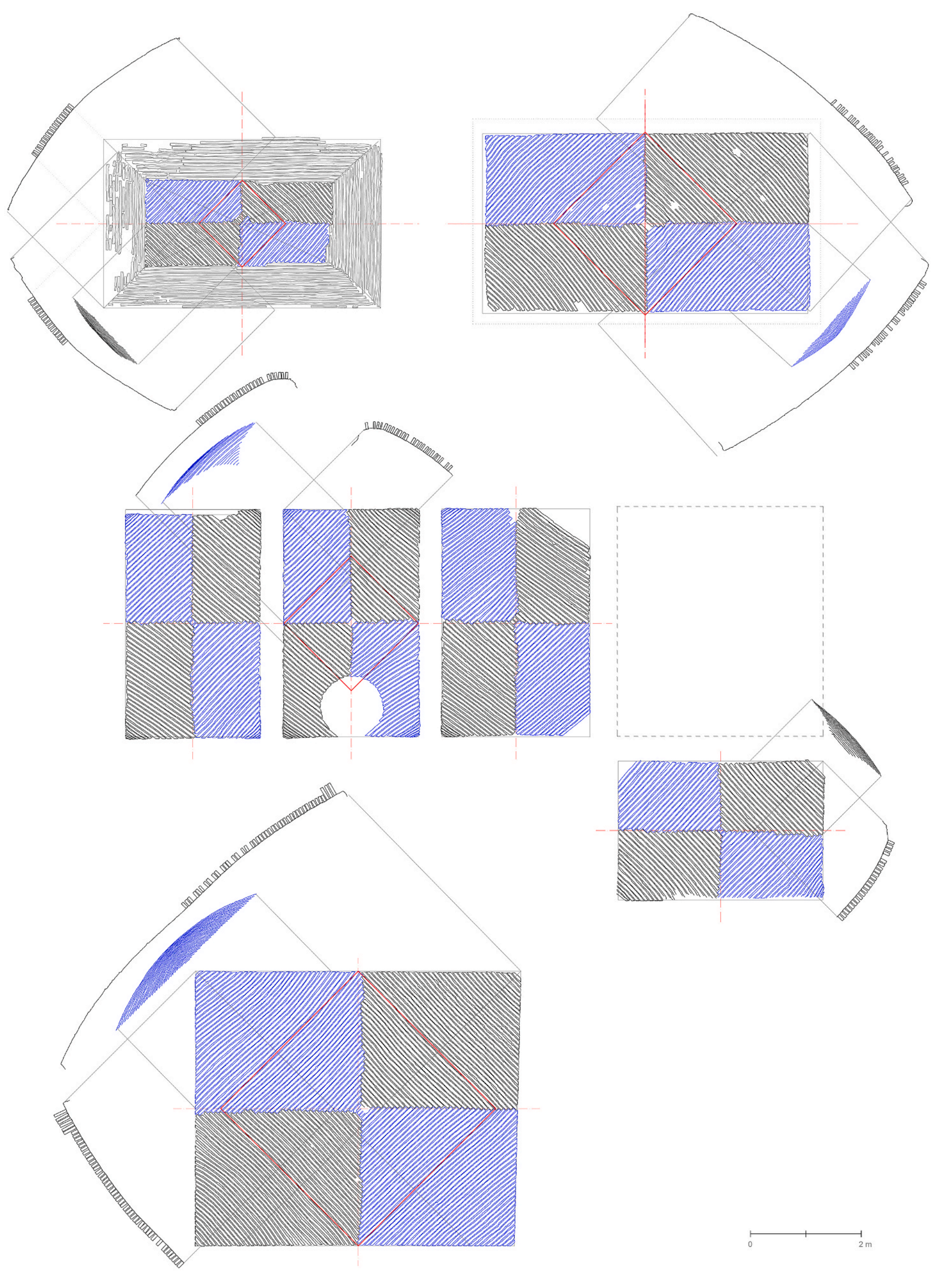

Fig. 7. Cases with diagonal brickwork: course layout, sections orthogonal to the direction of the courses and flat projection of visible courses.

lateral arches by locking the first bricks of the curved courses that are orthogonal to the arches. The same system is used in the rectangular plan vaults with curved courses at the ends and courses orthogonal to the longitudinal axis in the central part. It is difficult to establish the use of falsework as the courses do not form arches, leading us to think that some kind of support structure was necessary. Some studies suggest that the vaults in the Mole were built using a small number of falsework, and with a slight camber to compensate for the foreseeable surface deformation due to brick displacement (Maltese, 1960 in Leva Pistoi, 1969: 77–78).

We can appreciate the versatility of this type of brickwork in the vaults on irregular plans in case 2, where they cover parallelogram-shaped plans in a combination of directions that is surprising due to the surface extension in these extremely flattened structures (Fig. 8).

According to the results of the analysis, the courses describe approximately circular arcs in square plan vaults and in the corner areas of rectangular or irregular plan vaults. The courses are projected in plan as straight lines in the central part of the rectangular plan vault of the Mole, from the meeting point of the curved courses of the two corners onwards. In the building in case 2, the courses are curved over the entire surface, starting from the corners and from the midpoints of the sides of the parallelograms in plan. The concentric courses at midpoints do not form circles as they widen to fill the space and connect to the concentric courses at the corners. The versatility of the system means that course geometry can be adapted to the specific situation of this building with its irregular ground plan.

In the vaults with square-like plan, the circular courses coming from the corners meet in the axial lines of the vaults, fitting together until they define a curved quadrilateral in the central area. The termination is closed by the advance of the concentric courses, which in the case of the Mole (case 3) is replaced by a circular oculus surrounded by a ring of radial bricks (Fig. 8).

As for the structure perimeter lines, the particular solution of interlocking vault courses with arch courses can be observed both in the Mole and in the vaults in case 2. This solution, originally proposed by Antonelli, is intended to ensure homogeneity in structure behaviour, thus reducing its dimensions (Rosso, 1977: 14). The use of the curved brickwork and the repetition of this constructive detail in buildings after the Mole somewhat corroborate the idea that the solutions proposed by the architect had a notable influence in Turin at the end of the 19th century.

The analysis of the average circles traced by the lower edge of the courses shows how their centres are approximately aligned in a vertical direction, which could indicate the possible use of a formal control tool during construction, such as a rope or a rotating lath. This does not rule out the use of formwork or shoring structures to support the vaults during the construction process. In both study cases, the centres of the vault course circles are below the surface, while in the rounded barrel vault and in the fan vault, they are above the surface (Fig. 9). In the latter case, the intrados surface varies from concave to convex without any solution of continuity, as is also evidenced by the perimeter arches.

As for brick placement, the analysis of diagonal, transversal and longitudinal sections show how the bricks are arranged orthogonally to the intrados surface, with no perceptible staggering between one course

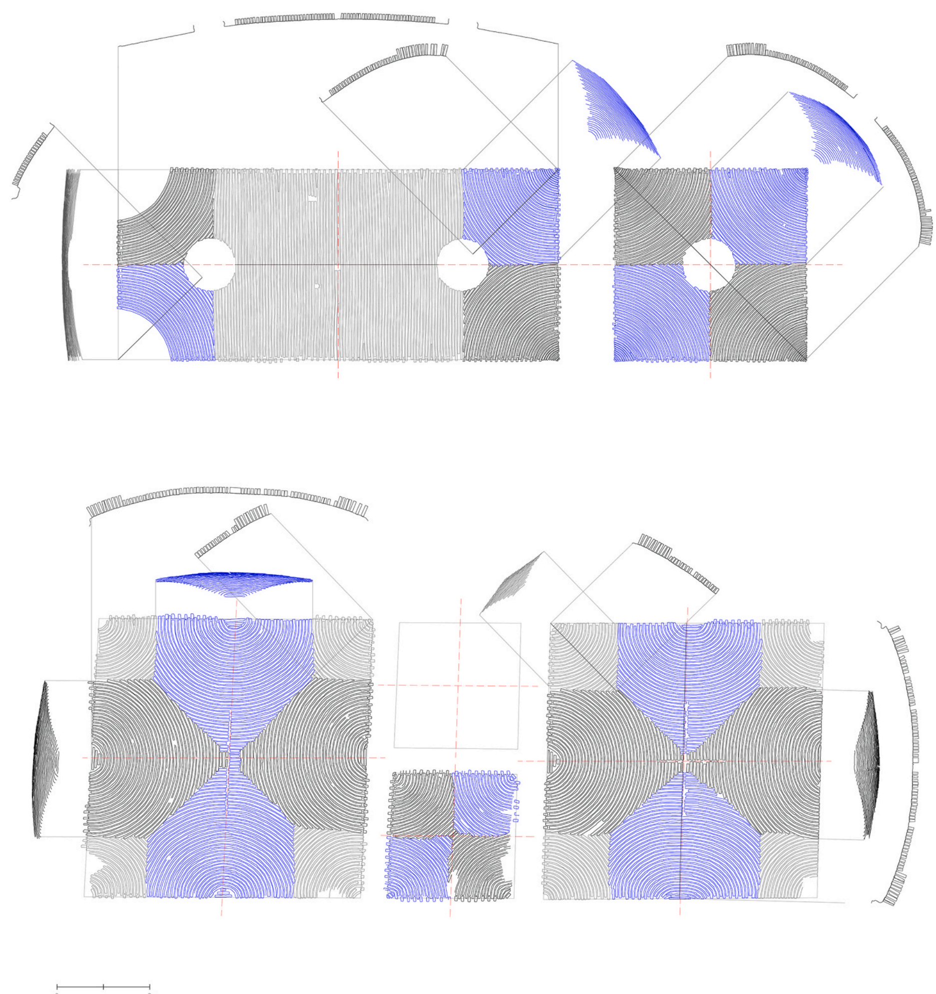

Fig. 8. Cases with curved and concentric courses: course layout, sections orthogonal to the direction of the courses and flat projection of visible courses.

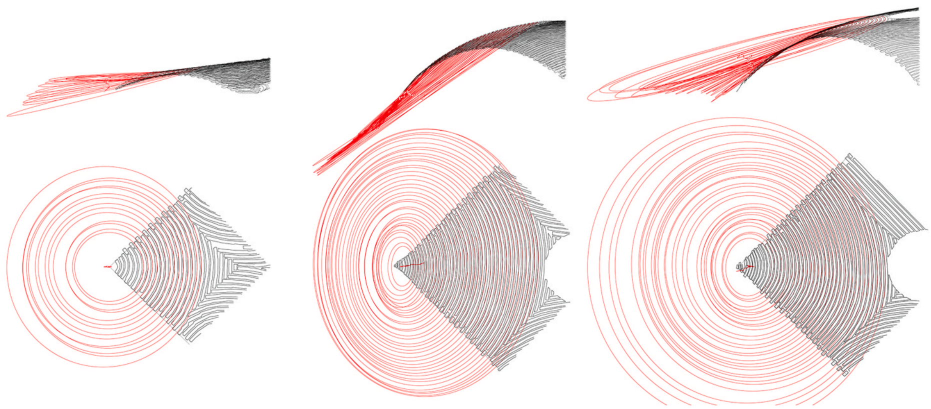

Fig. 9. Detail of the study of the course lines in the building in case 2 and in the two vaults of the Mole Antonelliana (case 3).

and the next. In the first vault sections, the bricks are laid with headers facing the intados, while in the central part they are laid with stretchers facing the intrados, probably to facilitate the curved design of the first courses, which have smaller radii. The difference in thickness between the springing area and the central area may also be related to constructive aspects. Curioni (1869: 190–191), for example, indicates that while for vaults with spans of less than 4 m it is preferable to maintain a constant thickness by laying the bricks lengthwise (stretchers) and obtaining an approximate thickness of 12 cm, in vaults with spans between 4 and 6 m it would be necessary to maintain this thickness in the central part and increase it in the imposts, where the bricks would have to be laid headers and reach a thickness of 24 cm. Increased thickness would have to start at horizontal plane level about 1/3 of the height from the impost plane. Chevalley (1923: 206) points out that in civil constructions the thickness of vaults can be half a brick header, one header or two headers. Thin vaults are preferably built in small rooms, while if the span is large the thickness should be increased.

Brick dimensions are regular in the cases studied, either 24 x 12 × 5 cm, the standard measurements for bricks used in construction at that time, or 22 x 10 × 4 cm, according to the measurement of the exposed faces of the vault intrados pieces. The spans of the vaults analysed do not exceed 6 m and feature a change in brick arrangement starting area.

4. Conclusions

This study enables us to make some observations on the use of brick vaulting in Turin during its expansion at the end of the 19th century. The specific context and conditions of the period have determined the definition of particular characteristics, such as the widespread use of diagonal and concentric brickwork, the extreme values of lowered vaults with metal ties and their extensive use on different building levels.

Although this type of vault generally does not require support structures during construction, we could deduce that in Turin they were probably built with the use of falsework. This finding is based on the cases analysed and written sources, in which no explicit references to construction without falsework have been found. One reason could be construction process requirements for courses that do not form self-supporting arches and need support, such as concentric courses or courses parallel to the sides in the springing area. The study of visible course lines corroborates this hypothesis for these types of brickwork, while in the cases of brickwork with diagonal courses from the corners, the use of falsework is still doubtful. On the other hand, the observed lack of any staggering between the courses suggests that the bricks were laid on top of formwork, and thus orthogonally to the surface of the vault intrados. Interest in exact form control noted in the literature also seems to indicate a need for guide structure construction. We could put forward a hypothesis that a reduced number of formworks were used due to extensive construction in Turin at the end of the 19th century, taking advantage of the properties of diagonal and concentric brickwork that allows to reduce formwork.

Finally, we should highlight the versatility of the system, which features different shapes, both regular and irregular, and different types of brickwork in buildings of the same period. Experimentation with traditional materials in renovated construction systems drives a significant change in the technique, seeking novel solutions and applying a method that allows the construction of this type of structure both in representative buildings and in the extensive construction of the modern city. On the other hand, the probable use of falsework in many cases places them outside the framework of the traditional technique of brick vaults by slices, which were built without falsework. These cases in Turin would therefore form a final focus in the Mediterranean basin, showing profound changes in the fundamental principles of this historical technique.

CRediT authorship contribution statement

Licinia Aliberti: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ana López-Mozo:** Writing – review & editing, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ana González-Uriel:** Writing – review & editing, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manuel de-Miguel-Sánchez:** Writing – review & editing, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **José Calvo-López:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.daach.2025.e00419.

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