



# Stonecutting and Early Stereotomy in the Fatimid Walls of Cairo

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## Abstract

Bab el Nasr gate, which was built between 1087 and 1092, is one of the three remaining gates in the Cairo Fatimid walls. Inside the walls, there are a great variety of stonework pieces that reveal the stereotomic knowledge of their executors. Specially, the inner space of Bab el Nasr gate is covered by a groin vault which stands out for the accuracy of its construction, despite its early execution date. In order to analyse the geometry and design of its construction, a photogrammetric survey has been carried out with the aim of comparing the solution executed in Bab el Nasr with other contemporary vaults. Furthermore, this paper reviews the Renaissance stonecutting texts and manuscripts which, centuries later, include the proposed solution in Cairo, and which are the basis for the creation of Descriptive Geometry as a discipline.

**Keywords** Descriptive geometry · Design analysis · Historical era · Medieval construction · Topography

## Introduction

The architecture of the Fatimid Cairo (969–1171) is considered one of the most exciting in the history of Muslim Egypt. During the reign of al-Mustansir in the eleventh century there was a great crisis due to social and political issues. This situation prompted him to ask the Armenian general Badr al-Jamali, who was successfully serving as military governor in Damascus, for help to restore stability. His performance brought not only order to the caliphate, but he also ordered the restoration and rebuilding of mosques and other significant buildings which had

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been damaged by rebels. Furthermore, he built new city fortifications to defend Cairo (Williams 1983: 39). Badr al-Jamali brought Armenian architects and masons from northern Mesopotamia to introduce the military architecture and the fortresses in Egypt. The city was enlarged, the original sundried brick wall was replaced by stone, and the gates were reconstructed into military defences. Stylistically, this project resembles contemporary architecture in Northern Syria, where Badr al-Jamali defended the Fatimid Caliphate before arriving in Cairo (Williams 1983: 39). Byzantine and Syrian stonework techniques were applied together in the construction process, in addition to the stone obtained from the North of Mesopotamia. Under those circumstances, there is an importation not only of material, but also of architects and possibly labour. This is an obvious demonstration of the direct transfer of knowledge between the building traditions of neighbouring regions from East to West. In this context, and due to this constructive influence, Bab el Nasr gate was designed and built with a series of interesting stonework pieces, especially the inner groin vault which is the case study examined in this paper.

There are several works which have studied the Fatimid walls and gates from a historical, architectural, and even artistic point of view (Williams 1983, 2008; Raymond 1993; Behrens-Abouseif 1998; Rabat 1995; Warner 2005). There are also some old generic plans and surveys available (Creswell 1978). But to date, detailed architectural surveys and stereotomic analysis of the stonework pieces of the walls have not been carried out. In addition, there is no recent and complete graphic restitution in scientific publications. Therefore, the main goal of this paper is to obtain a rigorous graphic documentation of the Bab al Nasr groin vault which serves as a basis for its geometric and constructive analysis taking in to account the context of its construction. With this aim, a photogrammetric survey of the vault has been carried out. The layout of the vault was analysed according to the performed survey, and also the similarities and differences to the theoretical solution. Through a comparative analysis between the restitution model and the solutions proposed in the Renaissance stonecutting treatises, it is possible to identify constructive features of the vault taking in to account its early date of construction. Furthermore, it would be possible to detect some innovative solutions compared to other contemporary similar vaults and to test the hypothesis about the sense of influences and transfer of knowledge. However, this research also has some limitations, since the photogrammetric survey is complemented with direct measurements and not with topographical support, which would be the best option.

## **Stonework in the Fatimid Walls of Cairo**

The Cairo Fatimid walls project is one of the most monumental constructions built before the Crusades (1095–1291) as an example of Islamic military architecture. There is evidence that at least three gates, Bab el Nasr, Bab el Futuh and Bab Zuwayla, were built by three Armenian brothers from Urfa (Edessa) who probably applied the stereotomic knowledge of their region (Raymond 1993; Rabat 1995). The Armenian stonecutters, who have been said to be monks as well as brothers,

used high-quality stone and carved masonry details in a variety of vaults, domes, and arches (Behrens-Abouseif 1998: 82). The Supreme Council of Antiquities (SCA) of Egypt undertook an extensive restoration of the Bab el-Nasr, Bab el Futuh and other parts of the wall in 2001, which resulted in the replacement of many masonry elements (Warner 2005: 87–88).

The walls present three constructive levels. The lower level, which includes the entrance halls of the gates, was originally at a higher level than the street, so that the gates had to be reached by ramps. In the second level we can find a set of internal galleries that run parallel to the perimeter and connect vaulted rooms and halls with loopholes on the perimeter side. The third level consists of a terrace protected by round-topped rectangular battlements. In any case, the most outstanding feature of Badr al-Jamali's fortifications is the great quality of the stone treatment and the stonecutting knowledge of their executors. This resulted in a great variety of arches, vaults and domes built with stonecutting techniques in the gates of the walls.

The three gates are masterpieces of stonework and decorative detail. Bab el Nasr and Bab el Futuh gates were the first to be built, and they are located in the north of the city connected by corridors and towers. In contrast, the Bab Zuwayla gate was later built in the South. The gates are integrated into the wall between two massive towers. Bab Zuwayla and Bab el Futuh are composed of two rounded towers, while Bab el-Nasr's towers are rectangular (Fig. 1). The towers of the three gates are solid stone up to the second level leaving a remaining space between them inside the gates. In this space there is an entrance vaulted hall built entirely with stonework

**Fig. 1** Bab el Nasr Gate. Photo: José Calvo, 2010



techniques. In Bab Zuwayla the space has a squared plan, and it is covered by a flat vault with round courses which rests on pendentives. In Bab el Futuh, the vestibule has also a squared plan and it is covered by a sail vault with round courses (Fig. 2). Finally, there are also vaulted rooms in the upper level of the towers, and they are covered by groin vaults.

The expertise of the stone masons who built the gates of the Fatimid walls of Cairo was demonstrated far beyond the entrance halls. There are also pieces executed with stonework in the private spaces inside the gates, the towers and the inner corridors that connect the gates. Inside the towers and the walls there are stairs supported by a set of sloping barrel vaults connected to horizontal-axis barrel vaults in the landings. There are different solutions to L-shaped vaults that cover the corners of the corridors. Spherical lunettes and splayed arches are located inside the loopholes, and we can also observe different types of rear-arches and pointed lunettes in the wall openings along the corridors (Fig. 2). Armenian masons also built a wide range of arches demonstrating a level of complexity from a geometric and constructive point of view, taking into account their early construction date. In the outer faces of the towers we can find, for example, segmental arches addressed with locked voussoirs, lintelled arches and blind arches in a curved wall (Fig. 2).

However, Bab el Nasr is the gate where the quality of the stonework is probably most evident. The two helicoid vaults (Fig. 2) built in Bab el Nasr gate are the oldest known models. There is a wider first stairway that connect the ground floor with the first level, and a second stairway with a smaller diameter that allows access to the terrace in the upper level. Both are supported by exceptional helicoidal vaults



Fig. 2 Stonework pieces in Fatimid walls of Cairo. Photos: José Calvo, 2010

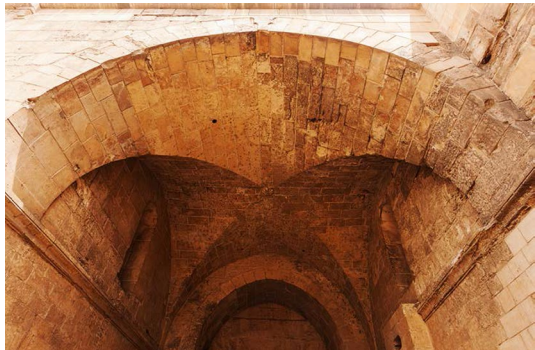
that could have been carved on site, attending to their execution details (Tamboréro 2006: 3026). In the towers there is a pair of sail vaults, and the entrance space has a rectangular plan, and it is covered by a groin vault that fits a squared plan (Fig. 3). In both sides of the room there are two small spherical shelled niches that incorporate small pendentives. The hall of Bab el Nasr, and especially the groin vault, is a masonry masterpiece that stands out for its execution and for constructive features such as the accuracy of the voussoirs' carving or the low thickness of the joints. Furthermore, the barrel vault that covers the entrance gallery in Bab el Nasr is a skewed barrel vault, which adds complexity to the geometric solution.

In summary, the masonry works executed in Badr al-Jamali's Fatimid walls present architectural elements unknown previously in Muslim Egypt. In fact, most features of the walls and gates are foreign to Islamic art, as the semi-circular arches, instead of the classic Islamic pointed arches, completely disappeared in the gates. In addition, we can find other innovative factors such as the use of pendentives. It is important to remember that all of these pieces, from the vaulted halls until the arches, going through the helicoidal vaults, were executed entirely with stonework techniques, which is clear evidence of this constructive innovation. All these new constructive practices in the architecture of Fatimid Cairo show the new Syrian tendency to stone constructions that includes classical patterns in non-classical buildings (Williams 2008: 142).

### Survey of Bab el Nasr Groin Vault

Bab el Nasr gate presents inside, after the main access, a space covered by a groin vault executed entirely with masonry elements. The main goal of the present study is to advance knowledge of the geometry and constructive features of this vault, which is one of the most representative examples of stonecutting techniques in the Fatimid walls of Cairo. With this aim, an architectural survey of the vault was carried out using photogrammetry techniques combined with direct measurement. Although there is not topographical support, the precision of photogrammetry itself for surveying vaults and stonework elements has been amply demonstrated in the

**Fig. 3** Groin vault in Bab el Nasr Gate. Photo: José Calvo, 2010





scientific literature (Aliberti and Alonso-Rodríguez 2018; Alonso Rodríguez and Aliberti 2019; López-Mozo et al. 2020; García-Baño et al. 2021).

The survey is based on 25 photographs in TIF format which cover the entire intrados surface of the vault. A Canon EOS 5D camera was used to take the photographs ensuring a 60% minimum overlap between them. The images have been processed using *Agisoft Metashape Profesional 7.1.3* automated photogrammetry software. The workflow consists of an initial phase of aligning the photos, detecting tie points and matching points and estimating camera locations. Afterwards, the process goes on to build a dense point-cloud with millions of coloured points that precisely define the shape of the intrados surface of the vaults. In this case, the dense cloud generated is formed by 4,198,445 points (Fig. 4). Regarding the precision of the model, the maximum deviations do not exceed 10 mm, which is an acceptable error rate considering that the joints between voussoirs range between 10 and 30 mm thick. Finally, the point clouds were exported in E57 format and loaded in Rhinoceros three-dimensional modelling software, where it was scaled and oriented basing on the previous measurements taken and considering the perimeter walls as vertical elements. This software simultaneously offers the functionalities of processing three-dimensional models and CAD assisted drawing. Thus, we have worked on the three-dimensional model, and we have obtained plans, elevations, longitudinal and cross sections in order to determine precisely the geometric characteristics of the vault.

The obtained results confirm that the vault is formed by the intersection of two elements whose axes are orthogonal to each other: a longer longitudinal cylinder (10.58 m long) and a transverse cylinder whose length (8.22 m long) fits the scope of the intersection, which approaches the square plan (8.20×8.22 m). The four opening arches of the cylinders present different conditions. The main access of the longitudinal cylinder opens directly on the wall. On the contrary, the back rests on

**Fig. 4** Bab el Nasr groin vault: dense cloud of points. Image: authors



a skewed arch whose heads, parallel to each other, are located in oblique planes to the axis of the cylinder. The openings arches of the transverse cylinder are blind arches in the sidewalls. There we find two spherical niches that incorporate small pendentives. The voussoirs distribution in both cylinders is generated by dividing the opening arches in 33 parts generating 33 rows, so that a row is arranged in the keystone. The beds joints are generated by the horizontal projection of the joints parallel to the axes of the cylinders. This arrangement allows continuity of intrados joints in both cylinders (Fig. 5).

From the data obtained in the architectural survey, we notice that the four opening arches are slightly pointed arches. Consequently, the vault keystone height in the intersection of the two diagonal edges is lower than the keystone in the opening arches and presents a deflection/span ratio of about 1/75. Following this ratio, the height difference of the vault keystone in respect to the keystones of the perimeter arches is proportionally greater for the longer longitudinal vault than for the transverse vault, which has a shorter axis. As a result, the bending of the centre of the vault is 150 mm with respect to the longitudinal cylinder arches (h1), and 110 mm from the keystones of the transverse cylinder arches (h2). The intersecting edges, however, are close to the ellipses that would correspond to the intersection of two theoretical cylinders with an elliptical cross section. Despite small deviations, they are practically elliptical curves that show no pointing. The originated small irregularities are probably manifested because of deviations caused by the construction of the piece itself. The height of the keystone with respect to the springer of the vault is 4.11 m, which is approximately 14 Roman feet (Fig. 6).

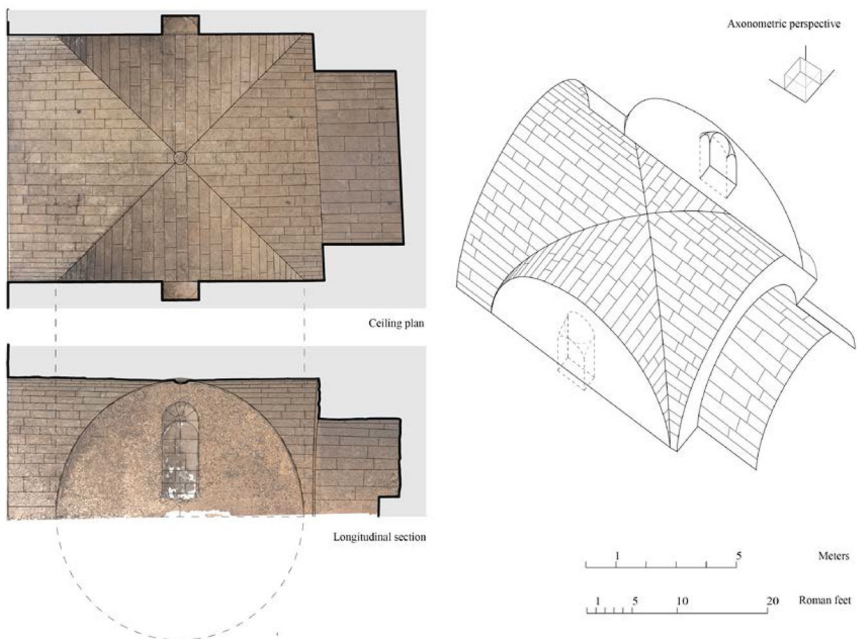


Fig. 5 Groin vault: orthogonal projections and perspective. Image: authors

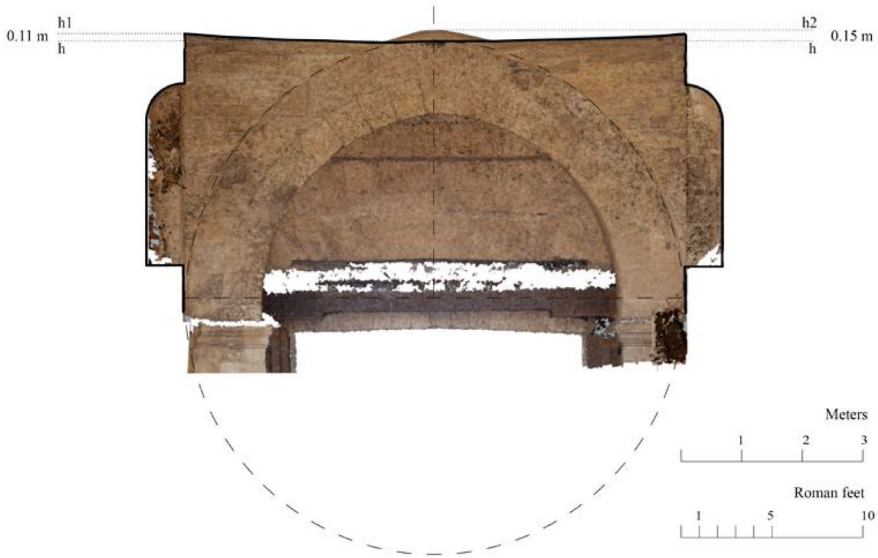


Fig. 6 Groin vault: cross section. Image: authors

Under these conditions, the vault is constituted by four surfaces, which are actually ruled surfaces whose directrices are the pointed opening arches and the two curves in the diagonal edges. The straight generatrices are parallel to the axis of the vault. This is a strange solution because medieval groin vaults generatrices are usually horizontal, keeping the keystone at the same height of the opening arch keystone. Choisy (1899, 2: 152) describes as a very ancient practice of the Syrian builders, the system of groin vaults in which the rows of both cylinders have continuity in the intersecting edge. He indicates that this type of vaults, which seem foreign to the Western architecture of antiquity, is the one adopted by the Romanesque architects, who introduced a modification to obtain more solidity. This modification consists of raising the vault keystone in respect to the opening keystones, providing a domed effect on the vault.

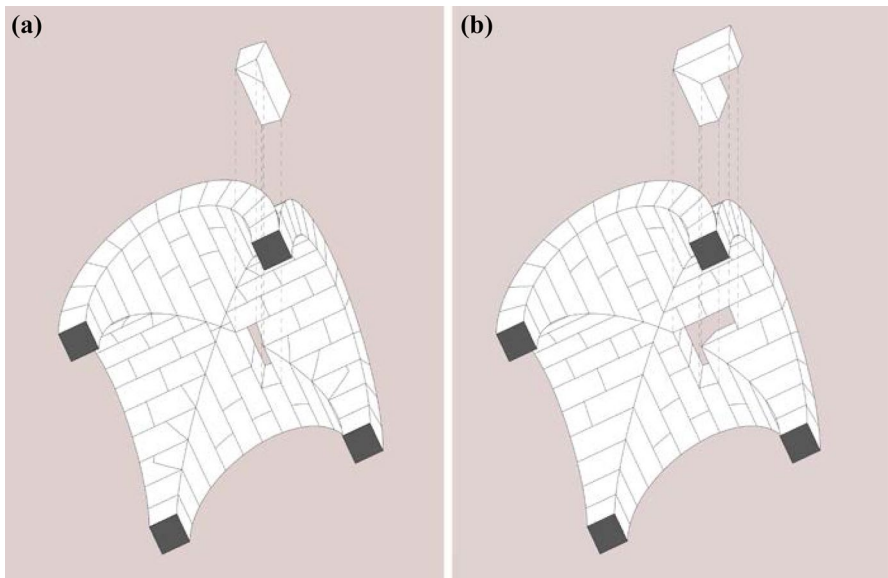
However, Bab El Nasr groin vault presents the opposite situation, with the keystone at a lower level than the opening arches' keystone. This unusual situation can be explained in the sense that the architect wanted the continuity of the edges. This resource could be used to gradually minimize the pointed shape from the opening arches towards the centre of the vault and to avoid the discontinuity in the intersection of the edges. The execution of the voussoirs is solved by a very accurate work, taking into account the small thickness of the joints. The result is a clean and continuous intersection of the surfaces, without distorting elements and with a very clear definition at the diagonal edges.



## Results

Regarding the use of groin vaults as a solution to cover spaces, Choisy (1899, 1: 518–519) mentions the existence of examples of groin vaults belonging to Romanesque architecture. Regarding the way to solve the intersection of both cylinders, the solution consisted of raising the opening keystone of the smaller cylinder when the height allows it to avoid the effect of penetration. Choisy considers that the oldest groin vault known could be probably the one that covers a tomb in Pergamum, dating from the Attalid time between the years 282 B.C. and 133 B.C. In it, we can see the solution adopted by the Middle Ages architecture of Asia to solve the voussoirs' tracing and carving, already mentioned by Choisy.

This construction system is very usual in medieval groin vaults. When the rows arrive to the edge, the voussoirs of one direction are cut by the other cylinder, but do not link the surfaces that intersect in it. This allows the carving without losing stone, avoids the problem of the incoming angles, and makes possible to work on-site without a geometric previous conception of the voussoirs (Fig. 7a). Rabasa (2007: 76) has analyzed in detail the way of carving the voussoirs of the edges of this construction system, indicating that although the squaring procedure, by the enveloping prism of the piece, is suitable, they can also be dressed by means of templates with the form of the outline of the faces. In Bab El Nasr gate, the most remarkable aspect of the vault is the constructive solution of the edges, apart from the accuracy of the voussoirs' execution. The voussoirs in the edges belong to the two intersecting vaults, so that their shape in the projection is like an “L”. The arms generate continuity in the successive rows making a lock between both, and



**Fig. 7** a Groin vault with linear—not “L” shaped—voussoirs solution in edges. b Groin vault with “L” shaped voussoirs and locked courses in the edges. Image: authors

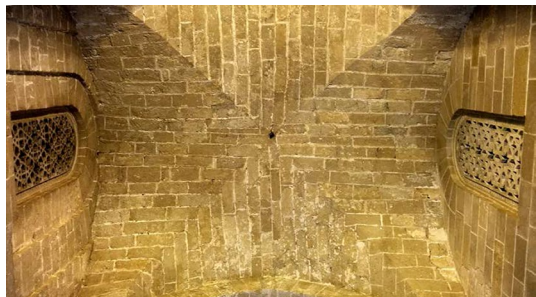
improving their structural behaviour (Fig. 7b). This arrangement requires a previous and accurate spatial conception of the final shape of the voussoir. Therefore, it requires a geometric definition and control of the surfaces that will form the voussoir faces and the angles between them. Thus, once arranged in their precise location they are perfectly integrated in the set, providing adequate beds joints and the continuity of the whole intrados surface. Additionally, the fact that the central keystone is at a lower level complicates further the intrados geometry, since the conditions of the intersection between the voussoirs' faces of the edge vary for each row.

The geometry of the voussoirs in the edges, which can no longer be carried out on-site, suggests the use of the method known as “by squaring”. This method consists on the creation of an enveloping prism of the piece, determined from its orthographic projections. Then, the masons eliminate the remaining parts from the prism until they obtain the desired shape of the voussoir. This procedure requires the use of stone blocks of greater size, and therefore, of greater weight. This implies a significant waste of material and complicates the execution for placement on site, since the “L” shape has a greater risk of fracture during the manipulation, the elevation and the placement in the formwork. It is surprising, at such an early date of execution, to see the use of locking voussoirs on the edges. Therefore, this is one of the few known medieval vaults executed with this system.

The usual way of solving the connection of the voussoirs at the edges, used even at a much later date than the construction of the Bab El Nasr gate vault, is to use voussoirs that only belong to the row of one of the cylinders, whose end faces are dressed on site according to the orientation and directions of the corresponding row of the perpendicular cylinder, with which it must be fitted. This solution, as previously mentioned, does not require a previous geometrical conception of the voussoir's volumetry for its carving before its placement in the vault.

To this type belong some of the vaults built by Norman stonemasons during the fourth and fifth decade of the twelfth century in Sicily. As an example, we can mention several vaults built in Palermo, in the Norman Palace, whose construction dates approximately from 1140. In them, there are evident problems that the stonemasons had to solve at the encounters between the two cylinders despite executing the solution of non-locked edges (Fig. 8). They were forced to lose the parallelism between the bed joints of each course, which sometimes

**Fig. 8** Groin vault with linear—not “L” shaped—voussoirs solution in edges. Norman Palace (Palermo, c. 1140). Photo: authors, 2016



**Fig. 9** Groin vault with linear—not “L” shaped—voussoirs solution in edges. Church of Santa María dell’Ammiraglio (Palermo, c. 1143). Photo: authors, 2016



**Fig. 10** Groin vault with linear—not “L” shaped—voussoirs solution in edges. Church of San Cataldo (Palermo, c. 1154). Photo: authors, 2016

even appear curved. Some of the rows in the final section next to the edge are also partially subdivided into two smaller rows in order to solve the connection. In addition, these vaults lack a specific keystone, so that the theoretical intersection vertex between the two edges is at the meeting of two of the bed joints of two rows. Another example built in Palermo is one of the vaults of the Church of Santa Maria dell’Ammiraglio, built around 1143, whose execution shows the same problems as the vaults of the Norman palace, although in this case the distortions introduced in the rows of the voussoirs are somewhat smaller (Fig. 9). There is a third building in Palermo: the church of San Cataldo, built in 1154 slightly later than the two previous ones, which also contains groin vaults executed using the procedure of non-locking courses. The rectangular plan adds an additional problem to the formal solution, and its construction reveals the important geometrical problems that the Norman stonemasons responded to with less skill, by using a solution in which two courses of one cylinder often

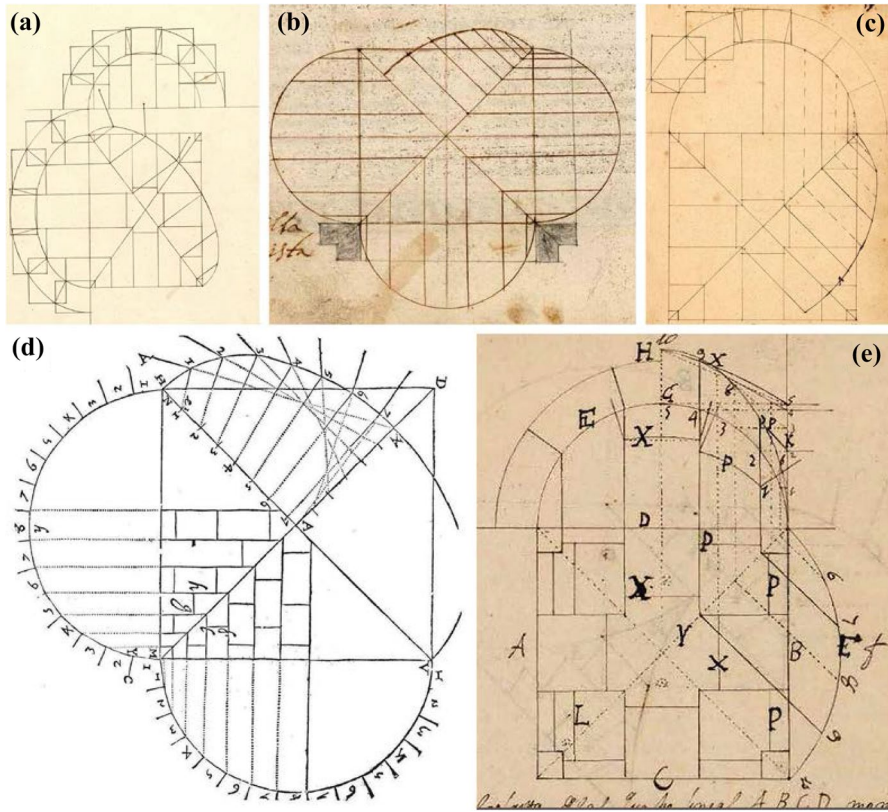
coincide with a single course of the other (Fig. 10). This fragmentation, which helps to constructively solve the encounter, is reminiscent of the techniques used at an earlier date for the construction of brick vaults by slices.

The lower level of knowledge of the examples mentioned above, whose dates are close to the Fatimid walls reconstruction by the Saladino Norman prisoners, indicates the transmission of knowledge from East to West, an idea suggested by Tamboréro (2006: 3027). The set of characteristics of the vault shows the high level of stonecutting knowledge of its architects in the medieval period, in which the transmission of knowledge was mainly done in a verbal way and whose graphic documents are barely known.

Centuries later in the middle of sixteenth century, with the appearance of the first stonecutting treatises and manuscripts, the traces of groin vaults were graphically solved by locking voussoirs in the edges. The first of these is the vault drawn in the oldest known text of Hispanic stonemasonry, the anonymous Manuscript of stonecutting Mss. 12686 of Biblioteca Nacional de España (c. 1544), linked to the Vizcaino stonecutter Pedro de Alviz (García-Baño 2017). It is a slightly rectangular vault, in which both cylinders are divided into seven courses of voussoirs, providing the continuity of joints at the edges. Although the horizontal projection does not show the quartering of the voussoirs in a specific way, the vertical projections show the enveloping prism of the voussoirs of each course in both directions, which allow us to determine the size of the block of stone necessary to dress “by squaring” the “L” voussoir common to both cylinders at the edge. The keystone voussoir, the elliptical curve intersecting the two cylinders, and the angles formed by the bed joints where the two cylinders meet are also completely defined (Fig. 11a).

With a similar approach, although with some modifications—especially in the way of drawing the horizontal and vertical projections and the solutions for their carving—there are models of groin vaults collected by other authors such as Alonso de Guardia (c. 1600), which includes three different solutions (Fig. 11b), and the Manuscript Mss. 12744 of Biblioteca Nacional de España (c. 1600), with a model very similar to the one in the Manuscript Mss. 12686 (Fig. 11c). The French Jousse (1642) proposes a groin vault with a square plan in which he obtains the templates to carve the voussoirs of the edges. In the same line is the groin vault included in his treatise by Gelabert (1653), which presents a unique method to carve the voussoirs of the edges directly by means of templates (Rabasa, 2011: 138–141). The vault included in the treatise by de San Nicolás (1639) is the first one that includes in the horizontal projection of the quartering of the voussoirs in each course (Fig. 11d). His drawings would be copied a few years later by de Portor y Castro (1708), who also included in his treatise three other groin vaults, with solutions for their carving “by squaring” and also by means of templates (Fig. 11e). In their solutions, they designed horizontal and vertical projections including the generation process of the ellipse in the diagonal edge determined by passing points. This process surprisingly responded to a constructive arrangement in the edges similar to which more than five centuries before was employed at Bab El Nasr gate.





**Fig. 11** Groin vault: **a** *Manuscript Mss. 12686*, c. 1544. **b** Guardia, A. *Manuscript of stonecutting*, c. 1600. **c** *Manuscript Mss. 12744*, c. 1600. **d** San Nicolás, F.L. *Arte y uso de Arquitectura*, 1639. **e** Portor y Castro, J. *Cuaderno de Arquitectura*, 1708. Images from the holdings of Biblioteca Nacional de España

## Conclusions

The Bab el Nasr gate is a case of stone construction that includes singular masonry pieces, such as a skewed arch, two spherical niches and, especially, a groin vault executed with great accuracy. But this is not the only outstanding stonework in Cairo built during the eleventh century. In fact, there is a surprising diversity of masonry works which includes arches, vaults, domes and even pieces whose design and execution are very difficult, as the helicoidal stair in Bab el Nasr gate. This could also inspire similar works in Europe subsequently, following the transmission of knowledge from the Eastern builders to the Western builders. In fact, as noted above, most features of the walls and gates are entirely foreign to Islamic art, apart from some Quranic inscriptions. This is probably due to the fact that the gates were built by three Christian monks from Urfa (Edesse), although there are no remaining similar works in that area. The Byzantine Empire covered a large area of Anatolia and the eastern Mediterranean, including northern Mesopotamia where Edessa is



situated. In fact, round arches with spherical pendentives, squinches and shelled vaults all belong to Byzantine architectural tradition that were applied to the walls design in Cairo walls.

Regarding the Bab el Nasr gate, the groin vault that covers the entrance vestibule has turned out to be a great masonry example. As we exposed before and after knowing the results of the research, there are several facts that give it a high quality. We can suppose that the joints are perpendicular to the vault intrados surface so that the external face of the voussoirs was not cut on site, but initially the finished pieces could be installed and finally they were precisely defined. Furthermore, the voussoirs have great length and the joints rarely have more than 3 mm wide, which gives to the work a remarkable execution quality. However, the most remarkable feature of the vault is the solution in the diagonals. The way in which the edges are solved, with locking voussoirs that belongs to the two intersecting surfaces, requires a previous geometric design of the surfaces that configure the voussoir shape, and the carving process must be done prior to the placement on the vault formwork, as mentioned before. The use of this advanced system in a vault built in such an early date is surprising, especially compared to the usual medieval systems with edges solved with linear voussoirs, not locking, and carved on-site. It shows the high level of knowledge and professional expertise of its architects, and especially if we take into account that they already used solutions in the eleventh century very similar to those that five centuries later would be seen in Renaissance stonecutting treatises.

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## References

- Aliberti, Licinia and Miguel Ángel Alonso-Rodríguez. 2018. Digital photogrammetry for the geometrical analysis of the umbrella-shaped dome in Baia (Naples). *The international archives of the photogrammetry, remote sensing and spatial information science XLII* (2): 23–28, <https://doi.org/10.5194/isprs-archives-XLII-2-23-2018>. Accessed 26 September 2021.
- Alonso Rodríguez, Miguel Ángel and Licinia Aliberti. 2019. Automated photogrammetry applied to the study of vaults. *EGA Revista de Expresión Gráfica Arquitectónica* 24 (35):152-159.
- Anonymous. c. 1544. *Manuscrito de cantería*. Madrid: Biblioteca Nacional de España, Mss. 12686.
- Anonymous. c. 1600. *Manuscrito de arquitectura y cantería*. Madrid: Biblioteca Nacional de España, Mss. 12744.

- Behrens-Abouseif, Doris. 1998. *Islamic architecture in Cairo*. Cairo: The American University in Cairo press.
- Choisy, Auguste. 1899. *Histoire de l'architecture*. Paris: Gauthier-Villars. facsimile ed.
- Creswell, Keppel Archibald Cameron. 1978. *The Muslim architecture of Egypt*. New York: Hacker Art Books.
- García-Baño, Ricardo. 2017. *El manuscrito de cantería Mss. 12686 de la Biblioteca Nacional de España*. PhD Dissertation, Escuela Técnica Superior de Arquitectura y Edificación. Universidad Politécnica de Cartagena.
- García-Baño, Ricardo, Macarena Salcedo-Galera, Pau Natividad-Vivó and Vincenzina La Spina. 2021. The aditus maximus of the Roman theatre in Málaga: An early model of Roman stonework vault. In *History of Construction Cultures* (vol. 2), ed. Mascarenhas-Mateus, 309–316., J. London: CRC Press.
- Gelabert, Josep. 1653. *Verdaderes traces de l'art de picapedre*. Palma de Mallorca: Biblioteca del Consell Insular de Mallorca.
- Guardia, Alonso. c.1600. *Manuscrito de arquitectura y cantería*. c. Madrid, Biblioteca Nacional de España. Notes on a copy of Battista Pittoni, *Imprese di diversi principi, duchi, signori ..., ER/4196*
- Jousse. Mathurin. 1642. *Le secret d'architecture découvrant fidèlement les traits géométriques, coupes et dérobements nécessaires dans les bastimens*. La Flèche: Georges Griveau.
- López-Mozo Ana, Enrique Rabasa-Díaz and Miguel Ángel Alonso-Rodríguez. 2020. Layout, construction and surveying of curvilinear ribs in late Gothic vaults. The case of Priego. In *Graphical Heritage. Springer Series in Design and Innovation* (vol. 5), ed. Agustín-Hernández L., 247–258. Cham: Springer.
- Portor y Castro, Juan. 1708. *Cuaderno de arquitectura*. Madrid: Biblioteca Nacional, MS 9114.
- Rabasa, Enrique. 2007. *Guía práctica de la estereotomía de la piedra*. León: Centro de los oficios.
- Rabasa, Enrique. 2011. *El manuscrito de cantería de Joseph Gelabert*. Palma de Mallorca-Madrid: Col·legi Oficial d'Arquitectes de les Illes Balears; Fundación Juanelo Turriano.
- Rabat, Nasser O. 1995. *The citadel of Cairo*. Leiden: E.J. Brill.
- Raymond, André. 1993. *Le Caire*. Paris: Fayard.
- San Nicolás, Fray Lorenzo. 1639. *Arte y uso de arquitectura, Primera parte*. Madrid: Printed by Juan Sánchez.
- Tamboréro, Luc. 2006. "The "Vis Saint-Gilles", symbol of compromise between practice and science". In *Proceedings of the Second International Congress on Construction History*, ed. Dunkeld M. et al., 3025–3040. Cambridge: Construction History Society.
- Warner, Nicholas. 2005. *Monuments of historic Cairo*. Cairo: The American University in Cairo press.
- Williams, Caroline. 1983. The cult of 'Alid Saints in the Fatimid monuments of Cairo. Part I: The mosque of al-Aqmar. *Muqarnas: An annual on Islamic Art and Architecture* (vol. I), 39–41.
- Williams, Caroline. 2008. *Islamic monuments in Cairo*. Cairo: The American University in Cairo press

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