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RESEARCH

A Geometric Analysis of Masonry Sail Vaults at the Magistral Palace, Valletta, for the Study of Maltese Stereotomy

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Abstract

The research deals with an interesting interdisciplinary case study for the knowledge and dissemination of masonry sail vaults in Malta between the 16th and the 17th centuries. In particular, it focuses on the sail vaults of the Magistral Palace, which have a distinctive structure. Based on a digital survey, the necessary data was extrapolated to critically analyse the geometry, through drawing and three-dimensional modelling. The paper, therefore, presents graphical and geometric investigations, which complement the study of the history of the Magistral Palace. Comparisons with the Maltese architectural context between the 16th and 17th centuries show the use of different solutions for the construction of sail vaults, according to different geometries. This implies knowledge of the international debate on the theory of stonecutting at the time.

Keywords Architectural survey · Geometric constructions · Rule-based architecture · Construction history · Magistral palace

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Introduction

The study of vaults represents an interesting challenge, given the vast typological variety and heterogeneity that exists in the built heritage. The continuous growth and improvement of surveying technologies, juxtaposed with informed studies and conscious reading of geometry and form, contribute to more comprehensive analysis and better understanding of this heritage, allowing comparisons and studies of the structure of various kinds (Calvo López et al. 2020; Rossi and Fiorillo 2020; Bianchini 2020). Reality-based modelling gives the possibility to model discrete surfaces that are increasingly close to real ones. Moreover, it facilitates comparison between design drawings and reality (Spallone 2019) and often the identification of rules and constraints that facilitate the development of automatic parametric modelling even of complex surfaces (Angjeliu et al. 2019; Vitali 2017).

The study starts to investigate architectural elements from the lower courtyard loggia at the Magistral Palace, until now undated. The centre of the city and the heart of the nation, since the time of the Knights of St John, the Magistral Palace remains the political, social and cultural centre of the Islands until this day. Understanding its transformation and development therefore remains of crucial importance. The scope of this paper is, therefore, to investigate and provide an initial interpretation of the unusually shaped sail vaults characteristic of one of the courtyards of the palace. Based on architectural surveys and digital elaborations, it was possible to elaborate data through the reading of the geometric matrices that compose it, produce an initial geometric analysis and also extrapolate an interpretation of its shape. In this way, the analysis of the characteristics and the particularities of these vaults led to the formation of hypotheses which in addition to providing preliminary answers, have posed interesting questions that lend themselves to future assessments.

The Magistral Palace: Context of the Investigation

Located in the centre of Valletta - the capital city of the Maltese Islands - the Magistral Palace originated as the Palazzo del Monte, a private residence of Eustachio del Monte, the nephew of Grandmaster Pietro del Monte (1568–1572). Fra Pietro assumed control and started residing in Palazzo del Monte in 1571 upon relocating to Valletta from Birgu. Soon after, the residence started serving as the informal Magistral Palace until the planned palace was to be built close to the land-front. The palace as intended in the designs of Francesco Laparelli, however, was never built and between 1569 and 1572, Fra Del Monte further expanded Palazzo del Monte with the acquisition of other plots abutting it. At the demise of Fra Pietro del Monte, the palace passed on to his successor Grandmaster Fra Jean l'Evesque de La Cassiere (1572–1584) and it is likely that at this point it was elevated to its official status as the Magistral Palace. Under Grand Master La Cassiere, the palace was subjected to the first transformation works aimed at enlarging the complex, until it comprised the entire city block. By 1576, La Cassiere asked for and obtained the newly built auberge of Italy, located on an adjacent plot to the palace. Works on the auberge are known to have been carried out under Girolamo Cassar (Ganado et al. 2001; Vella 2014). Under La Cassiere, the two building units forming the palace– the Palazzo del

Fig. 1 The courtyard of the Magistral Palace, Valletta, Malta. Image: Heritage Malta

Monte and the first auberge of Italy– remained as two distinct buildings, though it is most probable that some work was done to delineate and consolidate the compound's perimeter within the city block defined by Strada San Giacomo (current Merchants Street) and Strada San Giorgio (current Republic Street and St George's Square). The sloping terrain places the two buildings at different levels, with Palazzo del Monte set almost 1.5 m higher than the auberge. The difference in levels hindered the achievement of a coherent layout at the ground floor level, which would have required major interventions. In the absence of these works, the palace remained compartmentalised into two distinct parts. Grand Master La Cassiere, resolved the difference in levels between the two ground floors by connecting them through a doorway and a flight of steps located in the rooms at the back of the del Monte residence, overlooking the garden, hence creating a link with the lower courtyard (Abdilla Cunningham et al. 2024; Fig. 1).

The subsequent Grand Master, Fra Hugues Loubenx de Verdalle (1582–1595), further consolidated the building as a single palatial unit (Ganado et al. 2001; Vella 2014; Fig. 2). Rather than undertaking major reconstruction works to mitigate the levels, the existing fabric was retained. The first floor was further enlarged to include the 'winter rooms' and the treasury tower. The difference in levels at the ground floor level was also resolved with the construction of a Grand Staircase - a ceremonial flight of stairs (garigor, garagol) - which was inserted between the two older buildings, hence mitigating the connection whilst also introducing a more regal entrance to the first floor. A loggia with three vaults is presumed to have been introduced in front of these two accesses within the lower courtyard at this time. Both the Grand Staircase and the loggia are adorned with the head of a wolf, characterising de Verdalle's emblem (Fig. 3). A waterspout in the form of a wolf's head adorned the central arch.[1] Until this time, the courtyard lacked its defining arcade surrounding the perimeter. It is yet unclear when these arcades were built since no documentation survives. Beyond de Verdalle's symbolic wolf head-shaped spout, nowadays located at a rather

[1] The wolf is a symbol of Grand Master de Verdalle and features on the family's crest.

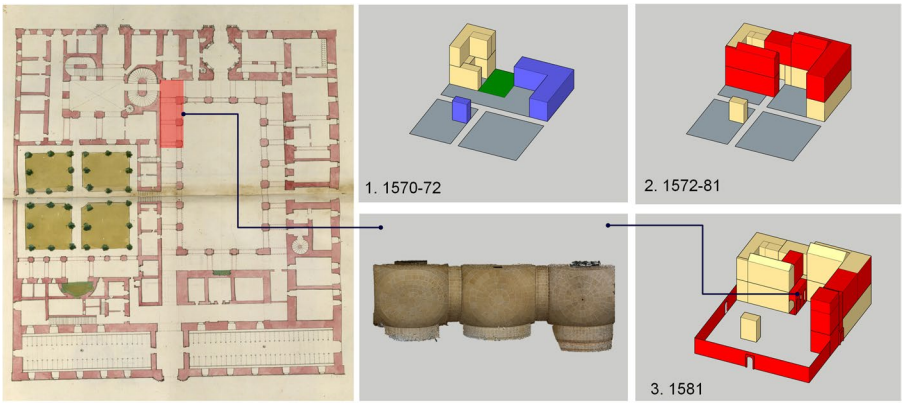

Fig. 2 Development stages of the Magistral Palace identifying the addition of the first loggia in the lower courtyard. Left image: National Library of Malta; 3D models: Christian Mifsud

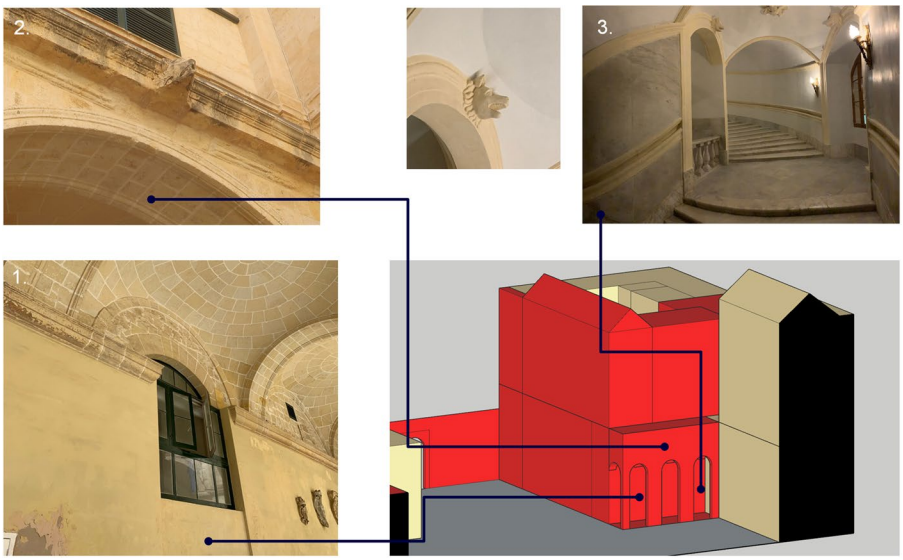

Fig. 3 Elements of the first loggia as presently visible on-site

awkward placement in the courtyard, there are no other emblems to indicate a period of origin.

The loggia is constructed with pilasters, and capped with sail vaults which serve as the platform for the corridor which passes above at the first-floor level and connects the State rooms and other spaces around it. Ongoing rehabilitation works of the palace carried out by Heritage Malta also investigate the development of the palace to understand its transformation through the ages. From a visual assessment of the site and a related chronological assessment of the structure, the following working hypothesis has been put forward. In the late sixteenth century, following the construc-

tion of the stables at the back of the site (overlooking current Merchants Street), an arcade is likely to have been built, starting from the de Verdalle loggia. This ran along the existing internal façade of the former auberge and connected with the stables. The second part of the loggia, running along the spine of the palace, was built once the construction of the rooms dividing the courtyards was completed.[2] The study and phasing of the loggia are proof that, contrary to previous belief, the loggia did not form part of the original Auberge of Italy and hence could not have been built as part of the auberge under the Maltese Architect Girolamo Cassar.[3] The loggia was built in three different stages, and a difference in the refinement of the construction techniques can be observed. Furthermore, since the first loggia constructed indicates stereotomical differences from the subsequent stages, it was thought opportune to investigate the methods of construction to potentially better identify the differences for revealing new insights on the undated transformations of the palace. It is also interesting that this indirectly provides insights into the stonemasons' construction techniques and may help identify the influence and points of contact that the stonemasons had with foreign masters beyond the Maltese shores.

The study presented here focuses on this loggia space, which consists of three sail vaults. The loggia served as a point of encounter which historically preceded the two entrances - the entrance to the personal lodging of the Grand Master housed in the former Palazzo del Monte and the Grand Staircase which leads to the State Rooms on the first-floor. The loggia was also a point which guided visitors through the two entrances and thence led into the different socio-political circles of the Grandmaster, represented by the different spaces that they were allowed access to.

Data Acquisition and Geometric Analysis of the Vault

The interpretation and geometric reading of the vaults of the loggia of the Grand Master's Palace were conducted from image-based and range-based surveys. The integration of the two techniques allowed for a better reading of the sail vaults both geometrically and colourimetrically and consequently allowed the production of a relatively accurate drawing. The on-site surveys were conducted on different days and times. The photogrammetric survey was carried out with a compact Canon PowerShot G9 Mark II camera that captured only the upper part of the vaults. It was equipped with a CMOS sensor of 1" (13.2×8.8 mm) and about 20 Megapixels. The shots acquired were processed in Agisoft Metashape software which made it possible to return a first sparse point cloud. To support the photogrammetric data, a laser scanner survey was carried out. The equipment used was Leica RTC360, with an action range of a minimum of 0.5 m up to 130 m and characterized by a data collection

[2] The third stretch of the loggia is likely to have been added once the new stables were constructed mirroring the older ones. The last set of loggias link directly to the entrances of the two stables placed opposite each other and the space in between serves as an entry hall space which from Merchants Street leads into the palace. Towards the middle of the third loggia, a connection between the two courtyards dates to the mid-18th century and was executed once the access to the del Monte wing was blocked off. Interestingly, this connecting access was introduced to create a visual axiality between the two side portals connecting with the two side streets.

[3] The building of the Auberge is attested in official documentation dating to 1581.

speed of up to 2 million points per second. The scan recordings did not entail the use of targets due to the VIS technology featured in the instrument. In the laser scanner survey, the area collected was more comprehensive than the photogrammetric surveys discussed in the case study. During the assessment, it was necessary to select the data and extract the interested portion of the point cloud, mainly the three vaults previously surveyed with the image-based technique. The photogrammetric model was then scaled and aligned according to the measurements extrapolated from the laser scanner point cloud, through the identification of corresponding points and assigning their matching Cartesian coordinates. The model was finally processed in Agisoft Metashape to obtain the textured mesh model and an orthophoto of the sail vaults.

The obtained data was then used to describe the geometric matrices underlying the stone vaults of the loggia. Given the complexity of the data to be analysed, it was decided to use a digital representation and 3D modelling procedure based on Non-Uniform Rational B-Splines (NURBS) that allowed an approximation of the morphology similar to that of the vaults surveyed. The software used was Rhinoceros (version 7), which allows for extracting a reproduction of both the extrapolated orthophotos and also directly from the 3D model through the drawing of polylines, curves and surfaces. To constitute effective analyses and interpretations, as frequent in such cases, the drawing of what is visible was not enough, but it was necessary to use precise geometric rules and comparisons with case studies similar to the one studied. Analysing the technical drawing in Fig. 4, it is possible to notice the uniqueness that defines each vault within this loggia. In the planimetric layout, the different measurements of the three rectangular vaults are visible.

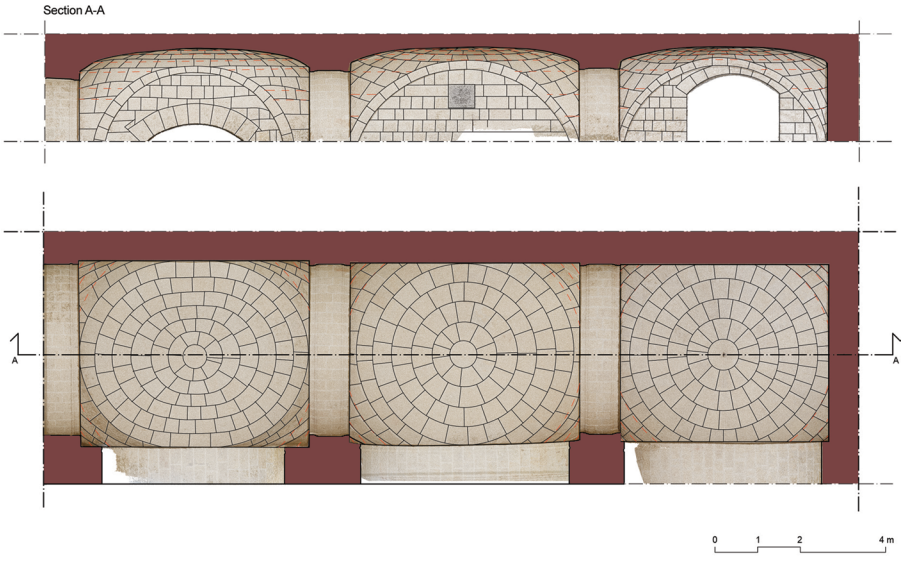

Fig. 4 Magistral Palace's vaults. Drawing of joints in the ceiling plan and longitudinal section based on orthophoto extracts from the photogrammetric process (real joints are in solid black lines, while the dashed lines follow a sufficiently regular geometric pattern)

Figure 4 presents two vaults with similar spans and one located in the corner, all with different dimensions. In addition to analysing the planimetry of the loggia, the distinctive layout of the vaults and how the ashlar joints shape them were also examined. In Fig. 4, the mortar joints characterising the vault have been outlined, highlighting the real joints in solid black lines while those that follow a sufficiently regular geometric pattern have been marked in dashed lines. It is possible to see how in the plan this presents a relatively regular concentric distribution and how this regularity is only lost towards the edges. In this case, the geometry also varies from vault to vault, and despite being presented with a similar plan on two occasions, the distribution of the ashlars is nonetheless different. The same analysis was undertaken for the sections of all the sail vaults of the loggia and it was noticed that a considerable difference existed between the ideal regular distribution following the horizon (dashed line) and the built design which differs noticeably (solid line). The composition of the ashlars represents one of the main characteristics that has caught the authors' attention and led to analyse of the possible causes of this divergence in the structure. Another interesting condition, that can be seen in Fig. 4, is the curvature of the vault system which, in this case, is not derived from a sphere but originates from a polycentric curve. Contextualising the observations in the history of the space, and its transformations, it was decided to focus on the first vault as a reference for a more in-depth analysis. It is however opportune to note that considering the consistency noticed through the remaining vaults forming the loggia, the authors will explore the other vaults' geometries forming the loggia in future investigations.

Different to the previous analysis, a further study was conducted in a 3D digital environment (refer to Fig. 5). Starting from the drawing of the vault joints, through an automated extrapolation present in Rhinoceros software, the lines were projected onto the mesh surface. Hence, the interpolation of the points on the previously projected curves in a 3D environment, made it possible to generate an approximate surface representing the surface of the vault. This model shows irregularities similar to the real ones which allowed the authors to study the progression of the ashlars directly in 3D space and to develop an initial interpretation. The joints drawn in the plan were once again projected on the surface of the reconstructed vault in 3D.

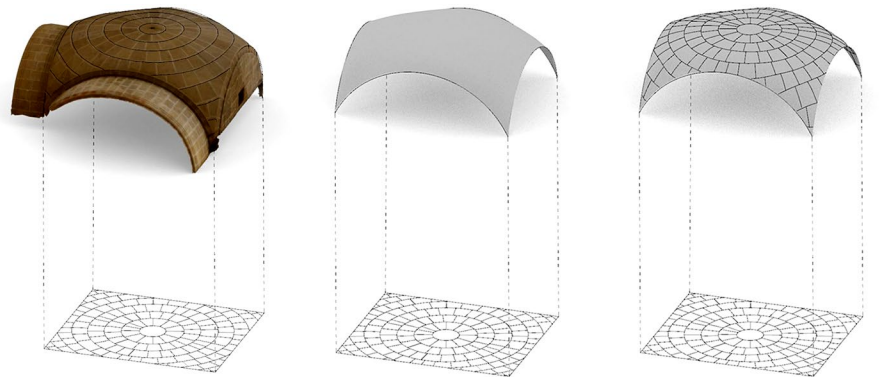

Fig. 5 Scheme of curve projection steps for generating a representative surface of the Magistral Palace vault

This network of curves generated in NURBs was more homogenous than the one produced with meshes (Fig. 5). As such, it was possible to extract sections of the reconstructed vault along the longitudinal, transversal, and diagonal axis and a comparison of the courses was carried out with those of the point cloud. This comparison highlights the good correspondence between surface projection and real vault. The external curvature of the joints was also analysed (Fig. 6) and once again confirmed the significant irregularity of the structure and the absence of precise symmetry. A further investigation was carried out by following the process in reverse. It was hence decided to represent a regular position of the ashlars on the 3D surface and then to project the regular network of curves onto a 2D flat surface on the plan. In this case, the projection returned curves that were completely irregular and divergent from the geometric matrix studied previously. These analyses have allowed the authors to express some initial hypotheses relating to the particular trend of the joints, caused by the polycentric surface that characterizes the vault and, most likely, by the structure movement and settlement which happened over time, that eventually skewed the shape of the vault.

The polycentric curvature was therefore further investigated with a geometric analysis. From a series of historical research and comparisons with treatises analysed by the authors, it was difficult to find evidence that would allow a correct definition of its curvature. A first hypothesis and geometric analysis are therefore being proposed here. For this study it was necessary to schematize the surface of the sail vault, eliminating some irregularities probably also due to structural failures over time or possible construction errors. The hypothesis is that the curvature of the vault is symmetrical. In addition, it is necessary to distinguish the geometry into two parts: the first corresponds to the pendentives - which seem to be formed by portions of the circumference of the same radius, and the second corresponds to the cap - which has more regular, more horizontal joints, and it is comparable to a circle with a larger radius (Fig. 7). The circumference c_1 near the pendentives, was created to make the edges of c_1 coincide with those of the section curve. This shape was then mirrored to the symmetry axis to create the c_2 circumference. Subsequently, it was necessary to identify the centre of the larger circumference c_3 capable of connecting the two smaller ones (c_1 and c_2). Points A_1 and A_2 of the circumferences c_1 and c_2 (chord of c_3) were joined to evaluate the perpendicular distance between the middle point

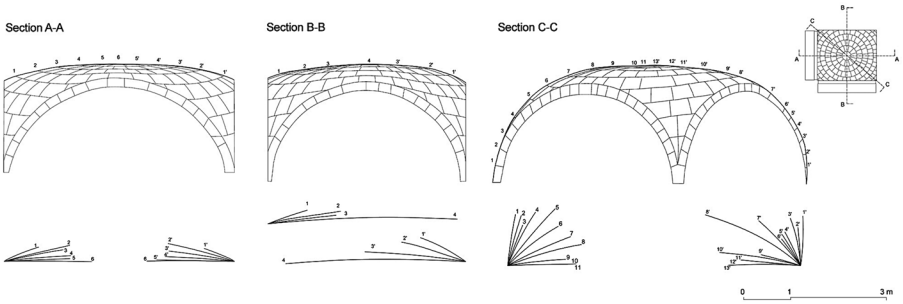

Fig. 6 Analysis of the curvature of the rows in the longitudinal, transverse and diagonal sections of the first vault of the Magistral Palace

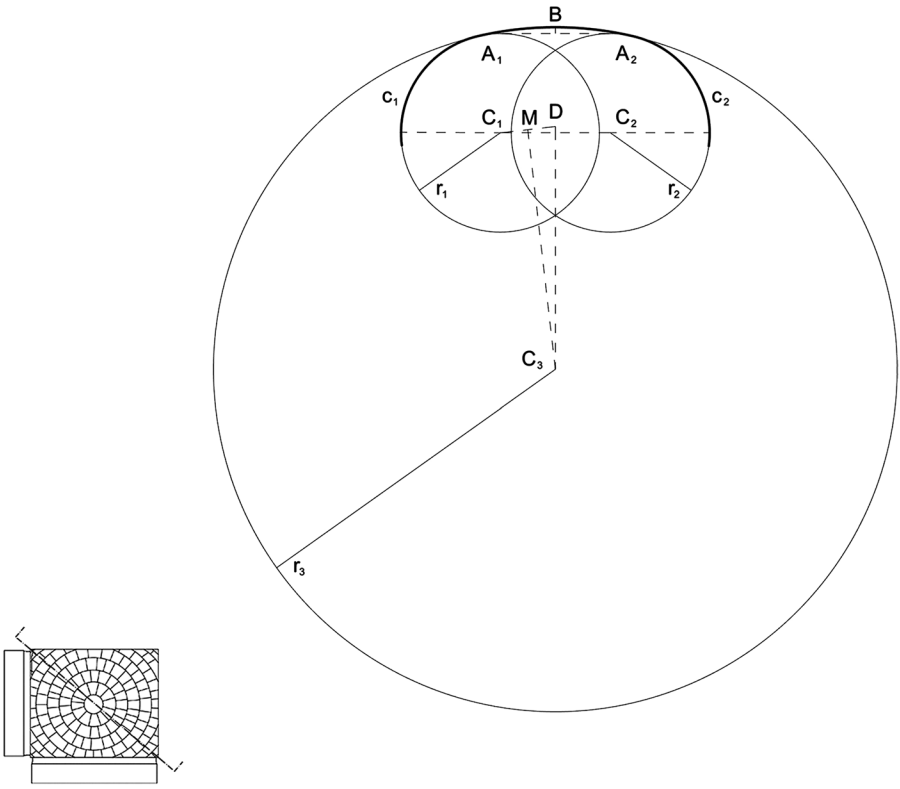

Fig. 7 First hypothesis of the geometric analysis of the vault diagonal profile

of distance A_1 A_2 and point B (belonging to the section curve). This distance was reported in the midpoint of distance C_1 C_2 and point D was connected to point C_1 (the same could have been done with point C_2). From the midpoint M of the section, the perpendicular was drawn up to the intersection of the symmetry axis. The point C_3 thus identified represents the centre of the circumference c_3 with radius r_3 which connects the circumferences c_1 and c_2 and represents the cap of the vault.

The Spread of Sail Vaults in Early Modern Maltese Architecture: Typologies and Construction Systems

Spherical masonry vaults were introduced in many of the large buildings within the new city of Valletta, not later than the 1570s. These can still be observed in the side chapels of the conventual church of St John, built between 1574 and 1578 by unknown masons, but most probably under the supervision of the Maltese architect Girolamo Cassar (Guido and Mantella 2008). These are segmented by a circular band in relief running at a tangent to the perimetral arches, by a second smaller upper circle closer to the keystone, and by eight radial ribs connecting the two circles (Fig. 8). This layout follows the subdivision of the voussoirs, whose joints correspond approximately to the reliefs so that the visual draught guided the stone cutting. The same

Fig. 8 Sail vault at St. John Church, Valletta

scheme is the one adopted in some of the side chapels of the church of St. Mary of Jesus, which can be dated to the same decade. All follow a system for the construction of spherical sail vaults, which remained in use during the 17th century, especially in some of the new parish churches built in the villages of the archipelago, reaching major dimensions and remarkable execution. In the church of St. Mary in Attard, for example, two sail domes built during the 1620s (Antista 2020) covering the bays of the transept show a perfect overlapping of the joints to the borders of the reliefs. The same happens in the church of St. Catherine in Zurrieq (Fig. 9) where the surface is visibly divided between a network of ribs and the surface resting on them.

As an alternative, at the Magistral Palace, the sail vault was tested in the last quarter of the 16th century with a daring approach, adopting a striking lowered section and a completely smooth continuous surface. The ongoing restoration works offer an opportunity for an in-depth study of these elements. The geometrical interpretations based on the surveys discussed in this study, help in the comparison of these vaults with other cases selected from the Maltese context, to identifying affinities, differences and experimental innovations.

While the vaults of the conventual church of St John show a semi-circular section, those of the court of the Magistral Palace are characterized by polycentric sections. Therefore, the latter is of a much more complex form to design and build, also determining greater horizontal thrusts and implying the knowledge of modern stereotomy, codified in the sixteenth century by Spanish architects like Alonso de Vandelvira. In the examined cases, the masonry apparatus can also be reconstructed, starting from the arrangement of the joints, distinguishing continuous systems which are characterized by a single surface (as in the case of the vaults of the Magistral Palace), from discontinuous systems in which the capping ashlars rest upon the ribbing structure beneath (as in the case of the parish church of Zurrieq, vaulted in the 1640s). This separation resembles the stereotomy model called '*por cruceros*' in Spanish treatises, a construction solution for a Renaissance model which takes advantage of gothic building traditions (Calvo López and Rabasa 2016). Incidentally, one of the objec-

Fig. 9 Sail vault at Zurrieq Parish Church

tives of the geometric analysis is to formulate hypotheses on the design references and the construction procedures. A better knowledge of their geometry is fundamental to attempting a connection between the Maltese masonry sail vaults to the Spanish and French models found in the stereotomy manuals (Natividad Vivó 2016; Palacios Gonzalo [1990] 2003: 254–259; Calvo López 2020: 427–433). As a result, it is possible to elaborate a hypothesis about the theoretical knowledge available to the architects involved in the construction of the investigated structures.

The sail vault of the sacristy of the church of St. Barbara in Valletta (Fig. 10), for example, adopts the simplest model with a spherical scheme. This is the same one codified by Alonso de Vandelvira under the title *Capilla cuadrada en vuelta redonda*, while in St. John conventual church, the already described vaults covering the side chapels show additional reliefs to the same ashlars' layout. The similar vaults built at Zurrieq, on the contrary, with the separation of a net of radial and circular ribs, are built according to a process which could have been similar to the one described under Title 135 of Vandelvira's manuscript, called *Capilla cuadrada enlazada* (Natividad Vivó 2017: I.141, 142, 239–243).

The lowered ones built on the rectangular bays at the Magistral Palace of Valletta are more directly linked to the model of the *Capilla perlongada (painel) por hiladas redondas* inserted in the manuscript treatise of Alonso de Vandelvira (Fig. 11). It is in the Iberian Peninsula that most of the known examples of stone sail vaults predating the Maltese ones can be traced, while in France its distribution was infrequent during the 16th century.[4] Interesting comparisons could be established with the lodged court-

[4] Few French examples, like the *pendentif de Valence*, go back to the 16th century, so that Jean Marie Perouse de Montclos identified the sail vault as a "Spanish" typology, despite being described by Philibert de L'Orme: 'la présence de voûte en pendentifs dans la France du XVIe siècle est quasi clandestine. En revanche, pendant le même siècle, la bóveda baída occupe en Espagne une place de choix, principalement

Fig. 10 La Valletta, sail vault over the sacristy in the church of St. Barbara

yards covered by masonry sail vaults of Iberian buildings like the Patio de los Óleos, in the Cathedral of Seville, or S. Jerónimo de Buenavista Monastery in the same city.[5] Andalusian architecture has been one of the main cores of innovation for the construction of sail vaults during the Renaissance, linked to architects like Diego de Riaño and Diego de Siloe (Natividad Vivó 2017: I.259–280). Yet such links between the two contexts are not easy to identify, as the names of the masons involved in the building sites remain unknown. The presence of an international community, as well as the continuous arrival of European architects and military engineers must have determined the migrations of knowledge (Antista 2022; Burgassi 2022). Undoubtedly, nothing similar appears in Sicily, in that there are no traces of sail vaults built during the 16th or early 17th centuries. This is uncharacteristic in an island which usually shared construction practices and masons, and which always represented an important connection between Malta and Europe.

Conclusion

The study conducted on the vaults of the Magistral Palace of Valletta allows us to reconstruct the geometric and construction characteristics and raises important questions for the sixteenth-century cases, linked to the origins of the design and construction models and any potential relationships with similar cases present in the Iberian

du fait d'Andrés de Vandelvira' (Pérouse de Montclos 2001: 207). On the French theoretical contributions regarding this typology, and its connection with Spanish stereotomy, see Calvo López 2016.

[5] Lastly, the Lonja de Mercaderes is a case of an institutional building presenting a sequence of sail vaults, even if not in the courtyard and characterised by an impressive variety of coffering designs. For its geometrical analysis, see Natividad Vivó 2017: II.206–215.

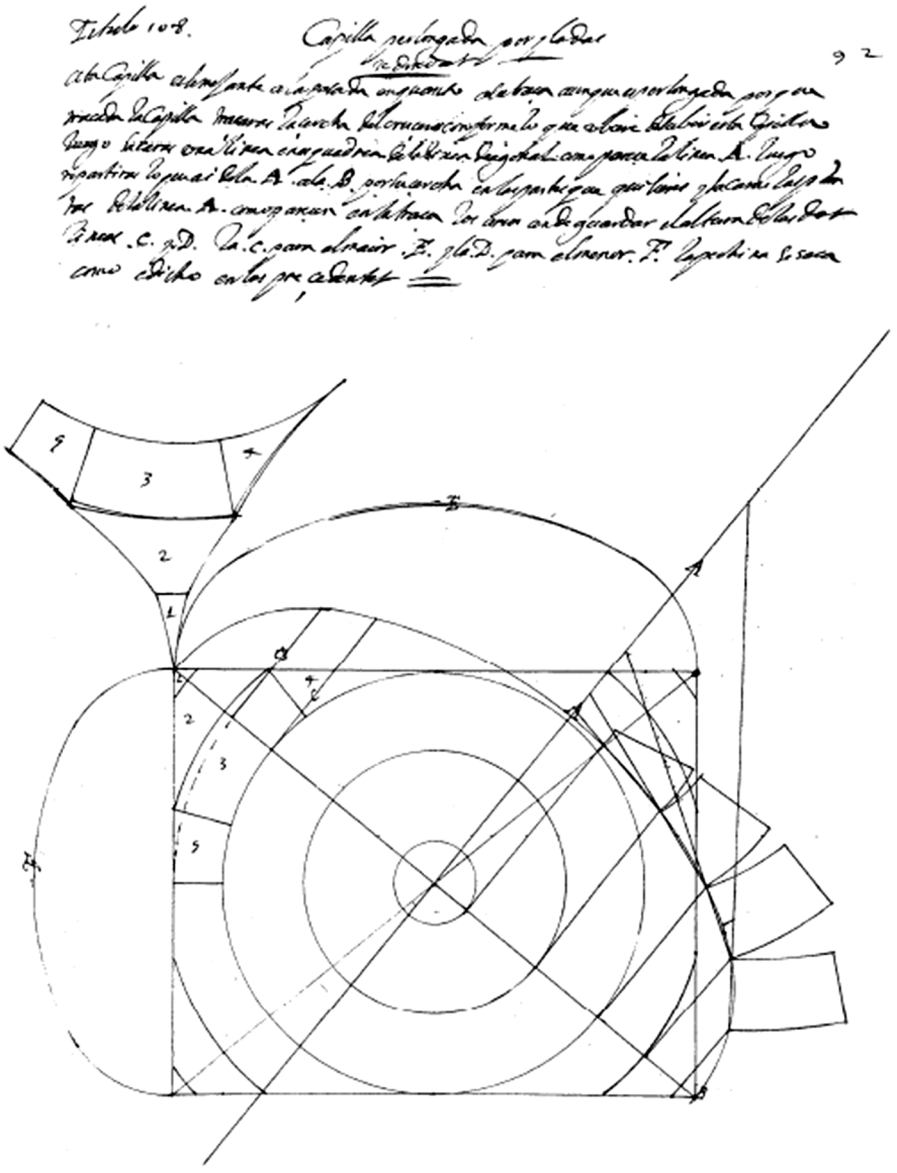

Fig. 11 A. de Vandelvira, *Capilla perlongada (painel) por hiladas redondas.* Image: Natividad Vivó 2017: I.96

territory. This study is a first analysis of the sail vaults in the Maltese territory and calls for future studies and surveys with the intent of allowing more comparisons, as well as with historiographical investigations that allow for better clarity in the dating and main personalities involved. Expanding the analytic survey to the whole courtyard, for example, the comparison between the vaults that cover the bays of the loggia of the Magistral building can also be useful to identify a possible sequence in the

construction phases, potentially leading to a better understanding of how the space of the courtyard evolved between the late 16th and 17th centuries. The differences in the ashlar layout also highlight possible restorations, as in the case of the third span of the surveyed loggia, whose pseudo-oval arrangement could be explained with a later reconstruction, when important interventions to the palace were carried out but not always documented.

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Author Contributions This essay is a collaborative discussion of the three authors who authored together the introduction and conclusion section of this paper. Christian Mifsud has carried out the photogrammetry survey and authored the section 'The Magistral Palace: Context of the investigation'. Sara Morena has analysed the geometry, created the technical drawing and written the section 'Data acquisition and geometric analysis of the vault'. Finally, Armando Antista has discussed and analysed the data and authored the section entitled 'The spread of sail vaults in early modern Maltese architecture: typologies and construction systems'. The authors read and approved together the final version of the manuscript. All figures are the authors' own unless stated otherwise.

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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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