The Racetrack Oval Frame Vault of Villa Borromeo in Cassano d'Adda

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Abstract

The paper describes the analysis of the oval frame vault of the ballroom of Villa Borromeo in Cassano d'Adda (Milan), one of the most important, yet not deeply studied, countryside villas of the Adda family. The vault is a particular example of a frame vault on an oval plan, where the main elements that characterize the space are the skene arches and the curved lunettes. The article sheds light on the constructive and geometric genesis of this particular type of vaulting, which was a common construction practice of architects and builders in the Modern Age in Northern Italy. The analysis of the vault geometries and construction techniques is carried out through a geometric and photogrammetric survey, the elaboration of drawings, and a 3D model.

Keywords Frame vaults · Villa Borromeo · Eighteenth century · Cassano d'Adda · Design analysis

Introduction

The vaulted systems have always been of interest due to their incredible design, daring solutions, and subtle construction techniques. Among the different vaulting types, frame vaults have been the least studied (Grimoldi 2009). They are mainly characterized by skene (surbased) arches that divide the ceiling into squares covered by vaults. There are many examples in Northern Italy, mainly in Lombardy and Piedmont, starting from the end of the sixteenth century.

The vault covering the ballroom in Villa Borromeo is one variation of this type of vaulting. The 'racetrack oval' shape of the plan (that is, an elongated shape with two parallel sides and semi-circles on each end) and the flat-curved lunettes are the most interesting features. They led to interesting questions: How does the geometry

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of the intrados mirror the constructive technique? What is the geometrical/structural relationship between the intrados and the extrados of the vault? How were the lunettes geometrically designed and built?

The vault was analysed through on-site observations, direct and photogrammetric surveys, and 3D modelling. The use of the 3D model and photogrammetry for the representation of complex structures such as the vaulted systems is becoming common both for the analysis of construction techniques (Attico et al. 2019) and geometrical genesis (Spallone et al. 2019).

This paper considers both the constructive and geometrical aspects of the unique frame vault of the Villa Borromeo ballroom. The building has not yet been the subject of systematic studies, and its construction history still needs to be studied in depth. This paper is intended to fill that gap.

Villa Borromeo in Cassano d'Adda and its Ballroom with a Frame Vault

Santino Langé describes Villa Borromeo in his book about Milanese villas (Langé 1972: 198–202), but the primary reference for this study is that of Laboni and Sannazzaro (2008: 39–48).

The building was owned by the Milanese Adda family, which has been documented in Cassano d'Adda since the fifteenth century. However, the Villa was not built until 1721, since it does not appear on the Adda family's estate list and in the maps of the Teresian Cadastre. The Villa was built following the tradition of retiring to the countryside during holiday periods.

The Villa plan is U-shaped with the main three-storey building in the middle and the wings extending forward, thus creating a square garden in front of it. The central spaces are the vestibule on the ground floor and the ballroom on the first floor. A similar layout has been used for villas in the Milanese area since the late sixteenth century. However, the original feature of Villa Borromeo is the racetrack oval shape of the vestibule and the ballroom.

Scholars agree in attributing the first project of the Villa, ca. 1765, to the architect Francesco Croce (1696–1773), who was already working around Milan on religious buildings and palaces, such as St. Michele ai Nuovi Sepolcri in Milan and Villa Pertusati in Comazzo (Lodi). It is believed to be Croce's work because of the similarities between the building in Cassano and some other villas designed by the architect, such as Villa Brentano in Corbetta (Milan), as well as some construction details, like the balcony of the north façade of the building which resembles the one of Palazzo Sormani in Milan (now a public library) (Grassi 1961: 94).

Another prominent architect worked on the Villa in the same century: Giuseppe Piermarini (1734–1808). Payments by the marquis Giovanni Battista d'Adda (1737–1784) to the architect from 1772 attest to his work; Villa d'Adda is cited in one of his documents dating back to 1781. The involvement of the royal architect Piermarini is a sign of the great social status of the marquis d'Adda, who married Margherita Litta Visconti Arese (1753–1778), a member of one of the most noble Milanese families. Giovanni Battista d'Adda was a member of the *Consiglio dei*

Sessanta Decurioni (Milanese City Council), an important Milanese cultural institute promoted by the empress Maria Theresa, the Società Patriottica, and was the *palchettista* (he had a theatre's dais) of Milan's Teatro alla Scala.

It is believed that Piermarini's intervention made partial changes to Croce's work, as some design discrepancies of the Villa cannot otherwise be explained. For example, the ornamental decorations of the main façade are different from the lower wings (Grassi 1961: 94). Thus, scholars agree to assign the authorship of the main central building to architect Croce, which is relevant for dating the ballroom construction, covered by the oval frame vault (Fig. 1).

The double-height ballroom is located in the middle of the Villa first floor, where the three central windows (and the other three above them) of the main façade are. The ballroom is in the shape of a racetrack oval, where the pilasters (*lesene*) have been placed following the oval form. The room is covered by a frame vault made of eight skene arches and eight flat lunettes. The lunettes are linked to the central panel (*specchio*) of the vault through curved lines. A moulding divides the two storeys of the ballroom, which has six doors, three windows, and three illusionistic paintings that represent doors; these are repeated on the mezzanine level, where small windows open to balconies with iron-shaped parapets, which used to host the musicians during the entertainments.

The ballroom is decorated with white stucco ornaments that frame the architectural elements on the walls and the skene arches. There is a painting of an illusionistic niche on the east wall with goddess Diana standing on a base. Francesco Corneliani (1740–1815) has been recognised as its painter (Bianchi 1996: 105). He also realised the staircase vault fresco and the Hall of Mirrors canvases

Fig. 1 Villa Borromeo and the ballroom

on the ground floor. Canvases and frescoes were probably part of one iconographic programme by Cornelianani for Giovanni Battista d'Adda around 1778.

Giving the benefit of the doubt all things considered, the ballroom frame vault's construction can be placed in the second half of the eighteenth century, between 1765 and 1772. The Villa went through many changes of ownership up to the nineteenth century. Vitaliano (1800–1879), the last descendant of Adda family, had one daughter, Costanza (1842–1891), who married Count Carlo Borromeo (1828–1889) in 1860, who then became the owner of the Villa. After years of neglect, the Villa was restored at the end of the 1980s, becoming a convention and reception centre.

Frame Vault Constructive Practices and Technical Literature in Northern Italy Between the Seventeenth and Eighteenth centuries

The vault of the ballroom of Villa Borromeo is an unusual variation of the frame vault typology, for which vaults are built using arches. The arches divide the room, forming a structural frame, allowing the spaces between them to be covered by various vaulting types. These vaults have been documented mainly in Piedmont [called 'fascioni' vaults by Passanti (1990: 44)], but they had been known and used in the whole Northern Italy from the second half of the sixteenth century (Grimoldi 2009). This construction practice is typical of Lombard architects and master builders, as proven by the significant number of frame vaults disseminated in Northern Italy, such as the case of the late sixteenth-century halls and atria of palaces in Brescia, Cremona, Milan and Turin (Fig. 2).

Some of the most beautiful examples cover the rooms of both religious buildings and palaces, such as the anti-refectory of St. Nicola Abbey in Rodengo Saiano (Brescia) and the main hall of Villa Obizza in Bottaiano (Cremona). The vault of St. Nicola Abbey covers a room of about 9.7×7.6 m and displays a huge painting by Lattanzio Gambara, one of the foremost sixteenth-century Lombard artists, which allows the vault to be dated to 1561. Stucco decorations were realised by Mantuan artist Francesco Oselli (Volta 2002: 182). The brackets that support the central vault with the painting by Gambara recalls the wooden-coffered ceilings with the cyma reversa profile that were very common in the area. Villa Obizza was commissioned by Giò Matteo Obizzi, noble councillor of the city of Crema, and completed in 1702 (Dusi 2008: 61). The frame vault covers the main hall (7×11 m) on the ground floor. The central panel is supported by large arches that have small vaults in between them.

Frame vaults are very common in Piedmont, covering the rooms on the ground floor or the atria of many palaces. The refectory of the former monastery of the Padri Somaschi and a room in the Palazzo Gotti di Salerano, both in Cherasco, are two famous examples (Sassone et al. 1994: 91–115). In general, this type of vaulting was built for formal, constructive, and functional reasons. It is often found on the ground floor, even in case of renovations for which it was necessary to maintain a fixed height. That is because these vaults make it possible to cover spaces with reduced heights while maintaining their lightness and elegance. Through lunettes or

Fig. 2 Frame vaults in Northern Italy; **a** St. Nicola Abbey in Rodengo Saiano (Brescia); **b** Palazzo Martinengo Cesaresco in Brescia; **c** St. Sigismondo refectory in Cremona; **d** Loggia di Brescia

small vaults, they also guarantee the opening of larger windows at greater heights than other solutions. This is the case of Palazzo Roncadelli-Manna in Cremona, which was renovated in the late seventeenth century. Most of the ground floor rooms are covered by frame vaults (Azzolini 1998: 61–69; Petracco 1998).

The intrados of frame vaults were often embellished by *quadri riportati*, ceiling pictures intended to look like framed easel paintings placed overhead. Frame vaults were easy and fast to build, allowing material savings: first, arches were created parallel or diagonal to the walls resulting in a framed structure, and then the vaults were constructed between them using the arches as guides and movable or light centring for geometric control. The brick pattern was often realised with the bricks laid flat (*in foglio*) instead of laid upright, making it possible to save materials and guaranteeing a lighter structure.

Frame vaults can be found until the end of the eighteenth/early nineteenth century, such as the one covering the gallery of the Cremona town hall designed by architect Faustino Rodi (1753–1833) and demolished in the 1920s (Jean 1995: 239) or those of the staircase of the Loggia in Brescia, designed by architect Antonio Tagliaferri between 1873 and 1878 (Lugato 1996: 123).

Some traces of these vaults' construction process can be found in the Italian technical literature of the Modern Age. They feature elements already known and common in Renaissance construction sites: *frenelli*, small brick walls, and the extrados ribs, which are thickenings of the masonry that stiffen the vault and allow

a better distribution of the pressure loads. These are usually placed on the extrados, but the frame vaults reverse this constructive logic by placing them on the intrados. Vincenzo Scamozzi refers to them when writing about the *fasce* in his treatise *Dell'idea dell'architettura universale* (Scamozzi 1615: 327). Here, the term *fascia* is comparable to that of arch or rib, a supporting band-like structure consisting of bricks, positioned on the vault extrados.

The first persuasive description of the frame vault building process is found in the treatise of Guarino Guarini, *Architettura Civile*, published posthumously in 1737:

Compartisco adunque la Camera, e vado tirando da muro in muro, o in quadro, o per linea diagonale varie fascie, le quali facciano in se stesse qualche compartimento, e poi gli spazj, che rimangono, riempio di diverse Volte secondo la capacità del campo [...] Questa maniera mi ha somministrato una gran varietà di Volte, le quali fanno nobilissima vista, e lasciano campi egregi per la pittura.

I thus compartition the room, and go forward drawing from wall to wall, either square [with the walls] or by the diagonal line, various bands, which in themselves make some compartitions, and then the spaces that remain I fill with various vaults according to the capacity of the area ... this manner has provided me with a great variety of vaults, which make a most noble sight and leave excellent areas for painting (Guarini 1737: 189, my trans).

The *fasce* (bands) are thus arranged between two walls in a room, parallel or diagonal, and divide the space that will be later covered by different vaulting types. Guarini also highlights the fact that these vaults are suitable for paintings and decorations.

In his *Istruzioni elementari*, architect Bernardo Vittone, the editor of Guarini's treatise, underlines the advantages of using arches/ribs in the vaults, placing them both on the intrados and the extrados (Vittone 1760: 506).

The peculiarity of the Villa Borromeo vault consists of a basic matrix—the frame vault—enriched by curved lunettes. The frame vault is placed on the racetrack oval plan so that the central panel becomes small, and the main elements are the flat-curved lunettes.

What makes the vault of Cassano innovative are two main considerations: (1) the sixteenth-century frame vault meets the typical central-plan of the eighteenth-century Villa (the racetrack oval plan of the ballroom); (2) the vault led the experimentation on curved lunettes to exceptional results (the vault is made of eight arches and eight curved lunettes and has just one flat central panel).

The Survey of the Frame Vault: Hand Measurement, Photogrammetry, and 3D Modelling

The geometric data of the vault were acquired through a direct survey (intrados and extrados) and a photogrammetric survey (intrados).

The on-site geometric survey of the intrados and extrados of the frame vault was done to check the existing floor plan drawings and draft the vault plan of intrados

and extrados and sections drawings. It was carried out using standard tools such as metric tape, laser distance meter, optical level, and calipers. The cross and longitudinal sections of the ballroom were created explicitly for this study and have been fundamental to carrying out the vault geometrical analysis (Fig. 3).

First, the plan was surveyed; then, the section survey was carried out transversely and longitudinally along the room's two axes.

The photogrammetric survey was performed to get the orthophoto of the vault intrados and generate the point cloud that could be later used to realise the 3D model. The intrados vault photographs dataset was acquired through a Canon EOS 1-D Mark IV camera (sensor: 27.9 mm×18.6 mm; maximum resolution: 4896×3264 pixels). The camera was placed on a tripod with the objective parallel to the ground, facing the vault intrados. The vault intrados orthophoto was to have a 1:20 scale resolution. Thus, focal length was fixed to 55 mm while the distance between vault intrados and camera to 6.5 m. Because the camera sensor dimensions

Fig. 3 Ballroom drawings

were known, it has been possible to calculate the dimension of the vault that the camera was able to cover with one photograph.

A grid was realised on the floor to mark the points where the camera would be placed to take each single photograph, to ensure a proper overlapping for the photograph processing in PhotoScanPro (homologous points). The standard photogrammetry overlapping is 80–85% on the x -axes and 55–60% on the y -axes. The room dimension is about 8×10 m, so the camera was placed on a grid of 0.66×0.8 m. According to the grid, the number of photographs on the x -axis is 15, and the number of photographs on the y -axis is 9, for a total of 135 photographs, plus 18 photographs taken without following the grid to help PhotoScanPro building the model. In this way, it has been possible to capture the sides of the vault and other elements that were ‘hidden’ when placing the objective parallel to the ground. The total number of photographs is then 153. The Pixel resolution (GSD) is about 1.35 mm/pixel, under 2 mm, so the resolution matches the 1:20 scale of representation.

The 3D model was created following Banfi’s modelling approach that allows an accurate 3D model by using the point cloud coming from either laser scanning or the photogrammetric survey (Banfi 2019b). For this study, the point cloud was gained from the photogrammetric survey, and exported in .e57 format. It was then imported into RecapPro2020 to decimate its points, thus reducing the file size. In Recap, the point cloud was cleaned by eliminating the points that provided ‘noise’ or created errors in the next phases.

The point cloud was then exported in .pts format and imported into Rhinoceros 6 for 3D modelling. The point cloud was anchored to the dwg floor plans of the vault intrados and extrados, which were also imported into Rhinoceros 6. Subsequently, following Banfi’s procedure, the geometric primitives (profiles) of the arches and lunettes were defined through point interpolation. Afterward, the vault surfaces were created, following the Grade of Generation 9 (Banfi 2019a: 141). The same method was applied to the extrados (*frenelli*, tie rods, ...). This allowed a 3D model that accurately follows the geometries of the vault (Fig. 4). Skene arches profiles were obtained through point interpolation and used in the geometric analysis.

Geometrical-Constructive Analysis of the Frame Vault

As already mentioned, the drawings of the ballroom were obtained from the direct and photogrammetric surveys. They were the basis for the analysis of the geometric-constructive features of the vault. Two analyses were used to assess the vault construction process: (1) the geometric genesis of room and vault (plan and section); (2) the construction techniques of the frame vault. First, the room geometries (oval) were analysed; then, attention was focused on how these geometries were actually built.

The vault covers a room with an oval-like shape of about 8.34×10.30 m. The height of the room is approximately 8.20 m. The vault consists of eight skene arches, whose spring-line is at a height of 6.35 m.

Fig. 4 Modelling phases: **a** image data acquisition and dense point cloud generation (Agisoft PhotoScanPro); **b** point cloud decimation (RecapPro2020); **c** primitives extraction through points interpolations and **d** surfaces generation (Rhinoceros)

The skene arches correspond to the pilasters that define the oval plan space: from the ground, the pilasters rise to the arches and folds according to their curvature. The four corner arches are the largest (1.80 m), as they correspond to two pilasters each, while the remaining four arches (1 m) correspond to only one. The space between one arch and the other is covered by lunettes, consisting of a tilted skene barrel vault. The shape of the room is similar to an oval because it actually consists of two separate semi circles joined by two parallel lines that delimit the room perpendicularly to the façade. This is why the four central skene arches are bigger (two pilasters each): they are on the point of connection between the straight line and the circular shape. The pilasters have a shape that can be approximated to an oval with a ratio of 5:6 between the minor and major axes (*ovale di terza minore*) (Dotto 2002: 52–53) (Fig. 5).

The study of the vault section was carried out on the four corner arches, sectioning them vertically in the middle to avoid the profile of the pilasters on the arches, which may not be accurate, because probably made of stucco. The arch profiles are made of two circle segments. The two circles derive from an oval whose axes have a ratio of 3:5 (*ovale di sesta 3:5*) (Dotto 2002: 44–45). That applied to all the four profiles (Fig. 6). Small deviations from the rigorous construction of the oval could be due to the arches empirical building process or the structural settling of the wall and vault. Even in section, the vault of Villa Borromeo cannot be considered as an ovaloid vault. That is because the vault is not obtained from the oval revolution but is the result of the polycentric shape

Fig. 5 Left: geometric analysis of the floor plan: two semi circles with straight lines (red); oval 5:6 construction (green line). Right: oval 5:6 construction (redrawing after Dotto 2002: 52–53)

Fig. 6 Arches profiles geometric analysis (black line for arches profiles; green line for oval) and oval 3:5 construction (redrawing after Dotto 2002: 44–45) with a thicker line for the arches profile

of the arches, arranged on the pilasters following an oval profile. The arches are built individually and do not form a continuous profile but are ‘interrupted’ by the central panel, which mirrors the shape of the room (a racetrack oval). Ovals or polycentric arches were easier to realise than the elliptical one: it is possible to create diverse skene arches made by different circular segments, giving the rise and the clear span of an arch (Huerta 2007: 234).

The vault rise-to-span ratio is approximately 1:5, corresponding to a rise of 1.8 m for a clear span of 8.30 m (cross section) and of 10.30 m (longitudinal

section). The two room sections represent the building features of the vault, which is made of almost flat lunettes and a flat central panel.

How were these geometries translated into being? The answer lies in the extrados as shown Figs. 7 and 8. With reference to Fig. 8, two semi-circular ribs define the short sides (1) consisting of two rows of bricks arranged with the shiner face exposed and following the lunettes curvilinear profiles at the intrados. The central panel (2) is also made of a rib (3) consisting of soldier-laid bricks (25–30 cm long). It was not possible to see the arrangement of the bricks in the central panel, as the usual layer of mortar lime covered it. On both sides of the central panel, two radial ribs (4) connect it with the two semi-circular ribs on the room short sides. These radial ribs

Fig. 7 Ballroom frame vault intrados and extrados: **a** frame vault; **b** lunette detail; **c** central panel rib; **d** *frenello* and tie rod; **e** lunette; **f** semi-circular rib and tie rod

Fig. 8 Comparison between frame vault intrados and extrados. Extrados: (1) semi-circular ribs; (2) central panel; (3) central panel rib; (4) masonry thickenings smaller arches; (5) lunettes; (6) haunches thickenings; (7) masonry thickenings major arches; (8) *frenelli* and tie rods

almost identically follow the profile of the smaller skene arches of the vault at the intrados. The lunettes have bricks laid upright (26.5 cm long and 6 cm thick) parallel to their longitudinal axis, visible in the lunette close to the main façade (5). The lunettes' haunches (*reni*) are reinforced by a masonry thickening (6) that connects them to the radial ribs. Four masonry thickenings (7) on the extrados follow the profile of the four major intrados arches: these are not real ribs, such as the radial ones, but structures made of bricks, whose height increases towards the centre of the vault. Next to these thickenings, there are four *frenelli* (8), consisting of two rows of bricks, shiner face exposed (25–26 × 13–16–17 × 4 cm), with two tie rods, which are incorporated in the central panel of the vault. It is possible to deduce that the thickness of the vault is about 20 cm, by comparing the measures of the bricks of the lunettes with those of the *frenelli* and considering the thickness of bricks (approx. 17 cm), plaster (intrados) and mortar lime (extrados).

Conclusions

The study carried out on the vault so far has made it possible to shed light on its construction features, but at the same time, it opens a series of questions related to the construction practices of the masonry vaults in the eighteenth century, especially regarding the frame vaults, not yet studied in depth.

The frame vault of Villa Borromeo was probably built using the same polycentric-arch centring. The arches that were built first worked as guides for the construction of the lunettes, which were realised using light formwork (Fig. 9). From the extrados, it is not clear how the construction of the curved lunettes was carried out, whether it has a brick rib, as in the vault of the main hall in Palazzo Gaifami in Brescia (Grimoldi 2007: 118), or it is just made of stucco, visible at the intrados but not at the extrados.

Fig. 9 Ballroom frame vault 3D modelling

Skene vaults have a strong horizontal thrust component, but in the case of Villa Borromeo, the vault relies on the eight arches that direct the thrust to the pilasters and the wall in eight specific points. The lunettes help to distribute the thrust uniformly on the arches and walls.

The vault has two tie rods that run parallel to the façade, perpendicular to the short sides, right above the four smaller skene arches. The tie rods were used to keep the structure stable during the mortar curing and then remained in the masonry of the vault. It was not necessary to add any more tie rods, either because of the shape of the vault or because inside the skene arches there are probably metal bars, even arch-shaped, such as the one in the vault of the main hall of Palazzo Soncini in Provezze (Brescia) or Palazzo Gaifami in Brescia (Grimoldi 2007: 118), or because of a combination of the two options.

Other studies could help to shed further light on the ballroom frame vault. A laser scanning survey would add additional reliable dimensional data to the geometrical analysis. Thermal camera image acquisition could help better understand some crucial points of the intrados: the connection between the bricks of the arches and the one of the walls or the lunettes; the presence of metal bars inside the arches; the construction of the curved lunettes. Analysis of the composition of the mortar would help the understanding of the vault construction. The mortar had to be quick curing in order to build a structure with self-supporting bricks. It could be made of lime, but local solutions cannot be dismissed, such as the earthen mortars typical of Cremona, found in the frame vault of Villa Obizza in Bottaiano (Dusi 2008: 64).

The vault of Villa Borromeo is unique because it merges the frame vault with the central-plan building, together with the exceptional use of flat-curved lunettes, which shape the room's interior space. This solution links structural and aesthetic functionalities, so that the spaces between the skene arches, covered by lunettes, were the perfect location for the musicians during the entertainments.

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