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# CRITERIA AND TOOLS TO CATALOGUE BRICK-MASONRY VAULTS. THE GIS-DATABASE OF FRAME, A FASCE AND PLANTERIAN VAULTS BETWEEN THE 16TH AND 18TH CENTURY IN NORTHERN ITALY

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**Abstract:**

The paper describes a proposal for criteria and tools to catalogue brick-masonry vaulted systems in Northern Italy between the 16th and 18th centuries. Along with the standard geometric typologies, three novel parameters (*maîtresses voûtes*, *voûte sur le plan d'une autre voûte*, constructive features) are proposed to include the constructive features in the vault taxonomy. The novel parameters help catalogue three vaulting types that can be considered the metamorphosis of cloister vaults: frame, a fasce, and planterian vaults. The database was realized in MS Access and then imported into QGIS 3.10. Database and GIS have been operative tools to form hypotheses on vault disseminations, highlighting the recurrences and specificities across time and space of some peculiar construction techniques. The database collects the acquired information on each vault (building type, geolocation, building date, vaulting type, vault dimensions and description and, whenever possible, photogrammetric survey, 3D modelling, and thermographic survey). In the future, the database should be published online, making the data available and building a broader dataset to share the information.

**Keywords:** vaulted systems, 16th-18th century, Northern Italy, Guarino Guarini, database, GIS

## 1. Introduction

For a long time, vaulted systems have represented a field to experiment with shapes and constructions for architects and craftsmen. An intriguing challenge – formal and constructive – that involved creativity, materials, structure – think about the huge vaults with the complex rib systems that covered gothic cathedrals or the refined stereotomy vaults, such as the well-known Town Hall in Arles, designed by Francois Mansart (1598-1666) in 1676.

Although the incredible variations of vaulting types, the traditional classification is based on geometric-typology shapes. If individual studies are going beyond a simple and superficial analysis – i.e., correlating the intrados geometry to the extrados or understating how the brick or stone arrangement affects the structural behavior of vaults – it is still missing an approach to the classification of vaulted systems depending on shapes and construction techniques, even considering a limited timeframe and geographical area.

The paper describes the need to go beyond the standard vault typology classification to understand vault design and constructive genesis. By doing this, it will be possible to understand how the construction techniques are the most diverse, even if considering one type of vault, showing what can be called “the metamorphosis” of vaulting.

Along with the standard vault typology classification (cloister vault, cross vault, etc.), novel criteria and tools are needed. This paper proposes a methodology to classify the vaults, which helps to understand even the hybrid ones and to represent and study their dissemination. The case studies are three cloister-vault-construction techniques variations (frame, a fasce, planterian vaults) in Northern Italy between the 16th and 18th century. The new parameters (*maîtresses voûtes*, *voûte sur le plan d’un autre voûte*, constructive features) include vaults constructive features and refer to historical architectural treatises to understand how architects and craftsmen designed and constructed vaults. The methodology could be applied to other typologies. In that case, the parameter “constructive feature” should be adjusted to the specificity of the vault typologies.

Once the criteria were fixed, the vaults were classified with a GIS-based catalogue that collects the information (vault description and dimension, drawings, thermography, 3D model, orthophoto, and bibliographical references) about each vault example. The GIS-based catalogue is meant to be an operational tool for the on-field research of case studies. On the other hand, by implementing the GIS-based catalogue on an online platform, it will be possible to share the data, possibly allowing other scholars to populate the database, increasing the research.

The author is carrying out the in-depth study of the three vaults families in Northern Italy (construction techniques, history, and dissemination) in her Ph.D. research at the

Politecnico di Milano (DAStU Department, Preservation of the Architectural Heritage, supervisor: prof. Alberto Grimoldi). However, the vault-GIS-based database is part of a wider project about vaulted systems catalogue, including Northern Italy and European case studies.

The paper structure is the following: paragraph 2 explains the research objectives; paragraph 3 presents a brief literature review on vaulted systems catalogues; paragraph 4 describes the previous works on vault database; paragraph 5 proposes three new parameters for vault classification that goes along the traditional typology; paragraph 6 explains the work carried out for the vault catalogue and the GIS database; paragraph 7 is about the potential of the database for future works and the conclusion.

## 2. Research objectives, method, and tools

The research proposes a novel approach for studying the vaulted system to be combined with the standard typology classification. The approach wants to help the analysis of design, constructive and structural features of vaulted systems.

The research is based on analyzing "the metamorphosis" of cloister brick-masonry vaults, but the same methodology could be applied to other vault typologies. It concerns the classification criteria of three-cloister-vault variations (*frame*, *a fasce*, and *planterian* vaults), mainly disseminated in Northern Italy (firstly Piedmont and Lombardy, secondly Veneto and Emilia-Romagna) between the 16$^{th}$ and 18$^{th}$ centuries.

The goal is to realize a sort of *raisonné catalogue* of vaulted systems founded on the shape-typology classification and vaults constructive features. Other parameters, rather than geometric shapes, were included to set up a more flexible and "open" vault taxonomy. The research proposes three novel parameters, borrowed from the stone stereotomy vault construction and the 18$^{th}$-century architectural treatises, especially the *Architettura Civile* (1737) by Guarino Guarini: *maîtresses voûtes*, *voûte sur le plan d'une autre voûte* and constructive figure (described in paragraph 5). They help describe hybrid vaulted solutions: vaults that do not match the standard vault typology or vaults that seem to belong to a standard vault typology, but which structure belongs to another kind of typology. For example, the vault covering the staircase of Palazzo Magio Grasselli in Cremona, renovated around the 18$^{th}$ century, is a combination of a cloister vault and a cupola (Brumana et al., 2018).

The research has oscillated between inductive and deductive methods. In the first instance, the identification of vault examples made it possible to highlight recurring features, which led to an investigation that was as extensive as possible, collecting the largest number of examples for each cloister-vault variation, examining the data using spreadsheets and GIS. It allowed to picture an overview of the variants, the construction figures, and the diffusion of construction techniques, forming first considerations. The approach then moved towards a deductive method, testing the hypotheses by searching for additional vault examples (from general or specific architectural literature) that could support or reject the first conjectures.

The phase includes collecting direct and indirect sources on each vault that would become part of the catalogue. First, it was necessary to review the existing literature. Those types of vaulting have not yet been the subject of systematic studies. *Frame* and *a fasce* vaults are usually called “compartimenti” or “modiglioni” vaults (Piccoli, 2001); while planterian vaults are usually associated with the ceiling structures built by architect Gian Giacomo Plantery (1680-1756) in Piedmont (Cavallari Murat, 1957), including some frame vaults (Spallone & Vitali, 2017). Secondly, general catalogues on villas and buildings in Northern Italy have been checked and, whenever it was possible, a monograph on specific palaces. From time to time, articles on vault construction techniques have been found. The literature review was accompanied by an on-site photographic survey in some selected cities and surroundings (Turin, Casale Monferrato, Alessandria, Brescia, Cremona, Milan, Bologna), getting an overview of the real dissemination in each territory. Then, starting from the catalogue first draft, some examples for each vault variation were selected and documented through on-site observation, photogrammetry, direct and laser scanner survey, 3D modeling, and thermography. In many cases, only the intrados was analyzed because the extrados was not accessible. The intrados and extrados analysis allows observations on the vault typology and highlights how some structures are not easy to "classify". It could be possible to distinguish between a “formal” typology of the vault, visible at the intrados, and a “structural” typology, visible at the extrados. The thermographic survey was useful for studying the brick arrangement when the extrados was not accessible and understanding how the bricks interlock the intrados and extrados.

Since the research is carried out in Italian, the terminology is based on the Italian language. For this paper, some terms have been translated, according to previous studies. However, vocabulary and technical terms are fundamental issues when dealing with online databases. Especially if one wants to extend the research to a broader audience, it could be recommended to publish it in English. Then, it will be necessary to consider each Italian technical term, finding the correspondent English ones, if possible.

## 3. Literature review on vaulted system studies and catalogues in Europe

The paragraph reports a short literature review on vaulted systems catalogues to understand criteria and methods of classification. Starting from French and Spain stereotomy studies, the paragraph describes the works on vaults carried out in recent years in Italy and United Kingdom, specifically focusing on the ones that have developed a database.

French and Spain studies mainly focused on stereotomy and the art of building stone vaults. Stereotomy has provided effective classification criteria thanks to constructive figures, such as the *maîtresses voûtes, trompes, arrière-voussure,* etc., representing a technique to build vaults or part of them. Thanks to the Renaissance stereotomy treatises, such as Philibert De L’Orme (1567) and Francois Derand (1643), it is possible to link stereotomy constructive figures to examples disseminated in the buildings across the territory. Stereotomy constructive figures help correlate the

technical literature to vaults tangible examples, specifically to correlate the *trait* (drawings of the vault and each stone) to its real construction application.

From the deep-rooted French stereotomy tradition, Pérouse de Montclos (2013) derives a robust vocabulary that allows him to draw a coherent and significant picture of the Modern Age vaulted systems in France common national roots and regional particularities. Modern-Age-French vaults main features are the variations of shapes and patterns, which define an incredible diversity of structures. By doing this, vaults do not match the rigid grid of typology. Vault shape and stone pattern, together with the intrados design, the arrangement of the lunettes, the connection between different vaulted surfaces become the constructive criteria for analyzing the vaults. The stereotomic vocabulary is supported by the corresponding constructive drawing (*trait*) derived from architectural treatises and examples disseminated throughout the territory. An attempt is made to understand the cultural and constructive meaning of vaults, and the catalogue is not just a repertoire of examples.

In Spain, Palacios (1990) creates a catalogue of vaulted systems that includes the models reported by Alonso de Vandelvira, author of the well-known *Libro de las traças de cortes de Piedra*, compiled between 1575 and 1590. Palacios gives an overall description for each *maîtresse voûte* and the method of making the *trait for each variant*, referring to Vandelvira. Then he reports some examples of each type of vaulting. However, there is no interest in tracing a constructive history of these *maîtresses voûtes*, nor even their dissemination, unlike the French case. In their research on late gothic rib vaults, Senent-Domínguez, López-Mozo, Martín-Talaverano, Pérez-de-los-Ríos, & Rabasa-Díaz (2015) have already pointed out the need to go beyond formal and stylistic criteria, focusing on vaults constructive features. They proposed a database finalized to collect vaults depending on key-aspects, not to develop an extensive repertoire of examples. The key-aspects regard specific research topics to create categories that help the search. Since the database would be open to an international audience, the terminology issue is a central aspect. The authors point out that considering countries with a robust technical vocabulary, it is sometimes difficult to translate into English specific terms.

In Italy, the well-known *Manuali del Recupero* of historical town-centers is more an operational tool for conservation activities than an in-depth knowledge of the historical building. Manuali includes the main information on construction techniques, materials, and geometric-dimensional data of each historical architectural element, but it is not easy to derive reproducible criteria and methods. Thanks to the research funding, "iDome Invisible | Accessible. Masonry Domes of the 15$^{th}$ and 16$^{th}$ Centuries in Campania. Innovative Strategies for the Interpretation and the Multi-thematic Inclusive Fruition of Vulnerable Architectures" (iDome, scientific coordinator Valentina Russo), the Federico II University in Naples has developed an online website about domes disseminated in Campania with the demonstration case of the dome of the church of Santa Caterina in Formiello (Russo, 2018).

In the United Kingdom, studies are focused on Gothic Architecture, mainly on the vaulted systems of cathedrals. Howard (1911) and Leedy (1980) focused their research on the fan vault: origin and cultural significance, construction technique, geometric design, and geographical dissemination, in order to highlight regional particularities, together with an apparatus illustrative and a catalogue of vaults starting from 1540. A more comprehensive approach is provided by Lancaster (2015). She examines six vaulting types (opus caementicium, brick barrel vaults, complex brick vault forms, vaulting tubes, hollow voussoirs, armchair voussoir) throughout the Roman Empire, especially in its provinces. By doing this, she tries to unravel some of the threads that affected their creation and dissemination: the exchange of ideas (and constructive techniques) between the capital and other cities, the different craftsmanship, the availability of construction materials, the contextual conditions. The vault database was imported into GIS, which helps form hypotheses that could explain the dissemination of the six vaulting types.

## 4. Previous work on vault catalogues and databases

This paper is part of a wider project that has been developed on vaulted systems catalogues and databases since 2017 (Brumana, Condoleo, Grimoldi, & Landi Brumana, 2017).

In the previous research, the starting point was the HBIM (Historic Building Information Model). HBIMs of vaulted systems is a punctual analysis – a node of information in the knowledge chain – of an architectural element of a building. However, there is no circulation of such data, which could implement the sharing of information. The increasing availability of HBIMs could allow access to these nodes in cross-sectorial studies (Brumana, Ioannides, & Previtali, 2019).

Databases and cloud-based platforms might represent a way to disseminate the acquired data stored into HBIMs, taking into account the privacy and authorship issues. The result is a virtual space where it is possible to connect information. In this regard, Virtual Hubs could be used as information systems that support the life cycle of vaults open data: publishing, discovery, and access (Mazzetti et al., 2015).

To build the project, it became necessary to set up: 1) criteria for vault classifications; 2) database model; 3) connection with a Geographic server; 4) online publishing. A database has been developed that takes into account the standard vault typology but also considers the hybrid solutions and the construction techniques. Particular attention is given to the geometric survey detail and scale/tolerance to aware the users of the kind of output they could use. The database structure is as follows: 1) main information: 1.1) Building information (name, address, country, regions, province, city, geographical coordinates, building typology); 1.2) Macro typology: horizontal (vault, slab, roof, etc.) and vertical elements (walls, windows, etc.). 2) Vault survey: 2.1) Typology: "Vault" including the standard vault typologies, and the hybrid ones, i.e., cloister vault turned to cupola; 2.2) Subcomponents: reinforced structural arches, *frenelli*, tie rods (intrados or extrados), trompe, etc.; 2.3) Brick or stone arrangement (along the directrix, along the generatrix, diagonal, herringbone, etc.) and description; 2.4) Materials: brick-block, tile brick, stone, clay pipes, etc.; 2.5) Texture: soldier laid, in foglio, etc.; 2.6) Sub texture (single or double texturing) and

description. 3) Sources: 3.1) Indirect: Bibliography; 3.2) Direct: Laser scanner, 3D photogrammetry, IRT, etc. Output (2D drawings, 3D model, orthophoto 3D, BIM Library, 3D PDF, etc.), scale/tolerance, and format.

So far, it has been populated with examples from Italy. The goal is to make the database crowdsourced, following a bottom-up methodology. The HBIM of the vault examples is realized with different levels of detail. Sometimes only the intrados geometry is modeled, and sometimes even the brick pattern. It makes understanding the interlocking between the intrados and the extrados. The brick pattern was modeled in the case of Sala Manfredini vault of Palazzo Magio Grasselli in Cremona (Brumana et al., 2018).

A further step was developed through an ontology-based vault database, which uses a set of ontologies to effectively combine data and information from multiple heterogeneous sources (Previtali, Brumana, Stanga, & Banfi, 2020).

## 5. New parameters for a more inclusive taxonomy of vaulted system

The typology is based on the idea that the vaulted structures derive from abstract geometric operations: for example, the cross vault is the interpenetration of two barrel vaults. While this is true in many cases, it becomes misleading because the intrados shape is affected by the construction technique. Some vaulted systems are made without centerings, and this changes their geometry because it creates double-curved structures. Even the construction technique and the way the bricks are laid modify the geometry: to obtain a more continuous structure in the corner, an arrangement of concentric circular bricks is adopted instead of a herringbone pattern. For these reasons, the intrados geometry can often be misleading to conduct a structural analysis because it not necessarily mirrors the geometry derived from the construction technique. Moreover, the geometry of the intrados can be altered by decorative partitions or plaster finishing. Furthermore, structural problems, such as settlements (that can happen during the centerings removal or the building life cycle), can alter the intrados shape.

Three novel parameters are proposed to include the construction technique in vault classification. The first and the second were borrowed from stereotomy: *maîtresses voûtes* and *voûte sur le plan d'une autre voûte*, which can be found in the well-known treatises of Philibert de L'Orme or Francois Derand. The concept of *maîtresses voûtes* is similar to the typology-geometric shapes: barrel vaults, cross vaults, cloister vaults, etc. The *maîtresses voûtes*, however, are also stone vaults "constructive principles". It means that they represent basic techniques for solving common "problems" within the stereotomy construction, from which it is necessary to start to solve more complex problems of solid interpenetration.

In stereotomy, the variations of stone arrangements are expressed through the concept of *voûte sur le plan d'une autre voûte*. It means that the vault is not realized on the plan usually adopted for its typology. For this reason, we found a cross vault on a circular plan (*voûte spherique faisant le plan d'un voûte d'arestes quarrée*), where usually the cross vault covers a square or rectangular plan. It implies a different geometric construction of each stone. This principle is that the same type of vaulting could correspond to a different stone pattern (arrangement). This construction method is also used for brick-masonry vaults. It means that if from the intrados I could classify one vault as a cloister vault, this would not necessarily mean that the vault is geometrically and constructively generated as a standard cloister vault. The parallel with stereotomy is only on a geometric basis and does not include the construction process, which is very different. Stereotomy provides, through the *art du trait*, the design, and construction of each stone, skilfully shaped to be placed in a precise spatial configuration; the masonry construction is based on the use of brick, an element made in series that can be shaped for specific purposes, but which is usually cut and adapted according to need.

The third parameter is the constructive figures, which characterize the vaulted structures both at a formal and a constructive level (Fig. 1). They were derived from the architectural treatises of the baroque period, such as the ones by Vincenzo Scamozzi (*Dell'idea dell'architettura universale*, 1615), Guarino Guarini (*L'Architettura Civile*, 1737), and Bernardo Vittone (*Istruzioni elementari*, 1760). Among them, Guarini seems to summarize the constructive features in his treatise better, although on a geometric level: these are the "fasce" (like arches), used in the construction of the *frame* and *a fasce* vaults; the pointed and arched lunettes, which lead towards the three-dimensional arches of the *planterian* vaults; the half cones, which allow the cloister vault to be connected to the four corners of the room.

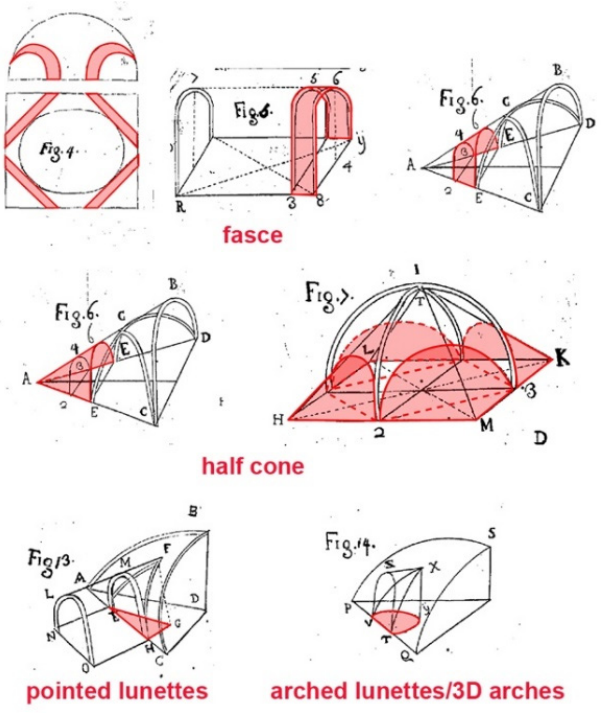


**Figure 1**: The constructive figures, after Guarino Guarini, plate XIX and XX (Guarini, 1737).

The "fasce" are stiffening elements that, if placed at the level of the intrados, divide the vaulted surface into various compartments. They can have both decorative and structural roles. They can also be realized only at the extrados for a structural function. In this case, the intrados is continuous. Fasce is the main constructive feature of the *frame* and *a fasce* vaults.

In this research, “pointed lunettes” means the lunettes that have a projection onto the plan made of two straight lines that meet at one point. “Arched lunettes” refer to the lunettes with a semi-circular or semi-oval plan projection.

The three-dimensional arch is a lunette whose projection onto the plan is a half-circle or an oval. It is different from the arched lunettes because it derives from the interpenetration of two solids of rotation (cylinders or spheroids) of different diameters, for example, a horizontal half-cylinder (barrel vault) and a perpendicular vertical half-cylinder. Mathematically, it generates a fourth-degree skewed algebraic curve, whose points lie on different planes. These are projecting curves whose inflection points, where curvature change occurs, generate those winding lines that characterize the *planterian* vaults.

Half cones can be used to realize the vault. Guarini shows a sail vault, rotated by 45° on a square or rectangular plan, connected to the four corners of the room by half cones.

## 6. The GIS-based catalogue of frame vaults, a fasce vaults, and planterian vaults

The study focuses on three typologies of cloister vaults characterized by three constructive figures: the *frame* vaults and *a fasce* vaults, based on fasce constructive figures, and the *planterian* vault based on the three-dimensional arches (Figs. 2 and 3). The other constructive figures (half cone, pointed lunettes, and arched lunettes) are sometimes combined in the three typologies.

| Vault Family | Vault Description | Constructive figures | Architectural treatises |
|---|---|---|---|
| Frame vault | The room is divided by arches parallel/orthogonal/oblique to the wall and the space between them is covered by different vaulting types | arches (fasce) | **Guarino Guarini,** Architettura Civile, 1737<br>**Vincenzo Scamozzi,** L'Idea dell'Architettura Universale, 1615<br>**Bernardo Vittone,** Istruzioni diverse, 1760 |
| A fasce vault | Sail vault rotate of 45° on a rectangular/square room | arches (fasce) | |
| Planterian vault | Cloister vault with 3D arches | 3D arches | |

**Figure 2**: Cloister vaults metamorphosis: frame, a fasce, and planterian vaults.

The research carried out so far has allowed finding a corpus of examples of *frame*, a *fasce*, and *planterian* vaults disseminated mainly in Lombardy, Piedmont, Emilia-Romagna, Veneto, Sardinia, Abruzzi, and the Czech Republic.

The recored examples (195) are witnesses of peculiar construction practices (in a broader sense) of the cloister vaults:

- *Frame vaults*: 142 examples, 102 from literature (of which 19 geometric surveys), 33 from on-field research (photos by the author), 7 geometric surveys by the author (laser scanner or photogrammetry or thermography).
- *A fasce vaults*: 16 examples, 13 from literature (of which 3 geometric surveys), 3 geometric surveys by the author.
- *Planterian vaults*: 40 examples, 36 from literature (of which 25 geometric surveys), 1 from on-field research (photo by the author), 3 geometric surveys by the author.

In the first instance, the case studies that were gradually being identified, with the related information, coming from the existing literature on the subject, direct surveys or inspections, were inserted in sheet work for cataloguing (in MSWord). The sheet work, named after the building with the vault, gives information on the palace location, the period of construction, the vault description, and the bibliographic references. The sheet work includes the on-field research data, such as thermographic and geometric survey (vault dimensions), photos, 3D modelling. The box with keywords highlights the elements that can help make cross-queries among the typologies. Keywords are related to the novel parameters, such as *maîtresses voûtes*, brick or stone arrangement, and constructive figure. The sheet work (Fig. 4) was the first level of data collection. A database was then set up (MSAccess) to store the information and to georeference them in GIS. The database is the first step into the sharing of the collected data. Along with the sheet work, the GIS seemed the appropriate tool to visualize a map of the dissemination and concentration of the three types of vaults, although the research is still on-going and opened to additional information coming from future studies.


**Figure 3**: Study of typologies of cloister vaults: a) frame vault of Villa d’Adda-Borromeo, arch. F. Croce (ca. 1765), Cassano d’Adda; b) frame vault of St. Sigismondo refectory (ca. 1758), Cremona; c) planterian vault, Palazzo Ghilini, arch. B. Alfieri (1732), Alessandria; d) a fasce vault, St. Lorenzo church sacresty, arch. G. Guarini (ca. 1680).

**BS. T. 57. Abbazia olivetana di S. Nicola, Rodengo Saiano**

**Localizzazione:** via Brescia 83, Rodengo Saiano (Brescia).

**Cronologia:** ante 1560.

**Dimensioni della struttura voltata:** in pianta 9,70x7,60m; altezza in chiave 5,76m; altezza della cornice 3,95m.

**Descrizione della volta:** la volta copre lo spazio antistante il refettorio dell'abbazia. È costituita da tre coppie di mensole, impostate su una cornice in rilievo sui lati lunghi, e da due coppie di mensole sui lati corti. Gli stucchi, realizzati nel 1560, sono opera del mastro Francesco Oselli, di Mantova, mentre i dipinti, datati al 1561, sono opera di Lattanzio Gambara.

**Riferimenti bibliografici:** VOLTA 2002, p. 182.

**KEYWORDS:** XVI secolo; Rodengo Saiano (Brescia); solaio ligneo; mensole; maestranze mantovane.

Figura BS. T. 57. Dall'alto verso il basso: la volta dell'anti-refettorio; pianta e sezione con ortofoto del refettorio; ripresa termografica e modello 3D della volta (Stanga, 2020).

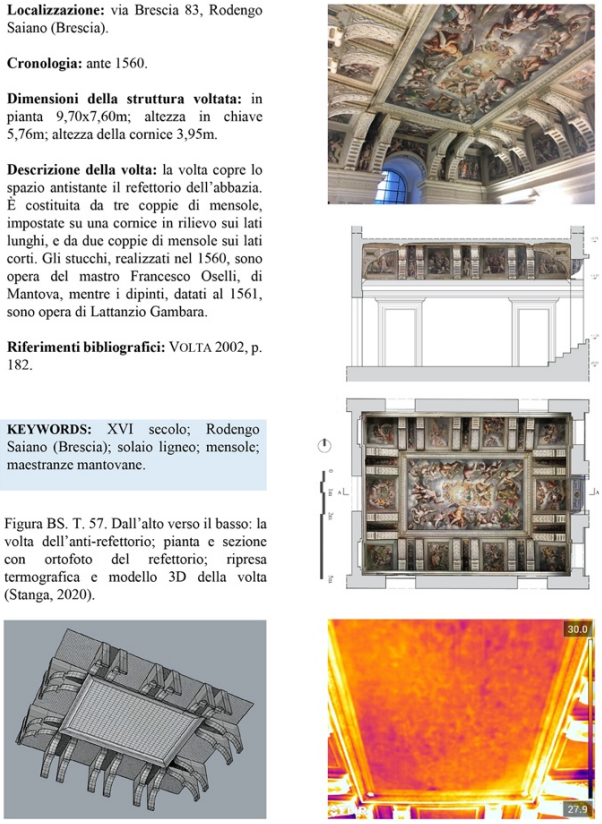


**Figure 4**: An example of vault sheet work (frame vault of St. Nicola Abbey, ca. 1561, frescos by Lattanzio Gambara, Rodengo-Saiano, Brescia). Each vault has a code (BS.T.57), the building name, the building address, vault dimensions and description, bibliographical references, photos, drawings, thermo camera photo, 3D model (whenever possible). The keywords in the box are the elements that can help in the cross queries, in this case: 16th century; Rodengo-Saiano; wooden ceilings; brackets (*fasce*/arches); Mantuan craftsmen.

One crucial step was realizing the database structure: it was necessary to think about the categories at play, realizing a functional tool regarding the research objectives (Fig. 5). The database is made of different tables:

- *Building*. To which belongs the table Building types (Palaces or churches); *Description* (name of the building); *Dates* (construction phase if possible); *City, Address and X, Y coordinates* to georeferenced the building.
- *Regions, Provinces and Cities*. Regions, Provinces and cities belonging to the study were added. Regions: Abruzzi; Emilia-Romagna; Lombardy; Piedmont; Sardinia; Veneto. Provinces: Alessandria; Asti; Bergamo; Bologna; Brescia; Cagliari; Cremona; Cuneo; Mantova; Milano; Oristano; Pescara; Piacenza; Reggio Emilia; Sassari; Torino; Verbano Cusio Ossola; Verona. 65 Cities.
- *Vaults*. To which belongs *vaults ID; buildings ID; Vault type* (Vault; frame; a fasce; planterian); *Vault material* (Brick; in foglio brick; voussoires; mortared rubble; wooden centerings); *Constructive figures intrados* (Fasce; pointed lunettes; arched lunettes; 3D arches; tie rods); *Constructive figures extrados* (half cone; frenelli – brick masonry walls; ribs; tie rods); *Arrangement* (Brick or stone arrangement can be parallel to the transversal wall; parallel to the longitudinal walls; herringbone pattern, concentric rectangular pattern, concentric circle pattern); *Type of sources* (direct or indirect); link to the photos; link to the 3D model on a360 (whenever possible).

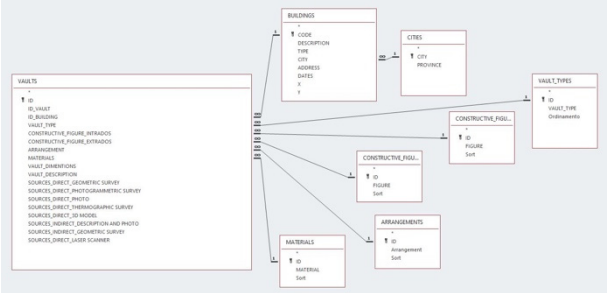


**Figure 5**: Vault database schema.

The database was populated by the 195 vaults that were studied for the research. Thanks to the database, it was possible to make queries highlighting the recurrence, in space and time, of specific construction techniques or vaulting types. The query was structured to make it possible to sort the vault depending on the city, or the province, the building date, the vaulting type, the constructive vault figures (intrados and extrados), the vault arrangement, the vault material, and the type of sources (direct or indirect) (Fig. 6).

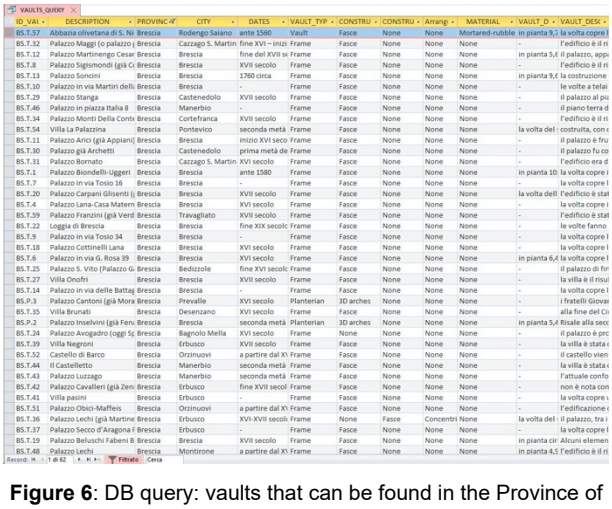


**Figure 6**: DB query: vaults that can be found in the Province of Brescia with Rodengo Saiano highlighted.

The idea to create a specific voice for intrados and extrados constructive figures is meant to allow more flexible research: if a vault is hybrid (for example, not just a frame vaults but a combination of frame and other constructive figures), one can search for "vault" and "constructive figures intrados" so the vault, which was stored with these features, shows up (Fig. 7).

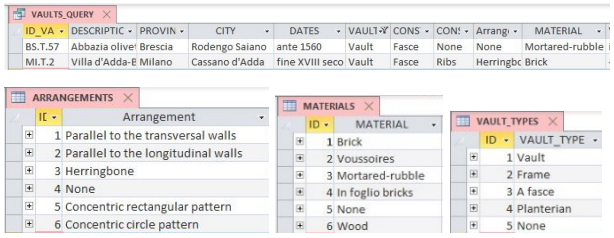


**Figure 7**: DB query: vaults that have the same constructive figures but different materials: BS.T.57 (BS=Brescia, T=Frame vault, n.57) St. Nicola Abbey in Rodengo Saiano; MI.T.2 (MI=Milano, n.2).

Particular attention was devoted to the type of sources: 1) indirect sources: description and photos from literature; geometrical survey from literature; 2) direct sources: a geometrical survey (hand measurement); laser scanner survey; photogrammetric survey; thermographic survey; photos. The indirect and direct sources were subdivided to highlight each information specificity. If thinking about sharing the database on a broader scale, the subdivision makes the researchers aware of the information provenance.

The database was then imported into QGIS 3.10 to visualize the map of vaults dissemination and concentration, even if the research is still on-going and the map does not mirror the real dissemination of the vaulting types. Because the database path is saved in QGIS, it is automatically updated in the GIS (Fig. 8). When clicking on one of the points representing a vault, the information is visible on the right side (Fig. 9).


**Figure 8**: Map of the dissemination of *frame* (blue), a *fasce* (orange), and *planterian* vaults (green) (GIS). The main concentration in Northern Italy is due to the broader research carried out in this area. It is possible to notice frame and planterian vaults in Sardinia, Abruzzi, and Prague. More studies could shed further light on these vault typologies in other nations or regions.

## 7. Conclusions

In this research, the database and the GIS are tools to collect vaulting types and information. They also help form hypotheses about the technology transfer of a particular type of construction technique.

The *frame*, a *fasce*, and *planterian* vaults dissemination depend on many factors, such as the availability of materials, the architectural traditions, the network of clients, architects, and craftsmen. The next steps will be to understand the distributive principles underlying the geographical and temporal diffusion in Northern Italy of the three families of vaulted structures.

The dissemination could involve other regions, even in Europe. It seems proven by previous research that shows the dissemination of *frame* vaults in the Czech Republic, such as the ones of the Klementinum Baroque Library and Italian Cultural Institute in Prague, and the Abbey in Broumov (Stanga, Hasníková, Brumana, Grimoldi, & Banfi, 2019). The presence of *frame* vaults in the Czech Republic can find an explanation in the work of Italian architects and craftsmen who traveled from the Lake Areas (Lugano, Lecco, Como) to work outside Italy (Della Torre, Mannoni, & Pracchi, 1997).

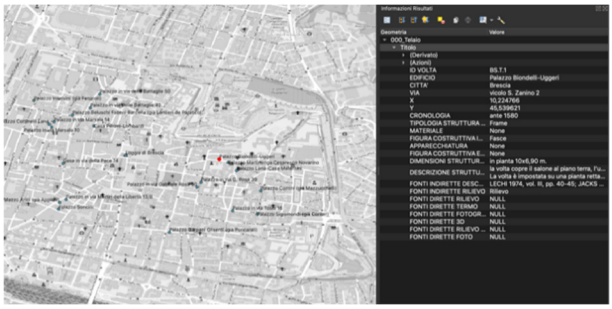

**Figure 9**: GIS map, close up to Brescia city, BS.T.1, Palazzo Biondelli Uggeri as selected entity.

The GIS-based catalogue opens towards sharing the data to a broader audience, scholars, experts, and non-experts. It could help to show and make people aware of the exchange of ideas about vault design and construction techniques between the 16$^{th}$ and 18$^{th}$ centuries. Since the work is part of a more comprehensive project, it will be implemented to make it available on an online platform, making it possible to work in a Common Geospatial Environment, where scholars could add their vault examples. In addition to the challenge of making the database available online, it will be necessary to think about a shared vocabulary of terminology by starting from the robust one settled up by the Getty Institute.

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