Brick Vaults in Southern Portugal

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Editorial

Brick Vaults in Southern Portugal

'Los nombres de las bôvedas son tantos, quantos son sus diferencias.'
[The names of vaults are as numerous as their differences]
Lorenzo de San Nicolás (1639) 1796, 124

There are many types of vaults, and vaulted architecture spans a vast universe of time, space, and typology. As a subject intersects multiple disciplines and fields of knowledge. Vaults can be understood from various perspectives – whether focusing on their structural role, their geometric form and resulting spatial configuration, on construction systems and materials, or on finishes and ornamental elements, both painted and sculpted in relief, thereby engaging other forms of artistic expression. Moreover, all these perspectives can be examined across different historical periods and in relation to their geographical distribution.

This issue of the *Revista de História da Arte* focuses on brick vaults within a broader concept of vernacular architecture. Consequently, stone vaults – whether built with ashlar masonry or rubble masonry, rendered and painted – are excluded, as these are generally associated with the major building sites that have shaped Architectural History. Therefore, the term vernacular is used here in an inclusive sense, not in its more recent and widespread association with the popular, but in a broader and etymologically rooted sense, referring to constructions deeply embedded in the building traditions of a particular place or region.

The region we have chosen corresponds approximately to the eastern half of southern Portugal, covering parts of the Alentejo and the Algarve. This area was selected due to the significant concentration of architectural examples featuring vaulted ceilings and a common set of construction principles – ranging from urban buildings to scattered rural settlements, from manor houses to modest dwellings, and from convents or parish churches to small, isolated chapels. This regional focus also aimed to explore Iberian affinities along the southern border areas of the peninsula, specifically the potential continuities between the Alentejo and the Algarve, on one side, and Extremadura and Andalusia, on the other. Within this scope, we have excluded structures strictly related to fortifications, as they follow different functional and constructional principles. Similarly, the chronological framework of the studies remains fluid – largely due to the nature of so-called 'anonymous' buildings, which have left little documentary trace, but also because of the relative continuity in the use of brick vaulting in Christian religious architecture. Despite successive typological transformations, this tradition endured from the late Middle Ages through to at least the 19th century.

The study of vaults, that is, load-bearing structures with a curved profile that rest on the walls of a room or built structure, giving rise to concave ceilings capable of supporting an additional floor or a walkable terrace, has been underdeveloped in Portugal. Research on these structures has primarily focused on the more complex ribbed vaults of the late Gothic period, built in stone masonry (e.g. Genin 2009a, 2009b and 2014), or on timbrel vaults (e.g. Fidalgo 1998; Rei and Gago, 2016 and 2018), a lighter and more cost-effective alternative, which spread across the Portuguese territory from the 19th century onwards but which can hardly support additional floors or bear the weight of accessible terraces on their extrados. The vaults used in a current context, constructed throughout the period from the mid-16th century to the mid-19th century, have attracted little attention from Portuguese researchers, who have also not been particularly interested in exploring the guiding thread that favoured the use of brick from the time this material began to replace stone in Gothic ribbed vaults until the spread of timbrel vaulting. This gradual change, particularly pronounced in regions where clay-rich soils were abundant, was further propelled by advancements in transportation during the 19th century. These improvements facilitated the trade of gypsum, a more efficient mortar than lime for securing bricks face to face. By choosing to work on brick vaults without no other constraints than the material and the geographical areas where they are most abundant, we seek to fill a significant chronological gap in the knowledge of these structures, while also reconstructing the underlying historical narrative of their evolution.

The studies presented in this issue build upon the findings shared at the scientific meeting *Forum Vaulted South – Vernacular Building Knowledge and Brick Vaults*, held at NOVA FCSH and the Ordem dos Arquitectos from 16 to 18 November 2023. This event discussed the outcomes of the exploratory project *Vaulted South – Vernacular Vaulted Houses in the South of Portugal*, funded by the Fundação para a Ciência e a Tecnologia (FCT EXPL/ART-DAQ/0171/2021; https://vaultedsouth.fcsh.unl.pt/). The editors of this issue are members of that research team, as are many of the contributing authors, in their roles as researchers or research assistants. Other authors provided external contributions that enriched the discussion. Both within the internal team and among external contributors, interdisciplinarity and institutional diversity were essential to the study of this subject. Based at NOVA FCSH through CHAM – Centro de Humanidades, which hosted the project, the research also involved the IHA – Instituto de História da Arte as an associated institution. The project team also included researchers affiliated with various research units at Instituto Superior Técnico, University of Lisbon, and, in its final stages, the discussion benefited from the participation of researchers from the Faculdade de Arquitectura at that same university and from ISCTE – Instituto Universitário de Lisboa.

We introduce the theme through fundamental research into the identification and analysis of the textual corpus – written knowledge – on vaulted systems in general, as presented in the article 'Architectural books and treatises: on the theory of vaults,' co-authored by the two editors, Margarida Tavares da Conceição, Mafalda Batista Pacheco, along with researcher Raquel Seixas. This study traces the evolution of theoretical discourse, from the emergence of the topic in architectural treatises to the dissemination of practical manuals in the 17th century. It highlights the delicate balance between architectural theory and the practical application of construction techniques, with the 18th century marking a peak in the codification of vault geometry. This period also saw the widespread diffusion of essential construction knowledge, much of which was nearly lost with the rise of reinforced concrete systems in the early 20th century.

Following this, Ana Costa Rosado's contribution, 'The incorporation of vaults in the traditional housing of the inner Alentejo,' offers a rare link between the survey of existing built examples and historical research, providing deeper insight into the possible origins and diffusion of this roofing type. The study distinguishes between two subtypes – brick vaults and timbrel vaults – tracing their emergence from the 17th century, their proliferation in the 18th and 19th centuries, and their continued presence even into the early decades of the 20th century. Furthermore, it introduces an important discussion on the potential influence of engineers involved in fortification works along the Alentejo border during the Restoration period, as well as the role of written treatises. This influence may have played a significant role in the introduction of vaulted ceilings in common buildings, offering one possible explanation for their widespread adoption.

The next article, 'Types of Vaults in Southern Portuguese Architecture', authored by two of the editors, João Vieira Caldas and Mafalda Batista Pacheco, alongside Sérgio Costa, expands upon the extensive survey of identified and documented cases, based on substantial field research. This study deliberately encompasses a diverse range of examples – manor houses, common dwellings, convents, and chapels – across both the Alentejo and Algarve regions. It highlights significant typological variety on multiple levels, including construction techniques, vault morphology, and the spatial distribution of vaults within buildings – an aspect already touched upon in the previous article. Most importantly, the authors tackle a complex and often debated issue: the chronology and diffusion of vaulted structures. In so doing, they critically challenge the long-standing myth of an Islamic origin for these vaults, a notion that is contradicted by the currently available evidence.

The knowledge gathered from examples surveyed in the area studied also highlights two key challenges addressed in the following article, the result of a collaborative effort among several and multidisciplinary members of the project team (Mafalda Batista Pacheco, Ana Paula Falcão, Maria da Glória Gomes, Rolando Volzone, Marina Parreira Folgado, and Sérgio Costa). 'Digital vaulted territories: development of a cross-tool platform for vaults' knowledge' discusses, on the one hand, the need to record, organise, and manage data storage platforms to ensure the reliability of quantitative analyses, while also facilitating open-access data sharing with the academic community and other audiences. The article also examines the use of digital tools for the surveying, representing and monitoring of this built heritage.

Closely tied to the need for accurate graphic surveying tools for research, Luís Mateus' article, 'From the empirical making of alentejo vaults to the generative geometry of the Arco da Rua Augusta vault', examines the application of digital surveying methods across different cases. The study demonstrates how modern surveying and graphic reconstruction techniques allow for a precise assessment of the irregularity and geometric uniqueness of vernacular vaulted constructions, in contrast to the precision of stereotomy in more sophisticated examples.

The need for rigorous studies employing technological tools underscores the ultimate goal of all surveys: the conservation of built heritage, whose material existence serves as a historical record in itself. In this context, this issue includes two complementary pieces: an interview and the presentation of two documentaries.

The interview with Manuel Fortea Luna, project consultant and specialist in vernacular vaults of the Spanish South, captures diverse perspectives on the material reality of these construction systems. Drawing from extensive experience in heritage consultancy, intervention, construction trials, and model-based simulations, Fortea Luna provides valuable insights into both the theoretical and practical aspects of vault building. The same concern – balancing the need to document surviving construction knowledge with the urgent demand for conservation and restoration of many identified examples – led to conversations with master vault builders. These discussions resulted in two documentaries: *Na obra com os mestres abobadeiros* (On the Work Site with Vault Builders) and *Ã conversa com os mestres abobadeiros* (Talking with Vault Builders), from which we present a short film teaser of the same name in this issue.

Thus, bridging the theoretical knowledge preserved in books to the still-living craft of vault building, this research paves the way for future studies in Art and Architectural History. It provides valuable contributions to Heritage Studies, which must inevitably be pursued through a multidisciplinary and institutionally diverse approach. This research also highlights the need to expand the study to regions of Spain, further broadening the scope of investigation.

We must also clarify an important and challenging editorial decision. For this issue, we collectively chose to present all materials exclusively in English. While this may seem paradoxical – given that both the authors and the subjects studied are largely connected to Portuguese reality – we deemed it essential within the editorial framework of *Revista de História da Arte* to facilitate broader discussion and comparative analysis beyond the Iberian world and Portuguese-speaking readership. The translation of technical vocabulary posed a particular challenge, demanding careful study and meticulous attention. Nonetheless, ensuring the widest possible dissemination of the research remained our top priority. Unless otherwise noted, all translations are our own responsability.

Finally, we extend our gratitude to all the authors who contributed to this issue with their valuable work, as well as to the reviewers for their generous participation in the scientific evaluation of the articles. We also sincerely thank the *Revista de História da Arte* editorial team for their trust and support throughout the editorial process – first under the guidance of former editor-in-chief Basia Sliwinska and later with editor-in-chief Madalena Matos. To all, we remain deeply grateful.

Margarida Tavares da Conceição,
Mafalda Batista Pacheco,
João Vieira Caldas.

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Contributions

ABSTRACT

Our search for codified knowledge about vaulted construction systems obviously started with classical texts on architecture. We wish here to explore the possibility of finding a theory about vaults that is capable of better organising a textual corpus on the subject. The fragmentary notes on vaults in Vitruvius' text are discussed as the foundational source for the book on construction and architecture. That being so, the contribution of Alberti's *De re aedificatoria* is detailed as being the truly fundamental text on this subject, as it is in fact the first structured discourse on vaults. Other steps in our search included the connections discovered between different works from the 16th to 18th centuries, including Portuguese manuscripts, and the final stage took us to the world of the *Encyclopaedia*, where reasoning and mathematical methods meet architectural and engineering theory and practice to offer a robust technical-scientific approach within the specialised literature.

keywords

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Architectural books and treatises:

on the theory of vaults

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Introduction

The first aim of this article is to present the results of a joint research project[1] which sought to identify and systematise part of the theoretical knowledge concerning the techniques for constructing vault coverings. From the outset, this research was deliberately partial, firstly because it sought only to organise a sample that can be related to constructed examples, that is, to the practical application of knowledge; and secondly because we tried not to lose sight of the fact that some of these practical cases fall within what is usually designated as vernacular construction,[2] where historical knowledge is even more sporadic than examples of so-called erudite architecture. While we are aware that the connection between construction practice and technical literature is difficult to study,[3] and this is not the approach taken in this text, the possibility of connecting the vernacular construction of vaults to theoretical knowledge – or knowledge codified through writing and illustrative drawing – must also be borne in mind, and this remained not so much a goal as a principle or motivating force. Ultimately, the survey carried out could contribute to a better understanding of the ways technical knowledge is transmitted.

So, if we assume that the theoretical level, or even the technical literature, would have little to tell us about common construction techniques, the survey that was conducted sought to align what (between provocation and enquiry) could be called a theory of vaults, at least in the sense of organising a textual corpus on the sub-

[1] Research undertaken as part of the FCT EXPL/ART-DAQ/0171/2021 project, 'Vaulted South – Casas vernáculas abobadadas no sul de Portugal / Vernacular vaulted houses in the south of Portugal' (DOI:10.54499/EXPL/ART-DAQ/0171/2021), coordinated by Mafalda Batista Pacheco, corresponding to task 1 led by Margarida Tavares da Conceição involving the participation of the researchers Raquel Seixas and Sandra M.G. Pinto, as well as Teresa Marques, as a project scholarship holder. Also noteworthy is the critical support provided by João Vieira Caldas and Nuno Senos, as well as the support provided by the project's partnership with the National Library of Portugal – Biblioteca Nacional de Portugal (hereafter BNP) and the Mafra National Palace Library – Biblioteca do Palácio Nacional de Mafra (hereafter BPNM).

[2] Vernacular construction and/or architecture is understood here not as 'simply' popular or rural, but as that which is inserted in a given regional or local environment which can provide specific constructive and formal responses.

[3] See the introduction to the thematic collection of the following issues of scientific journals

ject. A list was created of treatises and books on construction techniques, or at least those that partially deal with this topic, in order to decide on the list of sources that should make up the sample. While it is not reasonable within the scope of this research to produce an exhaustive compilation of all the existing titles, we have endeavoured to put together a group that sufficiently demonstrates the diversity of published texts on architectural and engineering theory. This diversity or level of sampling was intended to be both typological, geographical and chronological. Treatises, books and even handwritten notebooks were included, which is also why this set of sources is referred to elsewhere simply as 'written elements'.[4] Internationally circulated works were included, especially those from old Portuguese library collections, as well as manuscripts written by Portuguese authors. In the same way, we extended the chronological window and followed how the topic was approached in a diverse range of texts up to the 20th century.

The starting point of the enquiry was therefore to understand how architectural treatises, or classical books that form the basis of architectural theory, have dealt with techniques for constructing vaults. In this sense, Vitruvius' text was accorded special prominence, given its foundational status (and despite its fragmentary nature). However, it was Alberti's treatise, as a founding and formative text, that enabled us to develop this topic and recognise how many books in the 16th and 17th centuries dealt with the subject. We therefore chose to highlight only a few cases, understood as 'fragments' or 'pieces' of the best-known titles from the scholastic corpus. The next step concerned the links detected between certain 17th and 18th century Portuguese manuscripts, comparing two different approaches: firstly, the scholars who somehow followed the 'Albertian way' and, secondly, the surveying manuals addressing practical aspects, therefore supposedly open to the reality of construction sites. This is followed by the final stage which, through the Enlightenment, leads us to the world of encyclopaedias.

Since then, mathematical reasoning and methods found their way into the theory and practice of architecture and engineering, and a strong techno-scientific dimension within specialised literature grew even more throughout the 19th century. This scientific approach to the geometrical drawings of arches and the representation of vaulted solids in the written sources under study is based on Euclidean geometry, in which the study and representation of planes and objects in three dimensions are based on the axioms and postulates developed by Euclid of Alexandria, compiled in the famous *Elementa*. Euclidean theory formed the basis of most geometrical studies until the end of the Early Modern Age, when it was replaced by other approaches or branches of geometry such as Descriptive Geometry or Monge's Method. This area, developed by the mathematician Gaspard Monge between 1765 and 1789, is based on a projectional method representing

dedicated to the relationship between building techniques and architectural treatises: *Aedificare* 2 (Cardamone and Martens 2017, 27-35); and *Opvs Incertvm* 6 (Cardamone and Martens 2020, 8-11).

[4] Partial transcript available on the Vaulted South project platform: https://projetos.dhlab.fcsh.unl.pt/s/vaulted-south/page/Elementos_escritos.

objects in three dimensions on a two-dimensional plane, making it possible from these projections to determine the true magnitudes of distances, angles, areas and volumes, a development which contributed to the systematisation of technical drawing for construction as is still known today.
We can thus see that, while the discourse on vaults was structured around Euclidean postulates in the Renaissance, it later developed in the direction of mathematical understanding translated into technical representation, somehow moving the subject away from the discourse of architectural theory and more closely to books accessible to the world of construction practices.

Vitruvius, the matrix

While in Vitruvius' text we sought a kind of 'initial' knowledge about vault(s), we are aware that this is a complex source of controversial interpretation. The set of books or treatises that makes up *De architectura* was reviewed using both Portuguese (Vitruvius, ed. Maciel 2006) and English translations (Vitruvius, ed. Rowland 1999), and a comparison was made between the main annotated editions from the 16th century, which reflect the long transformation of a source text into a foundational (and canonical) text concerning a theoretical introduction to architecture (Pagliara 1986; Gros 2006; Rowland and Bell 2024). The intention was to emphasise two aspects: to clarify what was gradually added to the Vitruvian principles and to provide a contrast with Alberti's treatise, the *opus magnum* of the modern era.
Regarding the classical theoretical knowledge that Vitruvius was able to provide on the architectural culture of the Roman era, which was largely based on the development of techniques for constructing vaults, it can be clearly stated that he includes almost nothing on vaults, let alone dedicating any specific chapter to it. However, from the point of view of architectural discourse, it enabled vault construction techniques to be included by derivation into the illustrious mythological genealogy of the surpassing of the 'primitive hut' (Vitruvius, bk. 2, ch.1), that is, it allows this roofing system to be included in the art of construction, into the art of utilising and transforming the resources of nature.
Vitruvius gives expositions on different types of sand, lime, wood, stone and bricks throughout the Second Book, which is entirely dedicated to building materials rather than techniques, as is well known (Lancaster 2024). Nevertheless, *De architectura* also mentions wall coverings, from stucco to fresco painting (which are materials and techniques that we can find in vaults), in the Seventh Book. There

is, therefore, a list of materials and some technical considerations concerning their application, joining and mixing, from formwork to wall finishings.

We can see that the data on vaults is distributed across several book chapters, prompting us to question the scope of the topic under investigation. How can the topic of vault construction be delimited? Vitruvius only includes a more specific reference to vaults, not in themselves, but in relation to baths (the Fifth Book), where he mentions the structural advantage of cement working[5] and clarifies the convergence of different materials and the use of an implicit geometric definition through rulers and arches:

> If the vaults [*concamarationes*] are going to be made of masonry [*structura*] they will be more efficient. However, if they are going to be ceilings made of wooden beams, then suspend a terracotta ceiling underneath – but this is how to do it. Have iron bars or arcs made; these should be hung from the beams on iron hooks set as closely as possible to one another. These bars or arcs should be set in rows so that flat tiles can sit between any two of them and can be laid in place. By this method all the ceiling can be completed so that it is supported on iron. The upper joints of these coffers [*camararum superiora*] should be spread with clay worked with hair; the lower surface, the one that faces the pavement, should be plastered first with terracotta mixed with lime, and then finished in stucco or plaster. If these ceilings [camarae] are made double in caldaria, they will be more efficient, for then the moisture from the vapor will not be able to rot the timber of the beams, but instead will wander aimlessly between the two ceiling chambers. (Vitruvius, bk.5, ch.10).[6]

In this slightly more detailed explanation that Vitruvius provides about vaults, he points out two timeless problems: the need for solid structures (also mentioned in bk. 6, ch. 8), and the control of humidity, which is also indicated in relation to plasters (bk. 7, ch. 4). Moreover, the stated diversity of materials potentially involved underlines the difficult and costly nature of vault construction, reinforcing how their presence in any type of domestic construction is always a sign of wealth, skill and sophistication. **[Fig. 1]**

Other aspects that are particularly evident in the Vitruvian editions from the 16th century, such as those by Cesariano (1521) and Barbaro (1556),[7] include the linguistic and lexical complexities of the original text. Cesariano's translation is notably titled *li abstrusi & reconditi vocabuli*, highlighting these complexities. Indeed, the Vitruvian text cannot even be considered a model of the classical Latin language (Bosazzi 2000, 8; Gros 2006, 399-435). As might be expected, Barbaro's edition is more succinct and translates the first passage on vaults in this way,

[5] A possible interpretation based on Vitrúvio, ed. Maciel 2006, 196-197.

[6] Vitruvius, ed. Rowland, 72. We have highlighted the Latin words, taken from Vitruvius, ed. Bossalino 2002, 200.

[7] Cesariano shows the illustration *Balneum dispositio et eorum interiorum membrorum affigurata constructio*, while Barbaro (only in the 1567 edition, 264-265) includes a plan and section of the *Balnea*, showing the vaulted ceiling.

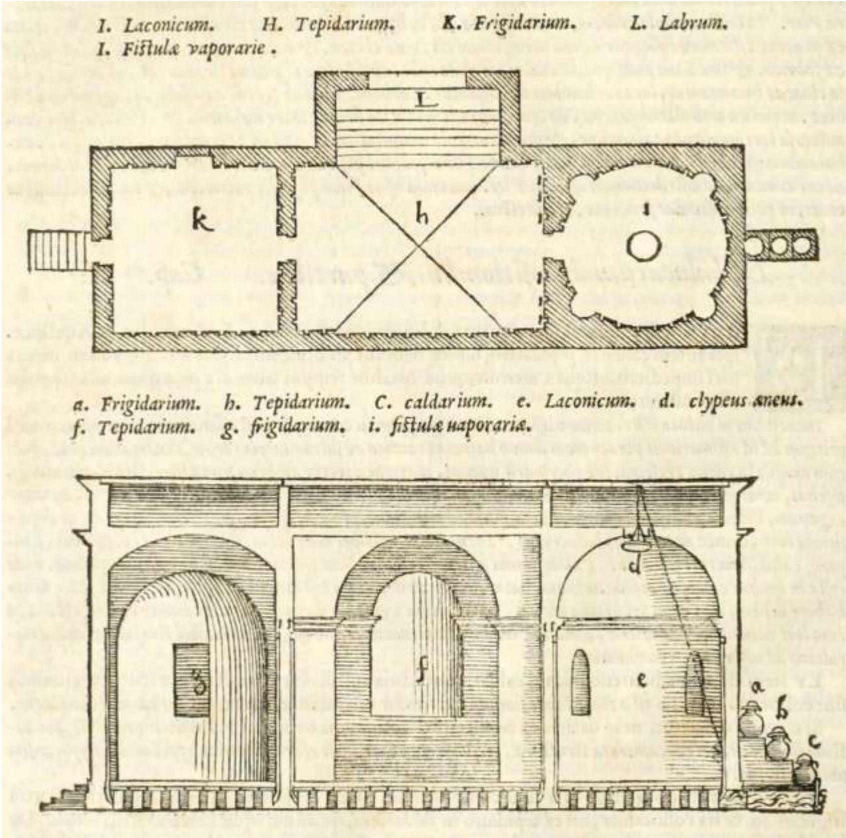


Fig. 1 Vitruvius, ed. Barbaro 1567, 198. BNP BA 259 V.

which is very close to the Vitruvian text: 'Le concamerationi, ò uolti seranno piu utili fe si faranno di muratura. Ma se si saranno tasselli, e di legname bisogna porui sotto l'opera di terra cotta (...).' (Vitruvius, ed. Barbaro 1567, bk. 5, ch. 10, 160-161). The failure to use the common word (*volta*) exposes the limits of the theoretical usefulness of the Vitruvian text in the early modern period with regard to vaulting techniques in the early modern period.

Alberti, the foundational text

The founding text of the modern discipline, the treatise *De re aedificatoria* by Leon Battista Alberti, which was presented in Rome around 1452 and, as is well known, printed on December 1485, before the Vitruvian text (ca 1486-1487), provides a clear explanation of many topics, including vaults, and these are expressed through the constructional discourse of architecture.[8] Alberti provides the first systematic presentation on vaults, with the subject included in a coher-

[8] To verify this, we used the Portuguese translation (Alberti, ed. Kruger and Espírito Santo 2011) and the English (Alberti, ed. Rykwert, Leach and Tavernor 1988), and occasionally the *editio princeps*.

ent and logical manner, with his usual proclaimed clarity. In the immense historiography on Alberti's work, it is important to emphasise that construction is a central theme in the theoretical conceptualisation of *De re aedificatoria*, further supported by the analogy of the building as a body or organism (Pagliara 2017).
In the Third Book*, On Construction,* and in a logical sequence (i.e. after the First, *The Lineaments*, and the Second, *Materials*), Alberti interprets the vault as a type of ceiling and precisely develops its essential relationship with other elements of the construction, without which it cannot exist, namely the foundations, the walls, and its fillings. He emphasises that the vault does not have an independent constructional existence but is part of the building as a whole.
Vaults are presented as curvilinear ceilings, explaining that by definition they are made up of arches. A simple and polished statement, worth emphasising for its unsurpassable correctness: 'A curvilinear roof [*tecta flexilinea*] is made up of arches; and the arch, as we have demonstrated, is but a curved beam. Ligaments also recur here, and material for gaps.' (Alberti 1988, 3.13,81-82).[9]
Only after explaining the various types of arches does he proceed with systematising the types of vaults, to which he devotes Chapter 14 of the Third Book, in around three folios, and it is worth noting the absence of a more specific Latin word:

> There are several different types of vaulting [*Testudinum uaria sunt genera*]. We must inquire in what way they differ, and of what lines they are composed. To make myself as clear and straightforward as possible, which I have endeavoured to be throughout this book, it will be necessary for me to invent new names. (Alberti 1988, 3.14, 84).[10]

He does not use the Vitruvian term *concamarationes*, nor obviously the more common word, *volta*.[11] Revealing the terminological challenge, he needs to coin new terms that are both linguistically valid in Latin and expressively precise: the vault is first presented as *tectum flexilinium* and then as *testudinum*, seeming to allude to a carapace, in the almost ambiguous sense of both *ceiling* and *roofing*, but clearly arched or vaulted. This difficulty, still noticeable in the present day when it is necessary to resort to everyday language to explain realities or constructional details, gets worse in the case of translations. Pagliara (2017, 39-41) rightly notes the difficulty of explaining constructional issues, emphasising that in this regard Alberti reveals the importance of knowledge based on observation, even more than on written sources.[12]
Given this, and accepting the terminological difficulty, and apart from poetical metaphors – 'the vast vault of the heavens', invoking Ennius (Alberti 1988, 3.14, 84) – in this short chapter the essential principles of the subject are well estab-

[9] Latin words highlighted from Alberti 1485, [fl. 48v]. For the Portuguese translation see Alberti 2011, 263.

[10] Latin words highlighted from Alberti 1485, [fol. 49v]. For the Portuguese translation see Alberti 2011, 266.

[11] Cosimo Bartoli, on the other hand, when publishing his translation of Alberti's treatise, and despite also using *testudine* or the plural *testudini*, adopted the more common word *volta* in the singular, and *volte* in the plural (Bartoli 1550, 91-92). It can be noted that the following terms, namely the English *vault*, the French *voute*, the Spanish *boveda* and the Portuguese *abóbada*, share the same root, deriving from the Latin verb *volvo*, *volvere*, *volvi*, *volutus* (as affirmed by all general language dictionaries), which means 'to roll'.

[12] The Portuguese editors of Alberti (2011, 266) note that this passage is the only time Alberti admits to a difficulty of expression.

lished. Firstly, the vault is related to the walls – it depends on the walls, on their solidity and also on the area and shape they specify. Secondly, the vault requires drawing or geometry. Thirdly, the vault requires different materials and a certain reinforced construction and assembly.

Alberti begins by distinguishing three basic types of vaults, with the other types being derived from these: the barrel vault, the groin vault, and the dome.[13] Each of these types will correspond respectively to other basic types of plan and area: quadrangular or rectangular (for barrel vaults); square (for groin vaults); and circular plan (for spherical vaults or domes). Once again, it is worth reading the exact words of Alberti himself:

> There are the various types of vaulting [*testudinum*]: the barrel [*fornix*], the camerated [*camera-camura*], and the perfectly spherical [*recta spherica*], as well as many others consisting of a certain part of these three. Of these the spherical by its very nature can be set only on walls that arise from a circular plan; the camerated requires a square plan, whereas the barrel covers any rectangular area, short or long, as may be seen in crypto-porticos. Any vault constructed like a hole bored through a mountain shall be called a tunnel vault or barrel vault, because of the similarity of its name. The barrel vault, then, is like a series of arches added on to each other, or like a curved beam stretched laterally, and hence it may be compared to a wall bent over our heads for protection. However, if a vault such as this, running from north to south, were completely transversed by another vault, running from east to west, it would create a vault resembling curved horns running out into the corners, which is therefore called 'camerated'. But if the apexes of many identical arches were to meet a point in the centre, a vault would be created that is like the heavens; this then we prefer to call perfectly spherical. (Alberti 1998, 84-85).[14]

Alberti goes on to justify how the vaults that derive from these first three base types are formed, which will not be described here. However, more important than the explanation of the different types of vaulting is the way Alberti explains the essential correlation between vaulting and walls, therefore in relation to the structure embodied by the building materials. As Pagliara pointed out (2007, 174-175; 2017, 37), the idea of 'ossature' is the basis for understanding the structural system. Alberti states, with rhetorical efficiency:

> The same method of construction should be followed for the vaults as is used for the walls. In fact, the bones [*ossa*] within the walls continue unbroken right up to the top of the vault; they are constructed in the same way and are set a

[13] In Portuguese, *abóbada de berço*, *abóbada de ângulo* (nowadays *abóbada de aresta*), *abóbada esférica* (nowadays *cúpula*), see Alberti 2011, 266-267.

[14] For Portuguese translations see Alberti 2011, 266-267. Latin words highlighted from Alberti 1485, [fol. 49v-50]; the editors note that the word *camera* will be *camura*, a word invented by Alberti (Alberti 1988, 379, note 56; Alberti 2011, 267, note 645).

correspondingly similar distance part. The ligaments stretch from bone to bone, and the section between is filled in with panelling. But there is this one difference: in a wall the individual stones and courses are set and laid together in straight lines along the horizontal and vertical, but in a vault the courses are laid along a curved line, with the joints of all the stones pointing towards the centres of their respective arches. For the bones the ancients would almost always use baked bricks, generally two feet in length. It is advisable to complete the infill panelling with an extremely light stone, to prevent any eccentric loading putting a strain on the wall. (Alberti 2011, 268).[15]

Alberti goes on to claim that the construction of vaults also often requires framing with inexpensive materials (branches or reeds), but that it is possible to dispense with such framing by understanding the construction system through its geometric and structural essence, through knowledge of the distribution of forces and the pressure exerted by them. He warns of the constructional care required in the connection between wall and vault, and in assembly and finishing times and rhythms. As such, Alberti points out all the issues related to this construction technique one by one. Finally, as a good Humanist and interpreter of Vitruvius, he declares nature to be the master by using an organic analogy:

In short, with every type of vault, we should imitate Nature throughout, that is, bind together the bones and interweave flesh with nerves running along every possible section: in length, breadth, and depth, also obliquely across. When laying the stones to the vault, we should, in my opinion, copy the ingenuity [*artificium*] of Nature. (Alberti 1988, 86).[16]

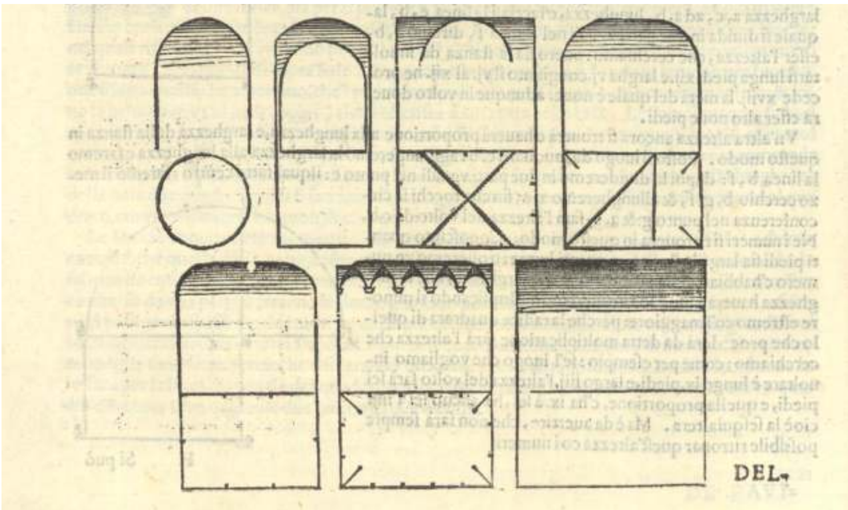
A few fragments from classical books

A survey of the wide range of architectural and engineering books from the 16th and 17th centuries reveals two aspects. The first is the almost total absence of constructive themes in the books more focused on handling architectural orders, a paradigmatic example of which being Vignola's book (*Regola delli cinque ordini d'architettura*, 1562). The same can also be said for the books of Serlio's treatise project, which as we know were widely distributed. Only in *Il Settimo Libro d'Architettura* (1575), a posthumous edition by Jacopo Strada, are specific references identified, on a case by case basis, and with regard to a particular building, on which some details of the constructive solutions are recommended (Serlio 1575, 18, 98, 112, 156, 194). The second aspect, which was far more significant and

[15] Portuguese version in Alberti 2011, 268.

[16] Portuguese version at Alberti 2011, 270. Latin word added from Alberti 1485, [fol. 51v].

Fig. 2 Palladio 1581, 1.24. BNP Res. 2817 A.



positive, refers to the assimilation and expansion of Alberti's lesson on building techniques through a logical systematisation at the theoretical or compendial level. Palladio's work stands out in this regard, as does the treatise by Scamozzi.

The compendial trait can clearly be identified in Palladio's *Four Books* (1570), which show a considerable capacity for synthesis and illustrative representation. A great connoisseur of building techniques, which have long been studied, but always offering new contributions, Palladio was the first to graphically interpret Vitruvius' schemes (Cellauro and Gilbert 2020). With regard to vaults, he emphasises the proportional rules of the dimensions (in terms of area and height), whether these be numerical or geometric rules, with the proviso of practically adapting the rules according to judgement and necessity. The designations that Palladio introduces are different from Alberti's, as he considers six types, in the short chapter 'Delle Maniere de' Volti' (On the types of vaults):[17] *à crociera* (ribbed vaults), *à fascia* (barrel vaults), *à remenato* (cove vaults), '(che cosi chiamano i volti, che sono di portione di cerchio, e no arrivano al semicircolo)' [that is, what they call vaults that comprise a segment of a circle that is less than a semicircle], *ritondi* (domes), *à lunette* (lunette vaults), and *à conca* (domical vaults) (Palladio 1570, bk. 1, ch. 24, 53-54; Palladio 1997, 59-60). He immediately points out that 'The last two types were invented by the moderns while the first four were also used by the ancients' (Palladio 1997, 60). His comparative chart is significant because it demonstrates the comparative understanding of the types of vault with the planimetric form of the compartments. **[Fig. 2]**

In contrast to the brevity of the Palladian text, Scamozzi's treatise *L'idea della architettura universale* (1615), although incomplete, is voluminous and shows a prolix author with an erudite expositional style which is replete with examples. Successor of Pal-

[17] In this passage we follow the English translation of the Tavernor and Schofield edition (Palladio 1997, 59-60).

ladio, his approach takes up three chapters (bk. 8, ch. 14-17) and expands on the subject of vaults and their types, with variations in designations, which we will not develop here, so as not to take us from the general purpose of the article, which is understanding the evolutionary framework of the conceptualisation of vault(s).

Subsequent treatises addressing the vault's issue continue to conform to scholarly systematisation, juxtaposing references from both ancient and modern examples. However, certain examples underscore the need of correlating theoretical principles with their practical implementations, a process which sometimes involves a degree of complexity. It is along these lines, and as a one-off exercise, that we will present two examples of Spanish and French works.

The first example is the book *Arte, y uso de arquitectura* (Art, and use of Architecture) by Fray Lorenzo de San Nicolás, who introduces himself as *Agostinho Descalço* (Augustine Barefoot), Architect and Master Builder, from Madrid (San Nicolás 1639, 1665). The son of a master builder, he apprenticed in his trade from an early age, combining practical learning with a solid theoretical education, enriched by the substantive libraries of the Augustinian Recollects (Díaz Moreno 2004, 157-179). Fray Lorenzo devotes several chapters to vaults, discussing their classification, outline and construction, recognising that 'los nombres de las bobedas son tantos, quantas son sus diferencias' ('the names of the vaults are as many as their differences', San Nicolás 1639, 90v). He explains and defines the different types, describing their characteristics, geometry, measurements and ratio of forces. He details techniques such as the use of wooden centering to mould vaults and recommends the use of thin bricks and plaster to reduce weight and costs without compromising structural stability (San Nicolás 1639, 124-140). Among his most significant innovations were mortared wooden slats vaults, light and economical, built with wooden structures covered in plaster, especially suitable for buildings with thinner walls (Hurtado-Valdez 2009, 105-106). He also addressed issues such as the opening of windows in the domes for natural light and their decoration, thereby combining function and beauty (San Nicolás 1665, 141-146). Throughout the book, Fray Lorenzo uses practical examples while developing his various themes. He shows drawings to illustrate the methods described, and explains them in detail, thereby making this knowledge more accessible and practical. Many of these drawings are directly applied to architectural examples (Novo Sánchez 2022). As such, starting from the 'Albertian theoretical line', he includes the need for practical experimentation, particularly varying the building materials. **[Fig.3]**

In contrast, Augustin-Charles d'Aviler's *Cours d'Architecture* (1691) is a work deeply rooted in the French classical tradition, marked by the systematisation and theoretical analysis of the classical orders. Associated with the work of the French academy, d'Aviler deepened the theoretical focus on vaults, which was presented in direct

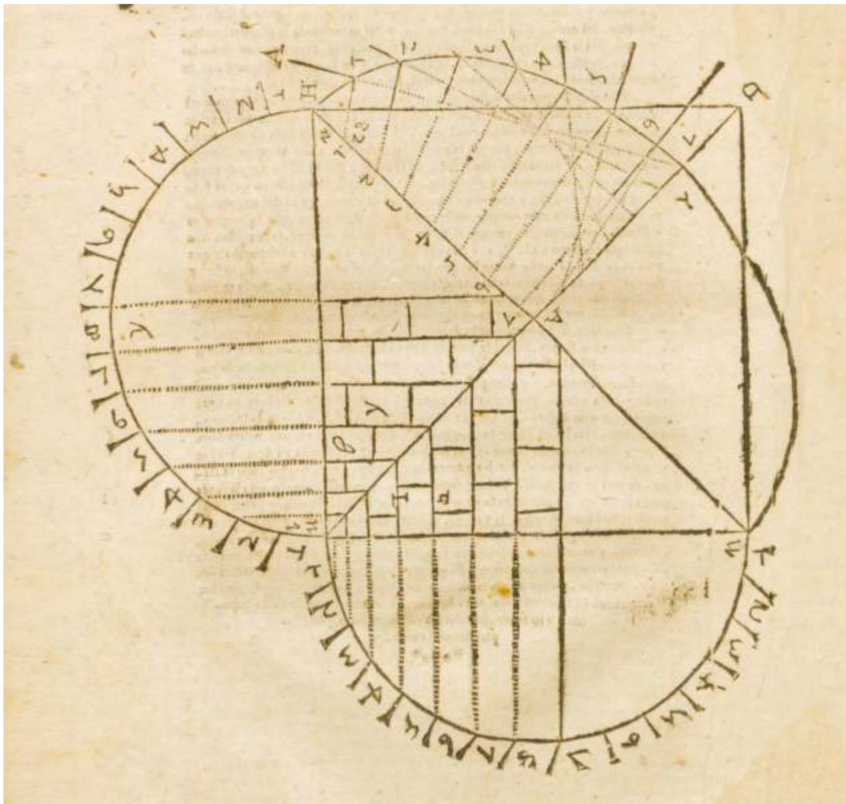


Fig. 3 Geometric diagram for the calculation and construction of timbrel vaults. San Nicolás (1639) 1736, 172. BNP 236 V.

relation to architectural orders, through emphasising their role in composition. With regard to vaults, d'Aviler showed a theoretical concern in systematising their history, classifying them into barrel vaults (*voûte en berceau*), groin vaults (*voûtes d'arêtes*) and domes (*dômes*). At the same time, he underlined the constituent elements, such as the *voussoirs* – individual stones that make up the structure – and the arches that guarantee stability. In addition to the structural aspects, d'Aviler emphasised the connection of vaults with the decorative arts such as painting and sculpture and included them into architectural discourse as an essential part of the royal classical ideal, where technique and decoration are combined. More than a technical or practical manual, this work stands as a defence of the *grand style*, the royal French architectural discourse centred on order, proportion and monumentality.

Some Portuguese fragments: pragmatic approaches

When narrowing down our search to the small and not very homogeneous group of Portuguese manuscripts from the 17th and 18th centuries, we came across the incomplete text of the *Tractado de Architectura que leo o Mestre e Architecto Mattheus do Couto o Velho no anno de 1631* (Architecture Treatise read by Master and Architect Matheus do Couto the Elder in the year of 1631).[18] The context

[18] BNP, Cod. 946.

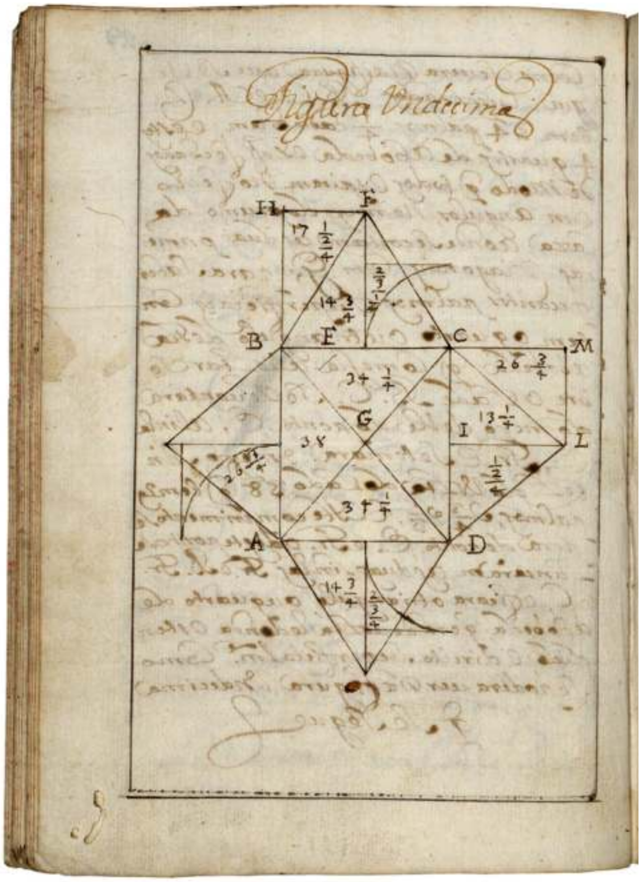
in which it was conceived and transcribed is important because this concerns the transmission of knowledge in the education and training of future royal architects, which included lessons in architecture and others in geometry. The codex contains a sequence of lessons, bringing together the subjects of theoretical learning in four sections (or books), strongly influenced by Alberti and Serlio. However, the work is incomplete and does not include the illustrations mentioned. The last section has just one chapter and the start of a second, which was indeed related to vaults. The text on the vaults is thus scarce, but significant. The author starts by referring to stone vaults and their types – *aresta* (groin), *engras* (domical), *lunetas* (lunette), *rincães* (corners), *meias laranjas* (dome), *perchinas* (pendentive), *arcos direitos* (flat arches), and *de viagens* (rampant), *contraviagens*, *sarapaneis* (three-centred) –[19] seeking to emphasise the need to design the constructional details as the only way to ensure the quality of the work (Couto 1631, 73). The accuracy of the detailed geometric drawing of the arches and vaults is not only important for a good understanding of the works, but also for taking precise measurements, for accounting for materials used in a construction project and the associated costs (labourers, construction site, etc), and for scheduling (Conceição and Pacheco 2023).

These pragmatic needs concerning building design and logistics, combined with scientific knowledge, lead us to another type of book, both handwritten and printed, which is that of practical measuring manuals. While we do not know whether the last book of Mateus do Couto's treatise would have taken this approach for the subject of vaults, we know that a few decades later, in 1660, João Nunes Tinoco, who would become the royal architect, appointed in 1665, organised the *Taboadas Gerais para com facilidade se medir qualquer obra do officio de Pedreiro, assim de cantaria como de Aluenaria, com outras varias curiozidades da geometria pratica muy necessarias para o mesmo effeito das mediçoens* (General tables to easily measure all type of work of the stonemason's craft, both stonework and masonry, with other various curiosities on practical geometry much needed for the same effect of the measurements).[20]

João Nunes Tinoco was the son of Pedro Nunes Tinoco, who transcribed Mateus do Couto's lessons into the *Tractado de Architectura*. His *Taboadas Gerais*, tables that were developed to facilitate basic mathematical operations, were (and still are) an instrument of scientific knowledge used in a constructional context that could be applied to the measurement of all types of buildings, from small-scale to larger ones, for which it is necessary to double the quantities in the tables. Tinoco deals with calculations and geometric figures, showing how to measure different vault geometries, both in brick and in stone: *meia laranja* (dome), *aresta* (groin), de *sarapanel* (three-centred) or *abatida* (recessed), using designations that recall those used by Mateus do Couto. While these *Taboadas* demonstrated the author's experience in building, Tinoco was also a very

[19] '(…) do montear das abobadas, asim por aresta, engras, lunetas, rincães, meyas laranjas, Perchinas, Arcos direitos, e de viagens, Contraviagens, sarapaneis, sobrearcos, Janelas em cantos (…).' (Couto 1631, 73).

[20] BNP, Cod. 5166. Selected quotes in https://projetos.dhlab.fcsh.unl.pt/s/vaulted-south/item/60429.



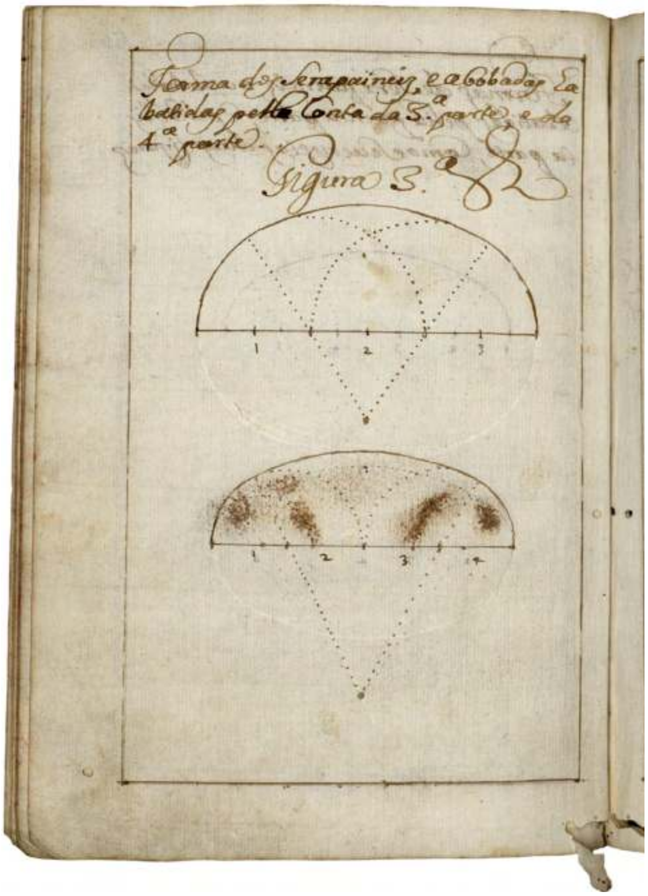


Fig. 4 'Figura Undecima', Tinoco 1660 [fol. 29v]. BNP Cod. 5166.

Fig. 5 'Forma dos sarapaneis e abobadas abatidas pela conta da 3ª parte e da 4ª parte', Tinoco 1660, [fol. 43v]. BNP Cod. 5166.

active architect involved in surveying fortifications. His compendium of measuring operations consists of a long sequence of tables, from arithmetic operations and the equivalence of measurement units to practical exercises. Here the aim is to learn the calculations, with the explanation of the building material being absent, and only the list of the different types of walls, vaults, roofs, tiles, water pipes being given to the reader. Special instructions are added for large works such as palaces and fortresses.

Tinoco takes a Euclidean approach in describing the procedures for drawing up the geometric figures that form the basis of architectural forms and that allow them to be measured, using text, geometric outlines and planimetric drawings as descriptive tools, such as the example for measurement of a house enclosed by a groin or barrel vault, with the measures for calculation according to the material used, whether brick or stone. At the end, a section with geometric drawings includes the geometry of recessed vaults by 'the third and fourth part' and by the 'fifth and sixth part' common in vernacular architecture. The manual was explicitly designed to be an instructional tool for architects, builders, artists and craftspeople (Conceição and Pacheco, 2023). In order to retain the acquired knowledge, we can assume that the recipients of these lessons produced their own notes and, later in their careers, organised them into new manuals, thus perpetuating the passing on of such knowledge. **[Figs. 4 and 5]**

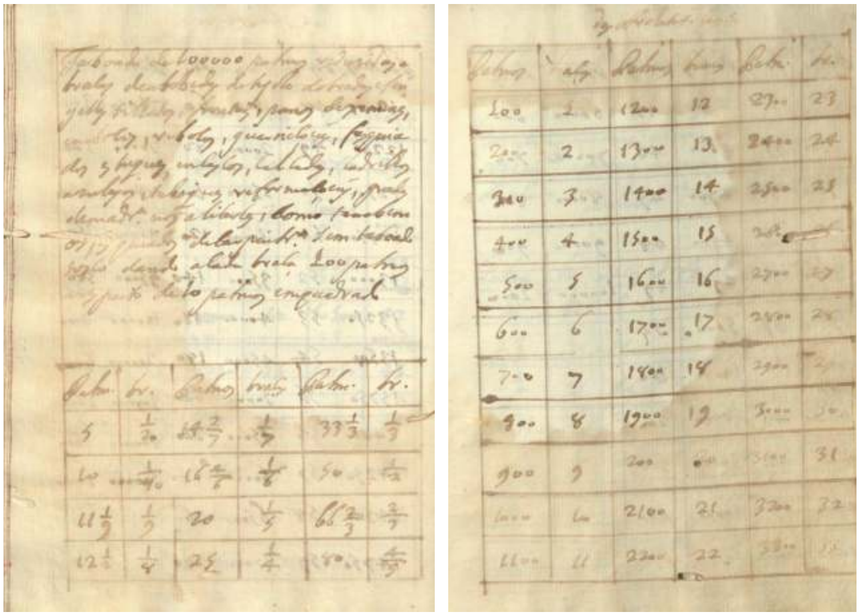


Fig. 6 'Taboada Decima, Abōbadas', Tinoco 1660, [fol. 9v]. BNP Cod. 5166.

Fig. 7 Calculation tables, Anonymous [post 1737]. *Medidor das obras* […], fols. 31v.- 32f., BNP Cod. 5167.

When reading *Medidor das obras de Architetura Militar e Civil assim de pedreiro como de carpinteiro, Pintura, Escultura, ferreiro e sarralheiro* (Surveyor for military and civil architectural works both by stonemason as by carpenter, painting, sculpture, blacksmiths and locksmiths),[21] an anonymous and undated manuscript from the second quarter of the 18th century (certainly after 1737), with the imbricated abbreviated handwriting of a mason 'surveyor' agent, direct references can be observed through the similarity of the drawings, tables and geometric procedures to the contents of the mason and carpenter offices in Tinoco's manual. This is not a direct copy of Tinoco's manuscript, as some of the content has been copied and reorganised in a different sequence, with new information being added. The features of the codex also show that it was revised and reorganised after it was written. This suggests that this was a preparatory version of the book and that the text would have been tidied up, just like some of the final drawings are inside an enclosure and identified as prints, and others remain in sketch format. The document has been extensively handled due to its function as a manual. Compared to the previous manuscript, chapters and sections have been added with warnings and practical examples relating to Lisbon. The practical nature of a *Surveyour* or *Medidor das obras* is also reflected in the book's final chapters on the differences between measurements for carpenters and bricklayers, the prices of various materials, from woodwork to ironwork, and the laws that must be observed in surveys in order to issue certificates with concrete examples from judicial records. **[Figs. 6 and 7]**

[21] BNP Cod. 5167. Selected quotes in https://projetos.dhlab.fcsh.unl.pt/s/vaulted-south/item/62437

These two handwritten manuals were created to transmit knowledge from a master to their pupils and from these to the work sites, as were printed manuals which were more widespread, such as *Advertências aos Modernos que aprendem os officios de Pedreiro* e *Carpinteiro* (Warnings to Modern learners of the trades of Masonry and Carpentry), published in 1739 and with revised editions by the author in 1748 and 1757, cited in the anonymous manuscript above. Its author, Valério Martins de Oliveira, lived in Lisbon and was a master mason whose career and official positions show he was well known (Pinto 2022). The manual *Advertências aos Modernos* was the result of a compilation of his professional experience, sharing scientific content and illustrations from the hand-written manuals that circulated in the field, containing elementary definitions of geometry, measurement of 'round works' (*obras redondas*), practical rules for measuring and executing stonework pieces and structures, general tables for stonemasons (to which he added those for carpenters in the 1757 edition), general measures and budgeting. Some themes were dealt with reference to foreign authors, along with examples from works he had built or inspected, and other aspects were introduced, such as proportion and architectural orders. The table of contents at the end of the book, together with the fact that it was a printed manual and therefore easy to consult, made *Advertências aos Modernos* a successful work which was successively republished until the mid-19th century. Something similar did not appear until the end of the 19th century, with Luís Augusto Leitão's *Curso elementar de construções* ('Elementary construction course', 1896), which will be dealt with later.

Another book published in the same decade, in 1733, but as part of the scholarly treatises produced in the ecclesiastical milieu, was *Artefactos Symmetriacos, e Geometricos: advertidos, e descobertos pela industriosa perfeição das Artes Esculturaria, Architectonica, e da Pintura* (Symmetrical and Geometrical Artifacts: warnings and discoveries through the industrious perfection of the Arts of Sculpture, Architecture, and Painting) by Father Inácio da Piedade Vasconcelos, who dedicated himself to the study of scholastic sciences at the Évora College of the Society of Jesus (Cabeleira 2022). This work was intended to address the scarcity of published treatises on architecture and art in Portuguese. In the chapter in which he was supposed to deal directly with the subject of vaults, he chose not to delve into this, explaining: 'That at this point we were going to deal with vaults, describing their construction, according to the differences between the various types. However, I see that today these works are made with such ease, and perfection, that it seems to me it will not be necessary to spend time outlining their handling' (Vasconcelos 1733, 397).[22] This omission may suggest that, in Portuguese construction of the period, vault construction techniques had already reached a level of maturity that did not require a detailed explanation. Alterna-

[22] Original: 'Que neste lugar se seguia tratarmos das abobedas, dizendo das suas fabricas, conforme as diferenças dos seus géneros; porém vejo, que hoje se fazem estas obras com tanta facilidade, e perfeição, que me parece não será necessário gastar tempo com a traça das suas operações.' (Vasconcelos 1733, 397).

tively, it could also indicate that Vasconcelos preferred not to go into technical details that he had not fully mastered and so referred explanations of these issues to master builders, such as Fray Lorenzo de San Nicolás, whose authority he recognised. The book *Arte y Uso de Arquitectura* (1639) served as his theoretical basis, as it presented constructional solutions that ensured the durability of buildings, especially regarding the use of vaults and abutments. It should be noted that this Spanish author was the first to mention the Alentejo-type vault, a traditional construction technique widely used by Portuguese masters (Huerta 2004; Rei and Gago 2018, 31-32).

The subject of vaults was dealt with indirectly by Father Piedade Vasconcelos in the chapter dedicated to the 'fortification of any Temple', where he discussed the importance of the thickness of the walls to ensure the stability of constructions, especially in buildings covered by vaults. He argued that, due to the weight of the stone vaults, the walls should have a thickness corresponding to a third of the width of the span of the church itself. Brick vaults, on the other hand, because they were lighter, enabled the walls to be thinner, with a thickness equivalent to the seventh part of the width of the span (Vasconcelos 1733, 393-394). He also emphasised the fundamental role of abutments in distributing the forces exerted by the vault on the walls, thus enabling them to be thinner without compromising the stability of the structure. In the case of stone vaults, he mentions that the thickness of the walls could be reduced to 'one sixth of the width' of the span by using abutments, which would compensate for the lack of thickness with greater resistance (Vasconcelos 1733, 393). This work, written from a cultured perspective involving mainly theoretical concerns, shows how construction issues required an approach that combined geometric rigour and practical solutions, illustrated with concrete data, to ensure the stability and durability of buildings.

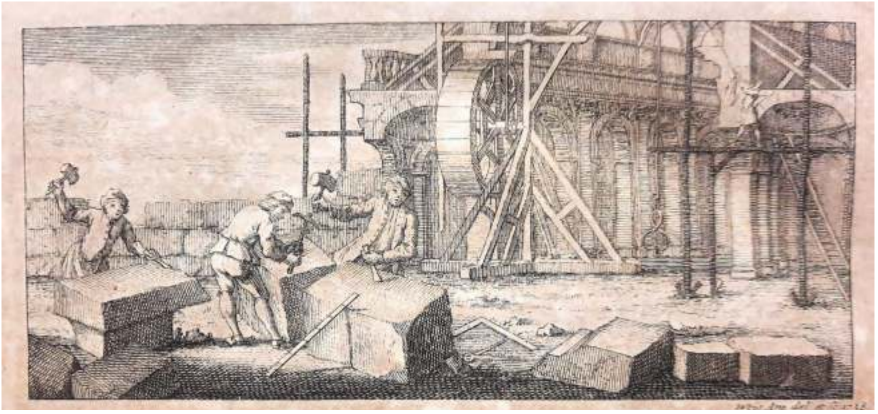
In line with 'reason'

This text represents a leap forward from Portuguese fragments containing pragmatic approaches to vault construction, in which knowledge based on an oral and practical tradition prevailed. This is not so much a chronological leap as a scientific and methodological one, with a move away from geometry towards the calculation of forces and the resistance of materials in the late 17th century, in line with Enlightenment 'reason' leveraged by scientific advances in the field of mechanical engineering. Until the application of this field of engineering to the design of the structural elements of the vault (arch, vault and vertical supports), calculations were carried out using empirical rules and methods based on geometric proportions based solely on the size of the spans and the profile of the arches (full, recessed or raised) and the type of masonry for the supports (cut stone, brick or concrete). With the assimilation of mechanical engineering concepts and methods, the scope changed considerably, and many other books were produced based on this new approach (Mascarenhas-Mateus 2002, 93-133; Pacheco 2018, 218-221). Due to its specificity, we would highlight *La theorie et la pratique de la coupe des pierres et des bois, pour la construction des voutes et autres parts des bâtiments civils & militaires*, an extensive work by the French military engineer Amédée-François Frézier published between 1737-1739 in three volumes, with a second edition in 1754, and simplified in 1760 in the version *Élémens de stéréotomie, à l'usage de l'architecture, pour la coupe des pierres.*

Frézier was then chief engineer and had just been appointed captain (1739) and promoted to the position of director of fortifications in Brittany. At the time he already enjoyed considerable scientific recognition for his previous publications, including the *Traité des feux d'artifice pour le spectacle* (1706) and the *Relation du voyage de la mer du Sud aux côtes du Chili, du Pérou et de Brésil* (…) (1716), the result of his scientific expeditions to South America. His involvement in military campaigns and accompanying fortification works, particularly in the West Indies between 1719 and 1725, formed an important part of his multidisciplinary training and professional experience. These factors also justified his contributions to Diderot and D'Alembert's *Encyclopédie* and the *Histoire générale des voyages* by the abbot Antoine François Prévost (Rabut 1992).

Frézier opens *La theorie et la pratique de la coupe des pierres et des bois, pour la construction des voutes* (The Theory and Practice of Cutting Stones and Wood for the Construction of Vaults and Other Parts of Civil and Military Buildings) with the proposal '(…) to give the theory of the Intersection of Bodies, since it is necessary to show how we can use them in Architecture to construct vaults (…) that valuing practice tends to be little theory.' (Frézier 1737, [n.p.]),[23] thereby revealing an Enlightenment perspective in terms of valuing understanding and reasoning. With precision, solidity and cleanliness, he studies all the types of vaults and figures that can be proposed and which he recognises through his experience. Lamenting the imprecision with which workers are trained in these matters and claiming that this part of architecture, 'undoubtedly the most difficult, often requires an engineer' (Frézier 1737, [n.p.]), he proposes through this work to instruct the master trainers with geometric rationalisations for the treatises and to convince them that an officer should have both scientific and authoritative superiority over the craftsmen employed in the royal works. The book claims to present a new approach to the treatment of stereotomy, presenting new areas such as *tomotechnie* (the cutting technique), *tomomorphie* (the shapes of the cuts)

[23] Original: '(…) de donner la theorie des Sections des Corps, autant qu'elle est necessaire à la démonstration de l'usage qu'on en peut faire en Architecture pour la construction des Voutes, (…) qui se sont telle ment bornez à la Pratique, qu'ils semblent mépriser la Theorie.' (Frézier 1737, [n.p.]).



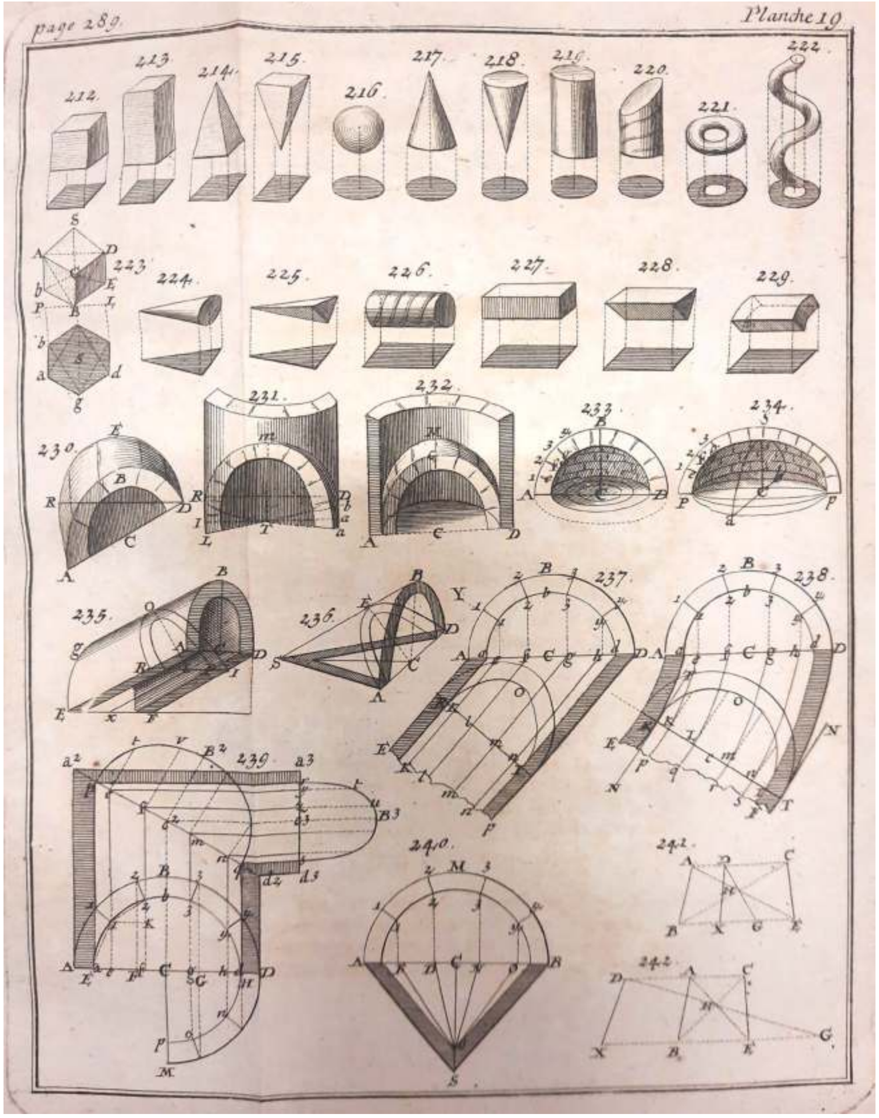


Fig. 8 Detail of the Third Book of the 'Treatise on Stereotomy'. Frézier 1739, vol. 3, 1. BNPM.

Fig. 9 Illustrative figures from the 'Treatise on Stereotomy' concerning the description of the division of solids, and the rules for drawing horizontal projection of round arch vaults. Frézier 1737, vol.1, 289. BNPM.

and *gonographie* (the description of angles), and outlines the principles of three-dimensional geometry using illustrations of the complex intersections between three-dimensional shapes, such as spheres and cones, applied to the constructive and structural problems of vaults.

It is not possible here to detail the contents of the three volumes dedicated 'to vaults', but we would like to highlight the value of theory and the demonstration of its usefulness. This is a richly illustrated work featuring geometric drawings described in the text, characterised by a high level of rigour and complexity. It employs reflections (the rotation of two-dimensional entities around themselves to position them in more advantageous spatial orientations for representing their true dimensions) and three-dimensional representations through the use of axonometric projections and perspectives with a single vanishing point, in addition to representations with plans, elevations, and sections. The third volume is notable for introducing the study of the structural behaviour of vaults, the forces acting upon them, and the lines of collapse developed through mechanical engineering. It also foreshadows introductory aspects of descriptive geometry. **[Figs. 8 and 9]**

The fact that Frézier was asked to collaborate on Diderot and D'Alembert's *Encyclopédie* is significant, demonstrating the scope of the systematisation of knowledge, and the true encyclopaedic spirit. This collaboration reflects a direct association between science, specialised language, and practical utility or applicability. In this context, the contribution of Quatremère de Quincy to the theory of architecture and construction is significant due to the importance of his complex work in codifying architectural theory in 'modern' terms (Lavin 1992). In the entry 'Voute' in the third volume of the *Encyclopédie méthodique* (1825, 618-636), dedicated to architecture (the so-called *Dictionnaire d'architecture*), a systematic theoretical framework is established. It includes the definition of the vault, its history, and the issue of determining its origins. Following this, it explains the constructive principles, the specificity of flat vaults, the constitutive elements of vaults, stone cutting techniques, and, finally, provides a comprehensive list of vault types.

Two Portuguese cases

Construction technique manuals underwent significant development in Europe during the 19th century (Mascarenhas-Mateus 2002, 46-56). In Portugal, after the cycle of the 17th and 18th century manuals, a publication of this type only appeared again in 1896, with the appearance of the *Curso Elementar de Construções* (Elementary Course in Constructions), by the military engineer Luís Augusto Leitão. It was designed for the course of the same name and organised into six parts.

In it, the teaching of techniques for constructing vaults was included within 'Construction works' which, among other topics, and in taking account of construction materials, machinery, earthworks, barracks and budgets, deals with 'Muros, paredes e abobadas de cantaria (…); descintramento das abobadas' ('Exterior and interior walls and vaults made of stonework (…); removing of the centering from vaults,' Leitão 1896, 250-266). While this range of topics is already familiar to us from the textbooks of previous centuries, there is a sub-chapter dedicated to 'vaults and the removing of their centering' (the process of removing the provisional support for their construction) where a new form of understanding and explaining the vault is provided through its constructive process and not through its geometry, as had been the norm.

Leitão starts with the anatomy of a vault with the nomenclature of its constituent parts, the geometric types, the materials used in the outer and inner surfaces of the vault (the extrados and intrados, respectively) and the layout of the arches that create it. He then goes on to explain in detail the construction processes that vary according to the need for centering and the materials used (cut stone, irregular stone, brick or concrete). He gives particular emphasis to the moment of removing the centering, the appropriate thickness of the vault, its keystone and possible openings for lighting or the passage of stairs or lifts. Finally, he describes the complementary works ensuring the conservation of the work, with the starting of the vault next to walls, the filling of the extrados and the water drainage system. **[Fig. 10]**

It is in this manual for the *Curso Elementar de Construções* that the characterisation of a particular type of brick vault found in the Alentejo (the central-southern region of Portugal), the *abobadilha* (timbrel vault), appears for the first time, which, although already in existence, became widespread in the 19th century. In the timbrel vault, the bricks are laid flat and bonded to each other with plaster and there is no need to use moulds or supports of any kind and can have very low deflections (Leitão 1896, 266). The explanation of the construction of a timbrel vault reinforces the new approach to techniques for constructing vaults, to the detriment of the geometric form, which had been practised until then.

The level of description of the techniques for constructing vaults in Leitão's manual would only be surpassed by the booklet *Arcos e Abóbadas* (Arches and Vaults) in the *Enciclopédia Prática da Construção Civil* (Practical Encyclopaedia of Civil Construction, 1930-1939) by the technical designer Francisco Pereira da Costa, where the definition of *Abóbada Alentejana* (Alentejan vault) also appears.

As this is a notebook, the theme is presented with a historical introduction to arches and vaults, and is followed by a structure similar to Leitão's manual, separating arches and vaults: the nomenclature of the arch; types of arches, in

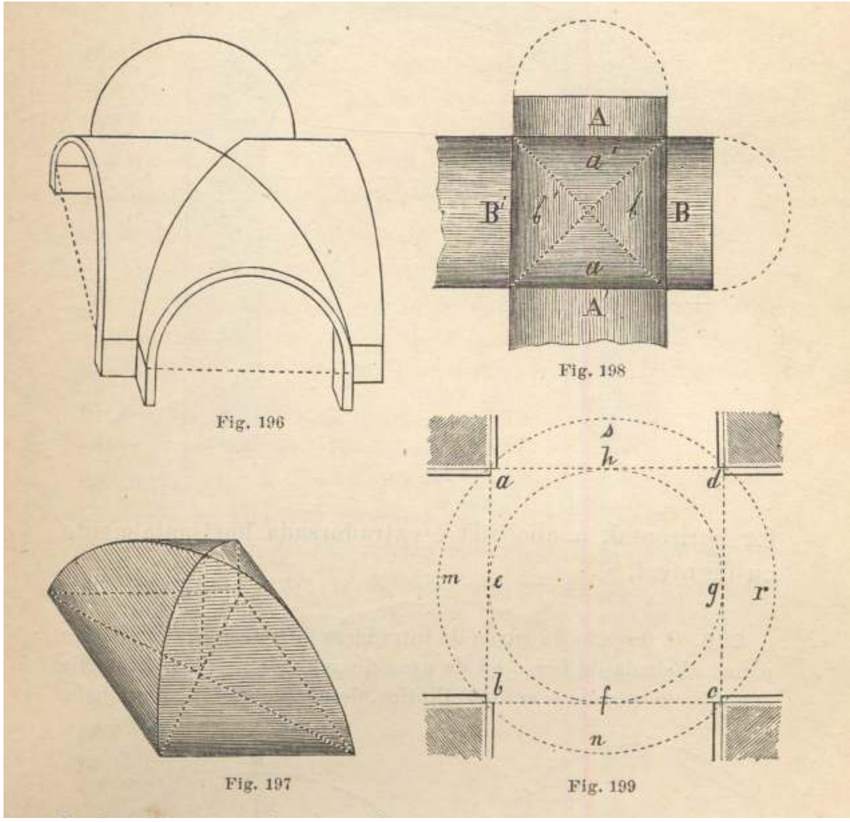


Fig. 10 Some types of vaults: axonometry of a groin vault (top left), plan of both groin and domical vaults (top right), axonometry of a domical vault (bottom left), and plan of a spherical vault with slopes applicable to the coverage of square or polygonal spaces. Leitão 1896, 255. BNP SA 5045 V.

particular brick arches (leaving stone arches for the 'Stonework' notebook); the layout of the different types of arches; the construction of arches, using formwork (or simple formwork, centering or camber when dealing with small spans); materials and mortars. The topic of the stability of vaults is introduced for the first time in a Portuguese manual, covering construction systems and typology, their structural elements (supports or 'ceiling heights', the starts of the curve or 'quarter points', the keystone, and thicknesses), statics (thrusts and loads), and the removal of the centering (already mentioned in Leitão's manual). Also new is the reference to vaults made with bricks exposed instead of the traditional whitewashing, choosing for this purpose a specific glazed brick and aligning the brickwork. This is clearly a reflection of the fashion that began at that time and continues to this day, in an attempt to emphasise traditional practices and knowledge.

In addition to its comprehensive approach to the topic of vaulted vernacular construction, this booklet also shows the constructional environment in Portugal in the 1940s, with the confrontation between traditional systems and the generalised implementation of new materials and construction techniques:

(…) reinforced concrete provides a very good advantageous solution for covering large spaces, creating flat roofs from which excellent decorative effects can be achieved. The construction of vaults today is only justified on further work on old buildings, where it is necessary to maintain their original design, but in these cases, reinforced concrete has no place. However, that is up to the builders. (Costa 1939, 15).[24]

Final remarks

We began this enquiry by examining how a discourse on vaulted systems was constructed through the earliest written works on architecture and construction in the European world. Our selection of sources was merely a targeted sampling, constrained by the need to study and publicise the vaults of houses in southern Portugal.

The near absence of the topic in the Vitruvian principles was noted, as was the formulation of the first actual definitions from the foundational text of architectural theory, Leon Battista Alberti's *De re aedificatoria*. This provided a definition (derivation or multiplication of the arch), a description of the main types and, most significantly, the correlation between the vault and the building elements that support it, stating the principle of proportionality between the area to be covered and the geometry of the vault. Moreover, this text made explicit that the vault is a part of a building, i.e. it is not an autonomous element, and that the vault combines layout and material, requiring different materials and a certain construction method of assembly and reinforcement. Finally, the vault is categorised based on its main types and variants. The Albertian text therefore establishes the canon of parameters to be considered.

Throughout the 16th and 17th centuries and the first half of the 18th, variations in the type of texts on architecture and construction, treatises, manuals, books, manuscripts and printed material showed the development of these premises. At times these were more erudite and used authoritative bibliographical citations or, more often, combined this literary background with the necessary practical experience. Measurement manuals showed how construction, geometry and calculus are indispensable to architectural production.

The selection of sources we have studied also shows that the existence of vaulted spaces involves different professional profiles, namely master builders, architects and engineers, mathematicians, stonemasons, and practical experts, whose language is necessarily diverse. However, there are important commonalities whatever the level of discourse. Firstly, the vault requires design, calculation and execution.

[24] Original: '(…) o betão armado resolve muito bem e vantajosamente a cobertura de grandes espaços, criando tecto planos de que se podem tirar grandes efeitos decorativos. A construção das abóbadas na actualidade só é justificável na continuação de edifícios antigos, em que é mester manter a sua traça primitiva, mas nesses casos, não tem lá lugar o betão armado. No entanto, isso é com os construtores.' (Costa 1939, 15).

Secondly, its construction requires learning, thus necessitating methods of transmission in which theory must never dispense with practical knowledge, which in turn must be informed by rigorous design. This dialectical and sometimes tense relationship, where language can be unclear and the work poorly executed, may allow us to glimpse how local cultures 'know how to make vaults'.

Until the end of the 19th century, the authors of treatises and manuals passed on technical knowledge about arches and vaults using a scientific method based on Euclidean geometry. They made use of text, geometric outlines and planimetric drawings as methodological tools for describing the procedures needed to create the geometric figures that form the basis of architectural forms and enable them to be measured. This form of representation mirrors the challenges in studying and projecting two-dimensional plans and three-dimensional objects at the time, when descriptive geometry had not yet been developed as an area that systematised constructive technical drawing with a projectional method.

The valuing of construction processes in the theoretical knowledge of vaults, developed from the 1800s onwards, would in turn end with the global spread of reinforced concrete construction. This predominance would gradually cancel out the use of vernacular or so-called traditional building systems, which would become a matter for heritage safeguarding.

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[25] Translated from Portuguese by David Hardisty.

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Abstract

Almost unparalleled inside Portugal and akin only to neighbouring Spanish Extremadura, the incorporation of vertical brick vaults and timbrel vaults is a distinguishing feature of even the most common housing types in inner Alentejo. Research based on *in loco* architectonic and photographic surveys in four inner Alentejo cities combined with analysis of archive documentation from the 20th and 16th-18th centuries has produced data on the usage and types of vaults, including identification of the various types and geometries employed. This research proposes a chronology of vault construction in housing, indicating a likely beginning in the 17th century and its proliferation during the 18th century. Besides presenting the results, this paper examines various hypotheses to explain the transfer of an erudite technique into traditional housing by contextualising the historic and constructive moment of the Early Modern Age in Alentejo, with urban transformation due to warfare and consequent fortification.

keywords:

TRADITIONAL HOUSING
VAULT
VERNACULAR CONSTRUCTION TECHNIQUES
TYPOLOGICAL STUDY
HERITAGE VALUES
ALENTEJO
EARLY MODERN AGE

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The incorporation of vaults in the traditional housing of the inner Alentejo

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Introduction

This paper addresses the inclusion of brick vaults inside the traditional urban house of the Alentejo, Portugal. The data was gathered within the scope of a research project dedicated to traditional urban housing of the Alentejo region, carried out between 2017 and 2022.[1] The data recorded also includes many other housing type related techniques, materials and information that enables the study of these vaults within the framework of the Alentejo's traditional housing and its respective evolution, thereby enhancing our understanding of the relationship between vault construction and other aspects of house construction in Early Modern Age Alentejo. The project's results were partially published in 2019, 2021 and 2022. The current paper adds new information to the 2021 and 2022 papers, namely additional cases in the city of Borba and archival data not presented in 2021.

This paper focuses on specific data regarding vaults found in Alentejo's common housing and presents hypotheses to be explored regarding their dissemination in the vernacular context. In this text, the terms 'vertical brick vault' and 'timbrel vault' will be applied to differentiate, respectively, between the curvilinear self-supporting structures built with bricks adjoining at their wider face ('vertical bricks'), and those with bricks placed with their wider side facing the inner surface of the curve ('horizontal bricks'). Nevertheless, when referring either to the broader category of tiled self-supporting ceilings or when the construction system is unclear or unidentified, such structures are referred to simply as 'vaults'.

[1] Financing from Fundação para a Ciência e Tecnologia (FCT), Portugal (SFRH/BD/116130/2016).

Ever since the records produced by the *Inquérito à Arquitectura Popular em Portugal* [Survey of Popular Architecture in Portugal] (Keil do Amaral et al. 1961), vertical brick vaults and timbrel vaults have been perceived as a prominent characteristic of traditional housing in the inner Alentejo. Nevertheless, the differentiation between each particular type of vaulting system is hardly ever provided in either the bibliography or historical documentation, thus hindering efforts to define the geographical scope and dating of vertical brick vaults and timbrel vaults. While some authors, such as Ribeiro (1961), indicate that we may trace vaulting techniques back to Roman times, there is still no actual evidence of recourse to brick vaults in common dwellings prior to the Early Modern Age (16th-18th centuries). Nonetheless, in erudite housing, vaults appear under roof terraces in the Alentejo region in around the early 16th century (Conde 2011). Over the 16th century, vaults in erudite housing became notably more numerous, a trend which continued into the 17th and 18th centuries. This accompanies a trend towards vaulting specific compartments of these houses, namely the noble spaces and the kitchen, in order to minimise the spread of eventual fires (Caldas 2009). In common housing, the chronology of usage becomes harder to determine, though there is little evidence of vaults in common housing in the neighbouring Algarve region prior to the 19th century (Caldas 2009, Pacheco 2021).
Regarding the particular case of timbrel vaults, their areas of distribution are more restricted than those of the more widely spread vertical brick vaults. On the Iberian Peninsula they have been identified on the Mediterranean shore of Levante, in the Murcia region, in the former kingdom of Aragón (Zaragoza 2012), and in the southwest area of the Guadiana valley. Timbrel vaults are often deemed less erudite than their vertical brick counterparts (Fortea Luna 2009) as they do indeed provide a cheaper solution given that fewer materials are required and the construction process is shorter due to a lack of any recourse to formwork (Santos 2000). Furthermore, their incorporation into religious and erudite buildings in Spain may be traced back to the Medieval Islamic *Shark-Al-Andalus* (Zaragoza 2012) and has been well documented through to contemporary times (Redondo Martínez 2013). Their usage in common domestic buildings has not yet been documented to the same extent.
Even given this perception as a 'second-class' solution (Fortea Luna 2009), the optimisation of costs, materials and construction saw this option become progressively favoured for traditional housing (Rosado 2021). In residential buildings in the region bordering the Guadiana Valley, the application of the traditional vaulting system, with bricks adjoining at their wider face, seems to disappear prior to the emergence of timbrel vaults. Sánchez (2000), Fortea Luna (2003) and López-Mozo et al. (2023) have produced inventories of vertical brick vaults and timbrel vaults across the border region in Extremadura (Spain), highlighting how the study of the technique in the area around the Guadiana Valley necessarily requires a transnational approach.

Nevertheless, these studies do not detail which buildings the vaults were constructed in (Sánchez 2000, Fortea Luna 2003) or record erudite housing (Lôpez-Mozo et al, 2023). Carmona Barrero proposes that the timbrel vault technique was imported from Portuguese Alentejo to Spanish Extremadura in around the 19th century by migrant masonry workers (Carmona 2011), a hypothesis the author bases on a study of masonry builder lineages (Carmona 2007). The frequent 19th century recourse to timbrel vaults in common houses in Southern Portugal is recorded in both the Alentejo and the Algarve regions and, in the latter case, at times associated with the regional pitched roofs *'telhados de tesouro'* (Pacheco 2021).

Nomenclature

One of the major issues concerning the study of the vaulting technique derives from the different nomenclature applied both in erudite texts and in popular construction, with variations even occurring in the naming of certain types of vault in accordance with the geographic scope of incidence. The names applied in this article to the different vault types are those registered in the inner Alentejo region and as used by local masons and inhabitants. They are barrel vaults (with *berço* being the Portuguese regional term, with those barrel vaults with very low arches under 120° described as segmental and corresponding to the Portuguese *berço abatido*), groin vaults, lunette vaults and sail vaults. The most difficult to translate was the trough vault,[2] a vault similar to the cloister vault but where the four concave surfaces meet on a horizontal plane instead of at a point as they would in a cloister vault, and which is referred to in Portuguese as *abôbada de engras* and in Spanish as *bóveda esquifada* (*plana*) (Mendez Lloret 2002). Thus, these are the six types of standard vault geometry found in the inner Alentejo. **[Fig. 1]**
Other examples incorporating mixed geometries are harder to label. Some examples blend characteristics of at least two types mentioned above, such as the appearance of lunettes in trough vaults, for example. A further study of cases in the region might eventually allow for the definition of new categories but, in the meanwhile, those cases of eccentric geometries have been assigned to one of the six previously described types. **[Fig. 2]**
We also clearly need to clarify the term 'row'. In this paper, it serves to name the area of a house between two load bearing walls, parallel to the façade. Hence, the front row consists of the rooms adjoining the façade, the second row relates to the first inner compartments, and the third row commonly references the compartments next to the backyard.

[2] Also referred to as a coved vault: 'a vault composed of four coves meeting in a central point, and therefore the reverse of a groined vault'. 'Coved vault'. *Webster's Revised Unabridged Dictionary* (1913). Retrieved 11 July 2024 from https://www.thefreedictionary.com/Coved+vault.

Fig. 1A Fig. 1B

Fig. 1C Fig. 1D

Fig.1 Examples of four of the vault's geometries described, as seen in the region.
A. Segmental vault, Rua Magalhães Lima, 77-79, Estremoz; B. Groin vault, Rua Dr Garcia Peres, 71, Moura; C. Trough or cover vault, Largo D. Diniz, 8, Estremoz; D. Lunette vault, Largo D. Diniz, 8, Estremoz. Source: author, 2019-2021.

Fig.2 Uncommon vault geometry found in Rua de S. Pedro 50, Moura. Source: author, 2019.

Fig. 3 Location of the cities of Estremoz, Borba, Moura and Serpa, inside the Alentejo Region in Southern Portugal. Source: author, 2024.

Methodology

While the collection of data on vaulting solutions was not the prime objective of the research project, traditional construction techniques nevertheless represent one of the features of vernacular architecture documented and studied within the scope of traditional housing typologies and their chronologies. The project's methodology combined fieldwork with morpho-typological analysis to correspondingly identify eleven types of traditional urban housing in the Alentejo region. The data was obtained via fieldwork involving architectonic and photographic surveys[3] of houses in four different cities – Estremoz, Borba, Moura and Serpa – all located in the inner Alentejo, in close proximity to the border with Spanish Extremadura and Andalusia. The cities of Estremoz and Borba are part of the sub-regional unit 'Marble Area' and Moura and Serpa are located in the sub-regional unit 'Left Bank of the Guadiana River'. We would duly emphasise that this border has no natural barriers; even the Guadiana River that defines some of its extension is shallow here. Thus, cross-border relationships have always been fluid, with an almost constant movement of people and ideas (Cosme 2000) in a dynamic that is hardly inconsequential to the history of construction techniques. [Fig. 3]

[3] Architectonic survey means measuring the entirety of a building, wall dimensions, angles and heights. In this case, measurements were made with laser meter and then used to produce technical drawings – plans and sections – of the building that register all its constructive elements. They are often accompanied by a thorough photographic register.

The research combined building surveys with documentary research covering both the private construction registers maintained by municipalities – *processos de obras* – and historic archive records from the 17th to 19th centuries. The former documents, municipal records, represent the building permits that include a description of the project, the property's location, one set of technical drawings detailing the existing situation and a second set with the proposed alterations. This information thus generates a complete understanding of the constructive characteristics of buildings alongside more recent alterations. The historic documentation presents descriptions of dwellings in a given time period, sometimes even with dimensions of houses/rooms, and allows for the representation of the evolution in housing and construction from the 1600s/early 1700s onwards, including changes both in the nomenclature and in the functions of compartments/rooms.

The total sample of buildings studied amounts to 507 cases, with 313 obtained from architectonic surveys and 194 from municipality construction permits. Of the latter, 108 buildings included some type of vaulting solution, with their regional distribution set out in **Table 1**. With the exception of two recently surveyed houses in Borba, the buildings studied in the sample, their respective vaults and the indication of the provenience of data, can be consulted in cartographic format, in open access (Rosado 2022).

In Borba, some vaults were identified in houses beyond the scope of the project but taken into consideration in this paper. In all four cities, houses with vaults account for around a fifth of the sample, as shown in **Table 1**. In total, the houses with vaults account for 21.3% of the case study sample.

	Total houses	Houses w/ vaults	% of houses w/ vaults	Vaults
Estremoz	141	29	20.6%	63
Borba	24	9	37.5%	28
Moura	143	30	21%	192
Serpa	201	40	19.9%	167
Total	511	110	21.5%	450

Table 1. Sample sizes for the cities of Estremoz, Borba, Moura and Serpa. Indication of the total number of houses studied, the number of houses identified as containing vaults, the percentage they represent in their samples and the total number of vaults per city.

The historic documentation analysed encompasses books of records [1], the property records of both municipalities and religious organisations [2, 3, 4], and tax inventories [5, 6] from 1626 to 1883, thereby enabling the drafting of an evolu-

tionary line for the traditional house types in the Alentejo from the mid-1600s onwards. In these records, the earliest mention of the construction of vaults inside a common house dates from 1673 [2] in the city of Serpa. The book of property records of the *Santa Casa da Misericórdia* religious institution registers and describes 123 dwellings of which five contained some type of vault. Of the total sample, houses with vaults made up a share of only 4%. In 2018-2019, in the same city of Serpa, the project's surveys registered 201 houses with 40 houses containing vaults – a sample percentage of approximately 20%. This apparent post-17th century spread in the vaulting technique is addressed below in the discussion.
The methodology based on *in loco* direct recollection of data and of primary sources ensures the sample of cases is diverse and, as all building data was registered in the context of the research, can be studied from urban scale to constructive details. Data obtained through other sources may be incomplete or lack the details the research is looking for.

Results

The Marble Area – Estremoz and Borba

The cities of Estremoz and Borba are located in an interior Alentejo sub-region named the Marble Area after a geological anticline formation of marble stone that spans 30 km in length by 10 km wide. Its territorial importance derives from its strategic location both on the ancient Mérida-Lisbon route and on the confluence of several key routes in the southern Portuguese road network. The cities of Estremoz and Borba were located on the second historic line of defence from Spain, protecting the road to Lisbon.
Traditionally, housing construction techniques included the use of marble stone for door and window frames but also alongside stone masonry for erecting load-bearing walls, almost always 60 cm thick. Besides stone, ceramics constituted a fundamental piece to this ensemble, whether applied in the form of brick, thin floor tiles or as semi-cylindrical roof tiles. Bricks served for masonry, often combined with stone, and almost always applied in the framing of doors and windows. Floor and roofing structures were often made out of timber beams and joists covered by thin tiles of approximately 30 x 15 cm, or, in the case of roofs, by roof tiles. Even if timber is the most common solution to structure upper floors, vaults are easily found, particularly over ground floors in the central and commercial areas of the cities.
In the Marble Area, the vaults identified were of the groin, trough, barrel and segmental types. There was only one sail vault registered in Estremoz and three vaults

Fig. 4 Vault in the entrance hall in Borba, Rua Marquês de Marialva 1. Source: author, 2022.

akin to the lunette type reported in Borba, which explains the classification of these two types as rare. These vaults, akin to lunettes, display eccentric geometries that resemble the intersection of a large groin vault with smaller lunettes, while not ascribing to the room's geometry, as represented in **Fig. 4**. The largest number of vaults are found at ground floor level (52 out of 62 in Estremoz and 2 out of 24 in Borba) and mainly located in the front divisions of the respective residences. These areas of a house are more easily identifiable by outsiders and serve either a social function – as sitting and guest rooms and entrances –, or host trading activities open to the public, such as shops or wine stores. In the former case, the recourse to vaults seems motivated by a display of ornamentation and wealth. In the second, there is a utilitarian character to the purpose of the vaults, that, when combined with arched walls, enable the installation of open space layouts. **[Fig. 4]**

In Estremoz, the majority of houses with vaults are located either within the castle walls (14 of 29) or in the downtown neighbourhoods of the late 16th century expansion (10 of 29). This duly reflects how the castle and its surroundings are not only the oldest area of the city but also remained the administrative centre until the 18th century. In Borba, 72% of the houses with identified vaults are located in the 17th and 18th century urban expansions, extending along the city's exit routes (Simões 2007). Furthermore, those found in older parts of the city correspond to wine stores. **[Fig. 5] [Table 2] [Table 3]**

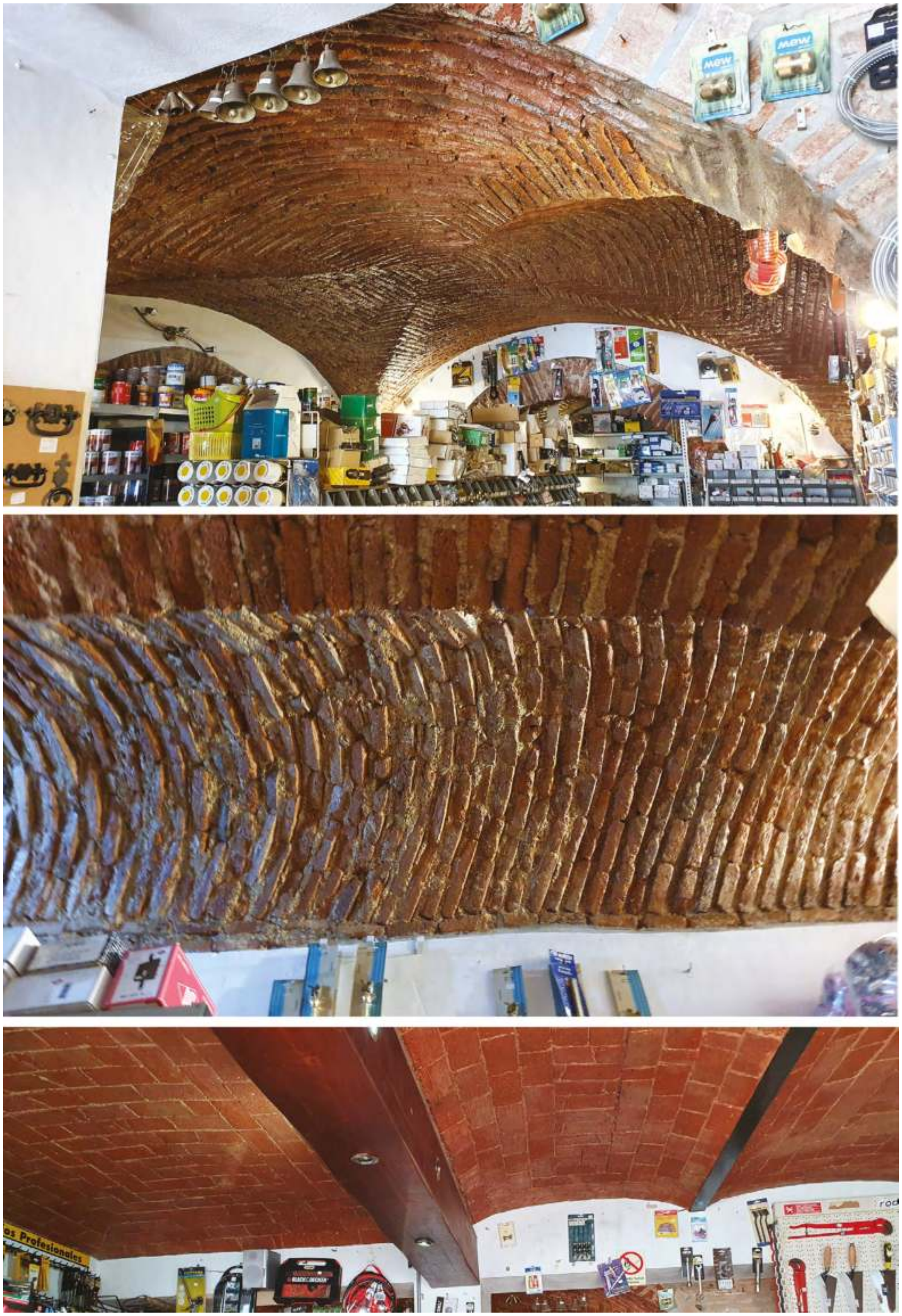

Fig. 5 Borba. Rua Marquês de Marialva 19. Four different ceiling structures in the same ground floor. The second and third compartments are covered by groin vaults; the front compartment shares an almost flat though timbrel vault, and timbrel vaults combined with metallic beams; and the side corridor displays a barrel vault. Source: author, 2024.

ESTREMOZ	*G	T	B	Seg.	L	Sa.	Tot.
Ground Floor	**25**	**7**	**14**	**7**	**0**	**0**	**53**
Front Row	15	4	4	1	0	0	24
Hall	1						1
Shop	3		1				4
Winery	2						2
Multi-use room		3	3	2			8
Sitting room	2		1	1			4
Kitchen		1					1
Garage	4						4
Second Row	4	2	9	1	0	0	16
Corridor			1				1
Circulation			1				1
Shop	1						1
Winery	2						2
Multi-use room		1	3				4
Bedroom	1	1	2				4
Kitchen			2	1			3
Third Row	6	1	1	5	0	0	13
Corridor	2						2
Circulation				1			1
Sitting room	11		1	1			3
Bedroom	2	1		3			6
Kitchen	1						1
First Floor	**1**	**5**	**0**	**3**	**0**	**1**	**10**
Front Row	0	4	0	0	0	0	4
Sitting room		2					2
Bedroom		2					2
Second Row	1	1	0	2	0	0	4
Circulation	1						1
Sitting room				1			1
Bedroom				1			1
Kitchen		1					1
Third Row	0	0	0	1	0	1	2
Bedroom				1			1
Kitchen						1	1
Total	**26**	**12**	**14**	**10**	**0**	**1**	**63**

Table 2. Vault types and distribution in Estremoz. *G – Groin; T– Trough; B – Barrel; Seg. – Segmental; L – Lunette; Sa. – Sail; Tot. – Total. Source: author, 2021.

Table 3. Vault types and distribution in Borba. *G – Groin; T– Trough; B – Barrel; Seg. – Segmental; L – Lunette; Sa. – Sail; Tot. – Total. Source: author, 2021 with updates in 2024.

Borba	***G**	**T**	**B**	**Seg.**	**L**	**Sa.**	**Tot.**
Ground Floor	**12**	**4**	**7**	**1**	**0**	**3**	**27**
Front Row	5	2	1	0	0	3	11
Hall	2					2	4
Shop	1	2					3
Winery	2		1				3
Multi-use room						1	1
Second Row	6	2	3	1	0	0	12
Circulation			2				2
Shop	4	2	1				7
Multi-use room	1			1			2
Winery	1						1
Third Row	1	0	3	0	0	0	4
Winery	1		1				2
Multi-use room			1				1
Kitchen			1				1
First Floor	**0**	**0**	**1**	**0**	**0**	**0**	**1**
Bedroom			1				1
Total	**12**	**4**	**8**	**1**	**0**	**3**	**28**

In this area, the incidence of groin and barrel vaults clearly predominates. Shops and rooms without any specific assigned use (multi-use rooms) account for those most frequently covered with vaulted ceilings. It is further worth mentioning the inclusion of vaults in kitchens, which often feature simple and unornamented vaults, with the barrel and segmental types emerging as the most common.

The building of vaults in non-residential spaces accounts for 1/6 of the total cases in Estremoz, while in Borba, the sum of working compartments such as shops and wine stores totals 16 cases of vaulted spaces out of a total of 28, reflecting the prevalence of vaulting in non-residential areas. Vaults are deployed in combination with brick arches with the goal of achieving wide open spaces to serve as wine stores, such as the example at Rua dos Banhos, 1, with 90 m^2 area of unrestricted space. [Fig. 6]

The left bank of the Guadiana River – Moura and Serpa

The area designated as the Left Bank of the Guadiana Region constitutes that area comprised by the border between Portugal and Spain, across the Sierra Morena

Fig. 6 Estremoz, Rua dos Banhos 1. Former open-plan winery. Plan and photographs, 2018. Source: author, 2018.

and the course of the Guadiana River. The Guadiana River defines the border between the two countries from Badajoz to Mourão, and then again from Pomarão to the river mouth in Vila Real de Santo António. Between Mourão and Pomarão the river enters Portuguese territory, and the border is primarily terrestrial. Unsurprisingly, the Portuguese Left Bank of the Guadiana was prone to instability and sovereign disputes ever since the drawing of the border in the 13th century (Cosme 2000). The notion of disputed lands would prevail in the name *Contenda* (dispute) used for the zone around Noudar. Later, the War of Restoration (1640-1668) heightened the level of conflict prevailing in the area and contributed to its depopulation and poverty. While the need for defensive structures would characterise the main cities of Moura and Serpa and their urban planning, the permeability of the border meant not only conflict but also fluid relations between the two sides, reflected in trade, migration and family bonds (Cosme 2000).

The presence of vertical brick vaults and timbrel vaults in southern Alentejo, and particularly on the Left Bank of the Guadiana, has long been documented in conjunction with the greater incidence of vaulting as the means of supporting upper floors, with the contrast prevailing to northern latitudes described in *Arquitectura popular em Portugal* (Keil do Amaral, 1961). Even if the proportion of housing with vaults in the sample is akin to that of the Marble Area, the total numbers of vaults registered are substantially higher. In broad terms, the common urban house of the Left Bank of the Guadiana takes up plots with long and narrow proportions. Both Moura and Serpa display the consequences of successive planned expansions, combined with organic growth along the routes leading out of the cities. Their constructive system is based on load bearing walls of stone and, to a lesser extent, rammed earth. In addition to vaults, wide masonry chimneys are pointed out as another distinctive local feature. **[Table 4]**

Similar to our findings for the Marble Area cases, the largest concentration of vaults appears in Moura in the city's commercial centre, the Arrabalde Novo, originally dating to the 15th-16th centuries, and the city's southern expansion in the 16th-18th centuries, structured around Rua de S. Pedro. It is important to highlight that in Moura the research registered 192 vaults found in 21% of the houses surveyed. In the older medieval neighbourhoods, the application of vaults is barely noticeable (4 vaults in 20 houses), while in the Arrabalde Novo they become standard, with 77 vaults counted only at the ground floor level. Furthermore, different vault and timbrel vault types frequently co-exist inside the same building in keeping with the different ceilings required for different purposes: the barrel and segmental types, for instance, appear linked to deep rectangular rooms, such as corridors, with their dimensions varying from 1.30 to 1.90 m in width and 4.70 to 20.90 metres in depth. Half of the barrel vaults identified (22 out of 41) in Moura cover corridors and circulation spaces.

Moura	*G	T	B	Seg.	L	Sa.	Tot.
Ground floor	**61**	**17**	**36**	**29**	**11**	**5**	**159**
Front Row	30	9	5	11	7	3	65
Hall	8	4	2	2	1	1	18
Corridor	1	1	2	2			6
Shop	6			4			10
Multi-use room	10	2		2	1		15
Sitting room	3	2			1	2	8
Kitchen			1	1			2
Garage	2				4		6
Second Row	20	5	16	11	3	2	57
Corridor			6		1		7
Circulation	9	3	4	3			19
Shop	3						3
Multi-use room	5	1	4	3	1	1	15
Sitting room	1						1
Bedroom	2	1	2	4	1	1	11
kitchen				1			1
Third Row	11	3	15	7	1	0	37
Corridor			4	2			6
Circulation	3	1	3				7
Multi-use room	3	1	4	3	1		12
Sitting room		1					1
Bedroom	1						1
Kitchen	4		3	1			8
Garage/ Stable		1	1			2	
First floor	**10**	**8**	**5**	**5**	**2**	**3**	**33**
Front Row	6	7	2	2	2	0	19
Corridor		1					1
Circulation		1					1
Multi-use room	1					1	
Sitting Room	4	1	2		1		8
Bedroom	2	3		2	1		8
Second Row	3	1	3	2	0	3	12
Corridor			3				3
Circulation		1		2		1	4
Multi-use room					1	1	
Sitting room						1	1
Bedroom	3						3
Third Row	1	0	0	1	0	0	2
Bedroom	1						1
Kitchen				1			1
Total	**71**	**25**	**41**	**34**	**13**	**8**	**192**

Table 4. Vault types and distribution in Moura. *G – Groin; T– Trough; B – Barrel; Seg. – Segmental; L – Lunette; Sa. – Sail; Tot. – Total. Source: author, 2021.

Table 5. Vault types and distribution in Serpa. *G – Groin; T– Trough; B – Barrel; Seg. – Segmental; L – Lunette; Sa. – Sail; Tot. – Total. Source: author, 2021.

Serpa	***G**	**T**	**B**	**Seg.**	**L**	**Sa.**	**Tot.**
Ground Floor	**71**	**22**	**14**	**33**	**6**	**1**	**147**
Front Row	32	9	9	5	3	1	59
Hall	8	4	3	3	1	1	20
Corridor			2				2
Shop	10	1	1	1			13
Multi-use room	3	1	3				7
Sitting room	1	2		1	2		6
Kitchen	2	1					3
Garage	8						8
Second Row	29	10	2	17	3	0	61
Corridor				1			1
Circulation	7	3	1	6			17
Shop	6	1					7
Multi-use room	12		1	3	2		18
Sitting room	1	3		3			7
Bedroom	3	3		1	1		8
Kitchen				3			3
Third Row	10	3	3	11	0	0	27
Corridor			3	2			5
Circulation	2	1		3			6
Shop	2						2
Multi-use room		1		2			3
Sitting room	1						1
Kitchen	5	1		3			9
Garage				1			1
First Floor	**5**	**8**	**1**	**0**	**2**	**4**	**20**
Front Row	5	4	0	0	2	3	14
Circulation		1				1	2
Reception/Visits		1			1		2
Sitting room	4	1			1	1	7
Bedroom	1	1				1	3
Second Row	0	2	1	0	0	0	3
Corridor			1				1
Circulation		1					1
Multi-use room		1					1
Third Row	0	2	0	0	0	1	3
Multi-use room		1					1
Sitting room		1					1
Kitchen						1	1
Total	**76**	**30**	**15**	**33**	**8**	**5**	**167**

Serpa provides an equally high number of vaulted ceilings, with 167 cases found in 201 houses studied (19.9%). Unlike the other examples above, in Serpa, the city centre inside the Medieval Wall still remains the administrative and commercial centre of the city, reflected in an almost constant updating of its buildings. The distribution of vaults in Serpa is therefore more heterogeneous than in the previous cases, and there are no immediately noticeably concentrated areas of vaults. The association between barrel and segmental vaults and corridors and circulation spaces also clearly emerges in Serpa, with 45% of the barrel vaults and 36% of the segmental cases constructed for these areas.

The kitchens once again register a greater predominance of simple vaults such as the segmental (6 out of 16). While there are six cases of segmental versus seven groin kitchen vaults, four of the seven groin vaults report to the kitchen in the same erudite house, thereby unbalancing the sample (kitchens otherwise almost always having only one vault). In that same erudite house, one upper floor kitchen features the only sail timbrel vault found in this room typology – Rua de Nossa Senhora, 1. **[Table 5]**

Overall sample

Following analysis of the total sample numbers, we encounter four common vaulting solutions, in addition to two occasional types and sporadic hybrid geometrical applications. The most common type in the sample is the groin vault, by a wide margin, followed by the barrel, trough and segmental types. The lunette and sail types, although not rare, were reported in smaller numbers, even if still accounting for a transversal presence across the study area. **[Table 6]**

The spaces most susceptible to finishing in vaults are those rooms that do not otherwise have a single specific purpose but which can instead hold several functions (90), and sitting rooms (51) for family gatherings and receiving visitors. The spaces dedicated to traversing the house, such as entrance halls (43), corridors (35) and circulation rooms (62) – thus, those rooms with proportions akin to other divisions in the house but without any other function other than passage between areas – are often vaulted and sometimes also decorated with stucco floral motifs. These cases also reflect a correlation between the vault types and the function and shape of their host rooms. The clearest example is the relationship between corridors and circulation rooms with barrel vaults and, to a lesser extent, with segmental vaults. Kitchens are the domestic space where vaulting appears in its simpler forms, with segmental types taking the lead (when overlooking the data imbalance caused by the kitchen in Serpa – Rua de Nossa Senhora, 1). Groin and

Table 6. Vault types per housing compartment. *G – Groin; T– Trough; B – Barrel; Seg. – Segmental; L – Lunette; Sa. – Sail; Tot. – Total. Source: author, 2021.

	*G	T	B	Seg.	L	Sa.	Tot.
Hall	19	8	5	5	2	4	43
Corridor	3	2	22	7	1	0	35
Circulation	22	12	11	15	0	2	62
Shop	36	6	3	5	0	0	50
Multi-use room	37	13	18	14	5	3	90
Sitting room	18	13	4	7	5	4	51
Kitchen	12	4	7	11	0	2	36
Garage	14	0	1	2	4	0	21
Winery	8	0	2	0	0	0	10
Bedroom	16	12	4	12	3	2	49
Reception/Visits	0	1	1	0	1	0	3
Total	**185**	**71**	**78**	**78**	**21**	**17**	**450**

trough vaults are associated with almost square-shaped compartments, regardless of their function. This also establishes a preference for more complex vaulting types in front rooms.

A significant proportion of the vault spaces on the ground floor of these urban houses have served for utilitarian purposes as shops (50), wine stores (10) or spaces nowadays transformed into garages (21). This fact is further highlighted by the concentration of houses with vaults in the commercial areas of the cities studied, such as the main shopping streets or the main squares and their immediate surrounding areas. Houses with vaults are also more common in the areas of these cities that correspond to their 16th-17th century expansions, which would undergo consolidation during the 18th century.

Chronological hypothesis

Traditional processes of architectural transformation, particularly in traditional housing, only ever advance at a slow pace. Many of the construction techniques documented in the surveys made for this research have in effect stood, with little alteration, for centuries. Yet, there are also periods when many simultaneous changes take place and the 17th century in Alentejo is one of those bubbling, breakthrough periods. This characterisation of the 17th century urban house draws on the historical records of Borba's 'Books of Records' for 1626-35 and 1670-80 (Cartório Notarial de Borba), on the Santa Casa da Misericórdia de Serpa 'Book of Records' of 1673, and on the Council of the City of Estremoz 'Book of Records' of 1674. The later 18th century changes were documented in the City of Estremoz 'Book of Records' of 1746-61 and the Estremoz 1789-1845 tax inventory.

Emerging from these records is an urban house that often mixes residential usage with productive activities, best exemplified in the existence of the wine stores in the Marble Area dwellings and that generally come with a backyard for storing crops, tools, or animals. During the 17th century, the occupation of entire upper floors – unlike the timber mezzanine *sobrados* –, particularly in central urban areas, underwent consolidation and became increasingly common. The second major theme in the transformation of the layout relates to both separating functions and the need to access the back of buildings. During medieval times, house compartments hosted more than one function, with the main prevailing division being that between the tasks ongoing in the public sphere – socialising, hosting, cooking – carried out in compartments adjacent to the front door, and the private sphere, with activities such as sleeping and storage taking place in inner rooms. As the rooms were adjoining, circulation and access to the backyard were achieved via the inner compartments. Early Modern Age records indicate how in houses with adjacent rooms, the existence of two rooms in the second section of the building allowed for the easy introduction of passages to traverse the house without compromising private domestic spaces. In the city of Serpa, historical records (1673) convey how these spaces for circulation resembled the other rooms in shape and dimensions, with a mistake in one house description entry reading '(…) another room that serves as corridor (…).'[4] Over time, the crossing of the house no longer takes place through the 'rooms that serve as corridors', as a new space with the sole function of circulation appears. There is the likelihood that allocating an entire room for circulation began to be perceived as excessive (although this would also always have been combined with other purposes such as storage), and so the need to optimise space may have led to reductions in the width of circulation spaces, thereby adopting a width/length ratio that we today identify as corridor proportions.

In this context of housing transformation, the construction of the upper floors gained in solidity, the average number of rooms in houses grew, and the dwelling layouts became more complex, with the separation of the production and living functions of the building through the introduction of corridors. All these changes drove a greater differentiation among spaces inside the dwellings. As a period of transformation, this nurtured the conditions for experimenting with new construction techniques and solutions. The written records of 1673 – but not those for 1626-1635 – register

[4] AMS/SCMS/M/E1/fl24/n.º 64.

the first mention of the incorporation of vaults into common houses. Out of a sample of 123 houses, there are five mentions of vaults. The first covers half a corridor,[5] while the other half is covered by an upper storey. The second is located over a squared compartment of 4.5 x 4.5 metres, with entrance from the main street, and there is an upper storey over the vault.[6] Two others are in ground floor rooms with upper floors above, and one of the rooms (reference 119) spans 4.5 x 2.75 metres.[7] A fifth is found in a front yard and is referred to as a 'narrow vault', with a 'narrow' storey above it.[8] The geometries of these vaults are never detailed.

Discussion

The open question regarding the building of vaults in common housing remains that of their chronology, particularly the beginning of their construction in domestic environments. The paragraphs above sought to add data to the analysis of this question. With vaults being a feature of erudite architecture, undergoing continuous application in religious buildings, the query remains how and when this erudite technique encroached into the vernacular sphere.

As stated above, the earliest documentary records on the usage of vaulted ceilings in common houses reported by this research study were those in Serpa dating to the year of 1673. Contemplating the construction panorama prevailing in the Alentejo region in those times, one finds a particularly interesting scenario. The second half of the 17th century was impacted by the instability prevailing since the beginning of the War of Restoration (1640-1668) and that would drag on – albeit with varying levels of conflict intensity – until the end of the War of the Spanish Succession (1701–1714). As a border area, and especially as a permeable frontier, the Alentejo region became one of the main stages of conflict. Hence, the last third of the 17th century and all of the 18th century would be marked by continuous construction of and experimentation with military fortifications, hosting large numbers of military construction experts and serving as a field of practice for almost all military engineers in the country (Conceição 2001). Around the same time, the teaching of Military Architecture in Portugal was encouraging the translation of state of the art foreign works and the development of Portuguese manuals, such as the 1660 presentation of João Nunes Tinoco's calculation tables for the building of vaults *Taboadas gerais para com facilidade se medir qualquer obra do officio de pedreiro, assim de cantaria como de alvenaria, com outras varias curiozidades da geometria pratica* (Pacheco 2021). In ensuing the adaptation of former – and now obsolete – fortifications to gun-powder age technological requirements, many constructive advances were implemented alongside the

[5] '(…) uma morada de casas que estão na Rua da Fonte Santa que estão po rcima das casas acima descritas as quais são duas casas térreas e um quintal das quais a dianteira tem de comprido seis varas e de largo três varas folgadas e um corredor tem de comprido quatro varas e meia e de largo duas varas folgadas e tem encima um sobrado que tem metade deste corredor e a outra metade é de abôbada e o quintal tem de comprido nascente e poente catorze varas e de largo cinco varas e terça e tem um poço mistigo às casas de bacho acima descritas (…) serem umas e outras da misericórdia e antigamente andarem ambas em uma e hoje estarem devididas (…) e partem (…) pelo levante com rua publica'. AMS/SCMS/M/E1, fl. 23, nº 60.

[6] '(…) uma casa que serve de sotão e que está metido nas casas que hoje são de Bento de Almeida e tem a porta para a Rua o qual tem de comprido quatro varas folgadas com o mesmo de largo e é de abobada e tem um sobrado por cima que tem a mesma medida e partem da parte do nascente com casas de Bento de Almeida (…) e pela parte norte com rua pública das pedras'. AMS/SCMS/M/E1, fl. 32v, nº 83.

[7] '(…) as casas que estão em quando se vem para o poço da talha em que hoje está um sótão de abôbada com uma alcoba e uma janela em a quina do canto da parede e tem por cima uma varanda de tijolo, digo, uma grade de tijolo e consta outro sim terem sido estas casas foradas antigamente a Pedro Afonso de Sousa em seiscentos Fs.[?] Por natal de cada ano e depois disto se fizeram obras e se puseram no estado em que hoje estão (…)'. AMS/SCMS/M/E1, fl. 43v, nº 113; '(…) uma casa que serve de sôtão em umas casas que João de Jorge [?], que estão na Rua do Poço Sameiro o qual tem de comprido norte e sul quatro varas folgadas e de largo duas varas e meia e é de abôbada e tem uma janela para a rua e parte pela parte do norte com Rua Publica do Poço Sameiro'. AMS/SCMS/M/E1,Fl. 47, nº 119.

[8] '(…) uma morada de casas as quais antigamente tinham uma porta por onde se servião para a Rua de João Bocarro Raposo e hoje está tapada e estão as casas metidas em outras que hoje são do

requirement for many structures other than city walls. Some of the equipment necessary to upgrading fortress-cities included headquarters, hospitals, water cisterns, bakeries and barracks. The techniques employed varied from the development of bastions to strategies to optimise space and resources, all detailed in Luís Serrão Pimentel's treatise on fortification *Método Lusitânico de Desenhar as Fortificações* (1680), a key to the theoretical framework of the then contemporary Portuguese military architecture. In this manual, Pimentel often orders the installation of vaults ('strong vaults'), especially in artillery buildings and the recourse to stone vaults for gunpowder storage facilities. Soon, vaults would begin appearing in other fortified buildings.

Barracks deserve a closer look as, given they were designed as lodging units, they shared constructive techniques and materials with the region's traditional housing. Nevertheless, in the spirit of military construction, their design follows a model (which evolved over time) and is based on the repetition of a module with easily and quickly built, standard dimensions (Rosado 2019). One of the early barracks models devised this module as a squared space covered by a barrel vault, and was built in Elvas-Corujeira (1697), Castelo de Vide (1714) and Estremoz-Loureiro (pre-1758). A more refined barracks model, with two storeys, was designed in the second quarter of the 18th century, with examples in Almeida (Conceição 2002) and Moura, where the barrel vaults had become a given feature over the ground floor compartments. Indeed, barracks represent the best example of the juxtaposition of state-of-the-art military engineering advances and the region's prevailing vernacular background, demonstrating how military techniques, such as vaults, could easily be implemented in common buildings – such as housing – throughout the region. **[Fig. 7]**

The large number of masons being trained in these techniques, and throughout such a large span of time, should be taken in consideration when searching for a vector of dissemination for vaulting in the interior border areas of the Alentejo, especially when portraying the overlap between the zones where vaults are more common and where the fortification campaigns focused their greatest efforts. Moreover, according to the written records, the time span between the last third of the 17th century and the beginning of the 19th century coincides with the rise in the number of vaults incorporated into common houses. Taking the city of Serpa as our example, in the book of property records of the religious institution Santa Casa da Misericórdia, a sample of 123 dwellings reports five containing at least some type of vault, resulting in a percentage of houses with vaults in the 1673 sample of 4%. In 2018-2019, the project surveyed 201 houses, of which 40 houses featured vaults – a sample percentage of approximately 20%.

Dr. António da Costa Monteiro e são duas casas térreas e um pátio que antigamente era casa dianteira das ditas casas o qual tem de comprido cinco varas e meia folgadas e de largo quatro varas folgadas e tem este pátio uma abóbada estreita e que toma de comprimento a largura do dito pátio e tem em cima um ourado [?] estrito e tem uma casa que serve de adega dentro deste pátio que tem de comprido quatro varas folgadas e de largo três varas e meia e outra casa que está de bacho da abobada entrando pelo pátio à mão direita tem de comprido três varas e meia e de largo uma vara e duas terças e tem em cima um sobrado que tem a mesma medição e partem pela parte do norte com casas do próprio Dr. (…) nas quais estão metidas (…) e pela parte do nascente com Rua publica de João Bocarro Raposo [Rua do Governador]'. AMS/SCMS/M/E1, fl. 45v, nº 116.

Fig. 7 Barracks in Largo Terreiro do Loureiro. Group view and the inside of one of the modules. Source: author, 2019.

Conclusions

The differences in the percentages of houses containing vaults between the sample gathered from historical records and that resulting from the 2018-2019 survey of the houses of Serpa indicates a very likely dissemination of the construction of vaults in common homes during the 18th and 19th centuries. This increase in number of constructed vaults in common dwellings extrapolates to the other three cities analysed, as – with the exception of Borba, which has a smaller sample of cases – the percentage of houses with vaults in the remainder cities also stands at around 20% in present day samples [Table 1], as is the case in Serpa. The four cities display continuous recourse to these structures during the Early Modern Age, which extends until the middle of the 20th century, especially in domestic buildings located within the commercial or central areas of these cities. These primarily incorporate four main geometries: groin, the most common by a wide margin, followed by barrel, trough and segmental vaults. Lunette and sail vaults, albeit not as common, also appear in the buildings of this region. It is also worth noting that some eccentric geometries appear, interweaving the characteristics of the more common vault types and sometimes not even adjusting to the shape of the compartment they are built in. It is highly likely that these eccentric geometries arise out of recourse to timbrel vaults in keeping with their greater flexibility in creating shapes.

In summary, the study presented here attests to the usage of vaults in common houses in the area of the Left Bank of the Guadiana River from as early as 1673.

The appearance of vaults in common houses in the last third of the 17th century coincides with a period of deep typological and constructive transformation that the urban house was then undergoing. This spanned a process of growth in area, in the number of housing compartments, and in the complexity of houses. Said complexity emerges in the physical separation of the productive household areas and the domestic spaces reserved for family life. The transformation also extends to the introduction of rooms solely dedicated to internal circulation, such as corridors to create paths and separate the passage of animals to the backyard and/or the transportation of crops, wine or olive oil from family living spaces. This separation would eventually lead, in the most commercially active areas of the cities, to the transfer of domestic spaces to the upper floors and thereby freeing the ground floor level – often entirely vaulted – to serve for commercial purposes.

Within this context of housing transformation, several factors certainly appear to explain the introduction of vaults into common housing and their subsequent dissemination, and should be pursued as future lines of research. One important factor within the context of the inland areas of the Alentejo region – bordering Spanish Extremadura and Andalusia – stems from the consequences of hosting major military construction campaigns for over a century. The constant works meant that the Alentejo was home to expert military engineers applying first-hand the innovative military construction techniques developed during the 17th century, such as defensive bastioned structures. Moreover, the constant working on fortifications ensured a regular flow of workers, and many of the region's builders and masons must have learned their trade on the military construction sites. As vaults – both stone and brick – were often employed in the building of fortifications, they would represent one technique military-trained masons were proficient in and likely willing to employ in other works outside the military context. Future research delving into the possibility of knowledge transmission from military construction to common buildings in the Alentejo region should analyse the impact of masonry workers as a vector of transference. A second path to explore vault dissemination inside vernacular housing should contemplate the study of the border area between Alentejo (Portugal), Extremadura (Spain) and Andalusia (Spain) as a whole region, considering the fluxes of trade, migrations and family relations that have been constant in the border area.

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Abstract

Much of the literature on Portuguese vernacular architecture has conveyed the notion of a 'vaulted south', understood as the territory where a certain roof-building technique is preferentially used across all building typologies. In Portugal, the massive presence of vaulted houses in the Alentejo and Algarve is practically common knowledge, but scientific research on this topic is only slowly expanding.
Other than the prevalence of timbrel vaulting and the ubiquitous use of clay brick, key characteristics of these traditional structures remain mostly unexamined, such as their true quantity and geographic distribution, their formal and constructive variety, their relation to spatial functions, and their symbolic significance. As for the origin and chronology of these vaults, explanatory myths persist in the absence of conclusive evidence.

keywords

BRICK VAULTS
TIMBREL VAULTS (ABOBADILHAS)
ALENTEJO
ALGARVE
VERNACULAR ARCHITECTURE
CONSTRUCTION HISTORY

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Types of vaults in southern Portuguese architecture

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Introduction

The notion of a 'Vaulted South', defined as a region where 'three-dimensional curvilinear self-supporting structures used as ceilings' (Rosado 2021a, 1) are predominantly employed across various building typologies – namely housing – has long been discussed in the literature on Portuguese vernacular architecture (Aguiar 1891; Amaral et al. 1961). In Portugal, specialists and the general public alike are aware of the prevalence of vaulted houses in the Alentejo and parts of the Algarve. However, although scientific interest in the matter has grown in recent years, its dedicated body of research still needs more output.

Based on several research missions conducted throughout the Alentejo and Algarve between December of 2022 and December of 2023,[1] this article aims to consolidate and expand upon the gathered information to clarify key questions regarding the precise geographical extent of this vernacular phenomenon, its distribution throughout erudite and ordinary buildings, the variety of vault types, the proportion of vaulted spaces within buildings, and the possible connections of the various types with the functions and social significance of said interior spaces.

The classification of vault types presents its own set of challenges, as the vocabulary used to describe these forms varies significantly across written sources, traditional jargon, and regions. To overcome this, a method has been adopted to systematise with greater coherence all vaulted forms documented during research.

[1] Research developed in the scope of the project FCT EXPL/ART-DAQ/0171/2021, 'Vaulted South – Vernacular vaulted houses in the south of Portugal' (DOI:10.54499/EXPL/ART-DAQ/0171/2021), coordinated by Mafalda Batista Pacheco and Margarida Tavares da Conceição.

This approach ensures that the analysis accommodates the full diversity of vault types while providing a structured framework for future studies.

Geographical and Historical contexts

The concept of a 'South of Portugal', comprised of the Alentejo and Algarve regions, can be defined in its broadest sense as a 'meridional half' of the country that meets its northern counterpart at a frontier line drawn by the river Tagus. The south-westward trajectory of this major body of water – from its confluence with the Erges, at the border with Spain, to its mouth in the Atlantic, near Lisbon – demarcates stark differences not only in geology, climate, and vegetation, but also in land tenure structure, social norms, cultural heritage and, consequently, architecture. This pithy geographic dualism, which has already been dubbed as a contrast of 'civilizations' – of 'granite' to the north and 'clay' to the south (Ribeiro 1961) – pertains to the notion that Portugal, as a predominantly 'vertical' political territory, intersects a sequence of latitudinal natural/cultural ecologies of the entire Iberian Peninsula (Marques 1995).

The similarities that the South of Portugal may lack with the North can be found in the Spanish regions of Extremadura and Andalusia, adjacent to the East, especially in the *montado/dehesa* landscape characteristic of this southwestern quadrant of the Iberian Peninsula: a traditional agro-silvo-pastoral system covering 4 million hectares in Spain and 1 million hectares in Portugal. In this landscape, scattered holm and cork oak trees (crown coverage of 10%-50%) and olive groves are integrated with pastures and agriculture, thriving in a Mediterranean climate with hot, dry summers and mild, wet winters. Annual rainfall ranges from 400 to 800 mm, and soils are typically poor (Fra Paleo 2010, 149-151).

The restrained use of timber and the local presence of quarries and clay pits imprinted a particularly 'mineral' character to the local traditional architecture, whose visual effect is further exacerbated by the limewash treatment of walled surfaces, of virtually universal application up to the middle of the 20th century. Behind these walls, a habit of vaulting architectural interiors has developed with particular incidence in Alentejo's hinterland, or *Alentejo Interior* (Rosado 2021b), and with notable intensity in the only portion of Portuguese territory to the East of the river Guadiana (and without any other major geographical features acting as a natural border from Spain). This *além-Guadiana* comprises the municipalities of Mourão, Barrancos, Moura, and Serpa, the latter two being the largest urban settlements of the subregion and having long been recognised as the main epicentres of brick vaulted construction (Amaral et al. 1961; Rosado 2021b). Other than these known

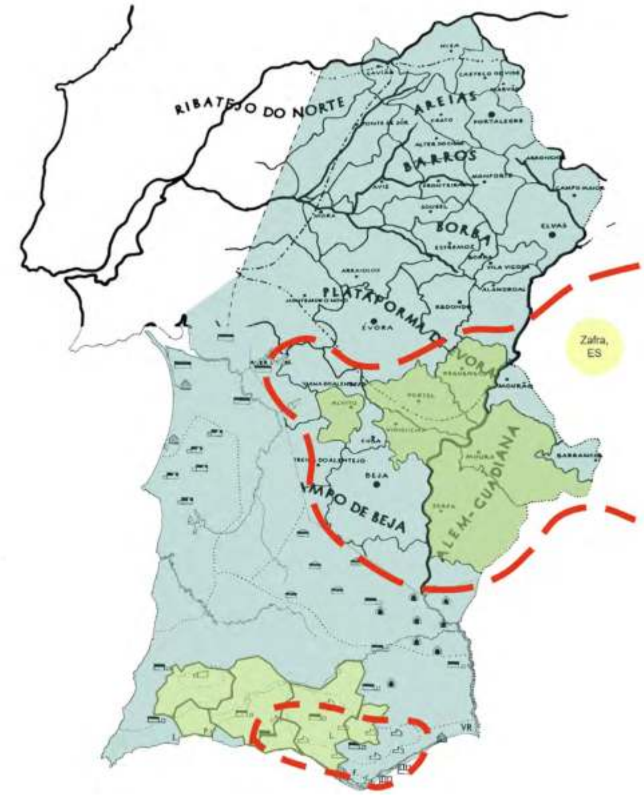

Fig. 1 Vaulted South. Dark green: general extension of the South of Portugal; light green: surveyed municipalities during the research project (see footnote 1); red dashed line: areas of prevalence of vaults. Source: authors, 2023; map source: Amaral, 1961, Zones 5 and 6.

cases, the significant presence of vaults in vernacular architecture has also been attested, by our survey missions, further east in Amareleja, Safara (civil parishes of Moura), Brinches, and Vila Verde de Ficalho (civil parishes of Serpa). To the west, the municipalities of Portel, Vidigueira and Alvito also hold many vaulted buildings. While the abundance of vaults in ordinary construction wanes beyond this nucleus, many such structures are otherwise generally known to exist throughout the entire Alentejo, especially in erudite civil and religious architecture of historically important cities like Beja, Évora, Elvas, or Estremoz.[2]

Compared to the Alentejo, the panorama of vaulted architecture in the Algarve is more restricted **[Fig. 1]**. Not only is the absolute amount of vaults lower and their locations within building layouts less varied, they are also rarely found in all the compartments of a house, with the notable exceptions of Olhão and Fuzeta (Caldas 2009; Pacheco 2009 and 2018). In these settlements of eastern Algarve (*Sotavento*), which originated as fishing villages, almost all vernacular houses are entirely vaulted (Pacheco 2009 and 2018).

While there is evidence of vaulted construction in ancient times in the South of Portugal (e.g. Roman villa at São Cucufate, Vidigueira), such edifices contain only

[2] Such a reckoning is provided by studies of Portuguese late Gothic architecture, such as in the work of José Custódio Vieira da Silva (1997).

Fig. 2 Narthex of Convento de São Francisco, Serpa. Source: authors, 2022.

barrel vaults, whose half-circular curvatures and brick placement indicates they were made with centering, relying therefore on techniques distinct from the self-supporting methods used only in later centuries in this part of the world. Although brick vaults in the vernacular architecture of the Alentejo and Algarve are often popularly associated with Roman or Islamic influences, the archaeological records do not support the hypothesis of a continuation between ancient practices and those developed in the Early Modern Era. Instead, the emergence of brick vaulting as a diffuse method of ceiling and roof construction appears to be tied to later historical developments. Brick vaults only began to play a significant architectural role after the definitive establishment of Christian states in the southern Iberian Peninsula during the late medieval period. Due to these territories' later period of annexation, the Romanesque mode is almost nonexistent. Vaults initially appeared in urban churches and convents, exhibiting clear stylistic characteristics of the Gothic mode, which amply spread south of the Tagus (e.g. Convento de São Francisco, Serpa, Fig. 2). These early examples are mostly erudite constructions, reflecting the growing architectural ambitions of the Christian Iberian kingdoms during this period. The technique involved in these medieval structures typically incorporated bricks for the web and key elements such as ribs and springing points, often complementing them with carved stone for structural elements such as corbels, and decorative details.

In the early Modern era, brick vaulting expanded beyond religious architecture and began to appear in residential buildings.[3] It first gained prominence in noble houses,

[3] The specific evolution of vaulted structures within military architecture is lacking in reference literature nor it was the focus of the research project that supports this paper.

Fig. 3 Ermida de Nossa Senhora das Pazes, Vila Verde de Ficalho. Source: authors, 2022.

Fig. 4 Dining parlour in Vila Mariana, Serpa. Source: authors, 2023.

where it was used to add functionality, comfort and prestige. Over time, this construction method became a feature of vernacular architecture, spreading across urban and rural areas. Rural chapels[4] **[Fig. 3]** are particularly notable for their vaulted interiors, which were constructed using local materials and often displayed a simplicity that contrasted with the more elaborate vaults of urban ecclesiastical buildings.

The 19th century marked the peak of brick vaulting in Southern Portugal, coinciding with the widespread adoption of timbrel vaulting.[5] This technique, which did not require centering, allowed for faster construction and a more efficient use of materials (Fortea Luna 2008). It became especially common in domestic spaces of relatively recent formulation (for the time and region), such as dining rooms, bedrooms, and corridors, particularly in the expansion and modernisation of older noble houses. Timbrel vaulting also became commonplace in new construction of the urban expansion of the time. The flexibility of timbrel vaulting facilitated its adaptation to various forms, including barrel vaults, groin vaults, and more complex geometries.

Even though some notable examples of 20th-century vaulted construction exist (e.g. Vila Mariana, Serpa, c. 1920, **Fig. 4**), the growing prevalence of reinforced concrete as a construction material and technique by the second half of the century led to a significant decline in the use of brick vaults. This shift marked the

[4] Portuguese: *ermidas*.

[5] Portuguese: *abobadilha*; Spanish: *bóveda tabicada*.

end of their widespread application in Southern Portuguese architecture. Today, the practice of brick vaulting persists primarily in restoration projects of old buildings and occasional new commissions by clients seeking to incorporate traditional architectural elements into their properties.

Materials and assemblage methods

The construction of vaults in southern Portugal is deeply rooted in the availability of local materials and the ingenuity of regional techniques. The primary material employed in these vaults is red clay brick, which defines their structural and formal character.

Each arched row was fixed in place using mortar, and the structure stabilised progressively during construction, rendering centering unnecessary. This method is particularly associated with older vaulting traditions in the region.

While bricks were assembled in a variety of arrangements that reflected the necessity of the vault's self-support during the construction process, these would be placed in two main positions in relation to the vault's intrados: perpendicular **[Fig. 5]** and horizontal/tangential **[Fig. 6]**. The second of these methods is called timbrel vaulting – or *abobadilha* in Portuguese and *bóveda tabicada* in Spanish – and has been the most studied feature of Southern Portuguese vaults so far (Rei and Gago 2016, 2017 and 2018). In this technique, bricks were laid flat and tangential to the curvature of the intrados, each brick being held manually for a short period while the mortar hardened, often containing varying proportions of gypsum (Fialho 2009).

The mortar used in vault construction varies across periods and locations. Historically, lime-based mortars were predominant, providing a reliable binding material for perpendicular vault assemblages. However, the introduction of industrial gypsum-based mortars in the 19th century revolutionised construction practices, giving rise to timbrel vaulting. These mortars, which hardened more quickly, significantly reduced the time needed for individual bricks to stabilise, making them ideal for techniques that required minimal or no centering (Fialho 2009).

The bricks themselves were typically slender, a crucial feature for achieving the lightweight structures characteristic of timbrel vaulting. These bricks generally measured between 250-300 mm in length, 35-70 mm in height, and 120-150 mm in width (Fialho 2009; Rei and Gago 2017). This slenderness allowed for precise placement and alignment and also enhanced construction efficiency (Fortea Luna 2008).

This method enabled the construction of thinner, lighter vault webs and encouraged a generalised depression of their sections, reducing rise-to-span ratios and enhancing

Fig. 5 Vault with bricks assembled perpendicularly to the intrados.
Shop in Rua Cons. Augusto de Castro 11, Moura. Source: authors, 2023.

Fig. 6 Vault with bricks assembled horizontally/tangentially to the intrados (timbrel vault). House in Rua das Manhãs, Alvito. Source: authors, 2023.

Fig. 7 Vault built with segments of *pedra caliça* in the same fashion as brick vaults. Shop in 3-5 Rua 5 de Outubro, Loulé. Source: authors, 2023.

the self-supporting nature of the vault. The efficiency and adaptability of timbrel vaulting contributed to its widespread adoption in various architectural forms.

Within our territory of study, a notable variation occurs in the Barrocal sub-region of the Algarve, where *pedra caliça*, a locally quarried limestone, is cut into brick-sized pieces and applied in vaults either alone or mixed with clay bricks. Despite this material difference, the construction techniques for *pedra caliça* vaults are the same as those employed for perpendicularly set brick vaults **[Fig. 7]**.

Irrespective of their construction material and technique, all vaults were traditionally plastered and whitewashed for, among other purposes, protection against moisture. Stripping vaults of these protective layers is a contemporary phenomenon that endangers these structures' preservation.

Clay bricks were not limited to the vault webs but were also employed in structural ribs. In Gothic architecture, brick ribs were prevalent, supported by carved stone corbels.[6] Notable examples include the ribbed vaults of the Convents of São Francisco in Serpa and Carmo in Moura, which reflect the region's adaptation of Gothic architectural principles using locally available materials. While some vaults show ornamental features whose sizable dimensions insinuate that they are partly made from bricks projecting out from the intrados, the majority of decorative elements were made by modelling the plaster layer. These coatings, often whitewashed, served both aesthetic and protective purposes, seamlessly integrating the ribs into the overall visual composition. In cases where vaults featured decorative or figurative paintings, the ribs were incorporated into the design and either painted to imitate stone or highlighted to emphasise their structural role.

Morphology of vaults in the south of Portugal

To avoid the limitations of language, a method of describing the vaulted form that is truly inclusive of all that is observable on the ground must detach from regional jargon or the metaphors employed by specific literary influences. It would even be advisable to avoid the word *type* altogether, as it might allude not only to a particular *shape* but also to a certain construction technique.[7] For our topic of discussion, a focus on *morphology* is being chosen. One of the easiest starting points to set apart vaulted forms is to adopt 18th-century architecture theoretician Amédé-François Frézier's distinction of 'simple' and 'composite' vaults (1737), in which the surface of the first can be (ideally) described by a single regular solid – say a cylinder or a sphere – while that of the second results from a combination – a mathematical *union* or *intersection* – of such shapes. In this strict geometric sense, barrel vaults, domes, and sail vaults[8] are 'simple', while groin or cloister/domical

[6] Portuguese: *mísulas*.

[7] Such is the case for regional definitions of timbrel vaults in Spain, either *bóveda catalana* or *bóveda extremeña* – they are in part set apart by their shape, in part by different assembly systems.

[8] Compared to half-spherical domes, the surface of sail vaults does suffer a transformation – the truncation of the spherical intrados by the confinements of the room it is placed upon. Still, this doesn't generate a groin in the intrados.

Fig. 8 Plaster decorations in the oratory of Casa da Quinta de São Brás, Serpa. Source: authors, 2022.

vaults are 'composite'. Additionally, some vaults have their intrados, or interior surface, composed of structural or ornamental components other than the actual shell, that can *add* or *subtract* volume to the final form. Some of these components play such a key role in the structural conception and construction process of a vault that they are distinguished by names of their own. Such is the case of a vault whose four webs are supported by an intersecting pair of diagonal ribs:[9] the ribbed vault. In this case, ribs are often the first to be built and act as centering for the remaining shell. Ribs, when existent, are the main load-bearers and can have a diagonal, transverse, or longitudinal placement below or interlocked with the vault's surface. Smaller, rib-like components like liernes and tiercerons,[10] found in some late Gothic buildings, do not play such a structural role as ribs, being mostly ornamental. Other components that increment the dimensionality of a vault include squinches, pendentives, keystones/bosses, corbels, and plaster mouldings.[11] Of these, only the last one is strictly decorative. Conversely, some other components render a vaulted form more complex by 'subtracting' material from its main shell, sometimes for structural design purposes, but mostly to provide lighting and ventilation to interior spaces. These include lunettes/penetrations and lanterns, which affect the vault's structure, as well as decorative wedges and creases on the layer of plaster **[Fig. 8]**.[12]

[9] Portuguese: *ogivas*.

[10] Portuguese, respectively: *ogivas, arcos torais, cadeias, liernes, terceletes*.

[11] Portuguese, respectively: *trompas, pendentes, chaves, mísulas, molduras de argamassa*.

[12] Portuguese, respectively: *lunetas/ penetrações, clarabóias, cunhas, alhetas*.

Fig. 9 Barrel vaults in ground-floor functional spaces. Cellar in Monte da Balsa, Portel. Source: authors, 2023.

Fig. 10 Barrel vaults in rural chapels. Ermida de Santana, Serpa. Source: authors, 2022.

Vaulted forms and their relation to architectural space

Barrel vaults[13] are the most common type of vault, present across all historical contexts and building types. Their defining characteristic is their association with elongated compartments, where one length is significantly larger than the width. This structural efficiency has made barrel vaults a universal solution for a variety of spaces, both functional and representational.

In housing, barrel vaults are typically found in more utilitarian spaces such as kitchens, wine cellars, and granaries, which often feature elongated plans. They can also be found in alcoves. For instance, the central corridor in the Casa da Quinta de São Brás in Serpa exemplifies their use in circulation areas, while the cellars of Casa Gavião Peixoto in Serpa or of Monte da Balsa in Portel demonstrate their employment in storage spaces [Fig. 9]. Their simple form and straightforward construction method have historically linked barrel vaults to ordinary construction, reflecting their functional adaptability.

In religious architecture, however, barrel vaults take on a more prominent role, transcending their association with simplicity [Fig. 10]. Since the late 16th century, they

[13] Portuguese: *abóbadas de berço, abóbadas de canhão.*

Fig. 11 Spherical domes in noble houses. Chapel of Quinta de Santa Cruz, Alcantarilha, Silves. Source: authors, 2004.

have become the most prevalent type of vault in church naves (and some chancels), often enhanced by structural reinforcements such as transverse arches or by the inclusion of lunettes for natural light. Barrel vaults are also commonly found in lateral chapels and sacristies, as well as in circulation areas of convents, such as corridors. While less frequent in cloisters, their use is not entirely uncommon.

Of equally simple geometry but more complex assemblage are spherical domes.[14] Practically non-existent in domestic Alentejo architecture, they can be found in some chapels of noble houses in the Algarve [Fig. 11]. The celestial symbolism, or even representations of the Divine associated with this shape – especially from the Renaissance onwards – led to its multiplication in religious architecture of the South in the Modern era, chiefly in choirs and their adjacent chapels or even in square-plan lateral chapels. There are occurrences of elliptical or spherical domes

[14] Portuguese: *cúpulas esféricas.*

Fig. 12 Domes in rural chapels. Ermida de Nossa Senhora de Guadalupe, Serpa. Source: authors, 2022.

constructed above lateral chapels that are rectangular in plan. In urban settings, domes are also found covering the nave of small square-plan churches lacking the protruding choir body.

The use of these domes in the southern region of the country, however, extends unexpectedly to numerous peri-urban and rural chapels, where they came to replace the medieval preference for ribbed vaults. These small chapels, sometimes completely isolated, often display the whitewashed, semi-spherical extrados of the dome covering the chancel. Far less common is the appearance of semi-spherical or elliptical domes over the narthex [Fig. 12], when such a space is present in the

Fig. 13 Sail vaults in domestic spaces.
House in Fuzeta, Olhão. Source: authors, 2018.

chapel layout, and even less so their use in sacristies, particularly since these religious buildings also do not always include them. However, the apotheosis of the brick-built semi-spherical dome, within the context of southern chapels, is represented by the rare cases where this type of roofing rests directly on the cylindrical wall of a circular chancel, or, in extreme cases, where the nave itself has a circular plan (without a separate chancel) and is covered by a dome.[15]

The sail vault[16] can be understood as a 'sliced' variant of the spherical dome. While rare in Alentejo, it is common in the Algarve – particularly in the municipality of Olhão. In ordinary urban dwellings, like in Olhão or Fuzeta, it is frequently applied over the main parlour, which is almost always quadrangular. In rural houses, whose layout is drastically different from their urban counterparts, sail vaults are found

[15] This solution is not exclusive to the south of the country, but it stands out in the vernacular context of the region and its brick vaults. The principal Portuguese religious buildings with circular plans and dome coverings – such as the Chapel of Santo Amaro and the Church of Serra do Pilar – were conceived within learned contexts, located in major cities – Lisboa and Porto, respectively – and are constructed in stone masonry. The Chapel of Santo Amaro is, in fact, an extreme example, as it features a small chancel that is also circular and covered by a stone masonry dome.

[16] Portuguese: *abóbada de vela*.

Fig. 14 Groin vaults in first-floor domestic spaces in Alentejo. Living room in Casa Rocha, Serpa. Source: authors, 2022.

in the aforementioned living/dining rooms but also in vestibules and in alcoves. This vault type, usually placed above square rooms, is sometimes 'elongated' to cover rectangular alcoves, making its distinctive *calotte* no longer spherical, but still a continuous curved surface **[Fig. 13]**. Sail vaults produce a particular plastic effect when they are constructed (rarely) in smaller dimensions and placed in a row to cover corridors.

Within composite vaults – that is, those composed of multiple, intersected curved surfaces – the most common are groin vault and domical vaults. Both types essentially originate from the intersection of two cylindrical surfaces arranged perpendicularly to each other. Groin vaults, in particular, result from the crossing of two semi-cylinders with the same radius, such that their highest generatrices are at the same level. The intersections correspond to two curves with the same rise as the directrices of the cylindrical surfaces, which project onto the plane as the diagonals of the square covered by their intersection. Constructively, they correspond to the two protruding edges that meet at the highest point of this segment of a square-based vault.

Throughout the Modern era, groin vaults[17] are found in all types of buildings and placements. They're mostly located in urban houses in the Alentejo where they can cover rooms with the most varied functions, from entrance halls and ground floor service areas to stairwells and first floor bedrooms and living rooms (e.g. Casa Rocha, Serpa, **Fig. 14**). They are also common in rooms with different uses in

[17] Portuguese: *abóbadas de arestas.*

Fig. 15 Groin vaults in ground-floor commercial establishments. Loulé. Source: authors, 2023.

two-storey rural houses, sometimes extending to larger farm dependencies (e.g. the granary/cellar building in Monte da Balsa, Portel). Their association with timbrel vaults, although proven in previous literature, remains weak in the buildings surveyed in our study.

In central Algarve, where vaults are almost only built on ground floors, even in urban dwellings, groin vaults are also common in ground floor service areas, as well as in the commercial establishments of the main urban towns and cities **[Fig. 15]**. They are rarer in rural areas, even in two-storey houses, where they are found supporting the pavement of kitchens and terraces. Minor usage in small alcoves has also been detected (e.g. Monte de Ângela Clara, Tavira). Their presence in ordinary architecture, urban or rural, fades towards the eastern and western edges of the region.

In religious architecture, even if they can cover all sorts of spaces, they are more expressive in cloister galleries. They normally result from the intersection of each gallery's longitudinal barrel vault with small, transverse barrel vaults directed at the cloister's opening **[Fig. 16]**. This originates a succession of groin vaulted spans that may or may not be separated by transverse arches springing from the pillars.

Domical vaults[18] (also less precisely referred to as 'cloister' or 'trough' vaults) result from the intersection of cylindrical surfaces that, contrary to the groin vaults' four corner resting points, spring from the full walled perimeter of the (rectangular) room they cover. From the point of view of a dweller, their webs form concavities toward the centre of the compartment that sometimes describe perfect half-circles, but

[18] Portuguese: *abóbadas de barrete de clérigo* or *abóbadas de engras*.

Fig. 16 Multi-span groin vaults in religious architecture. Cloister of Convento de Santo António, Loulé. Source: authors, 2023.

Fig. 17 Domical vaults in early modern erudite domestic architecture. Room in Palácio Ficalho, Serpa. Source: authors, 2022.

mostly follow a depressed curvature.[19] Two pairs of identical webs are formed at opposite sides, the largest of which would ideally form an intersection line ending at the vertices of the smaller webs and placed at the vault's maximum height. In built practice, however, this top line is rarely emphasised as a re-entrant 'groin'. Instead, the two pairs of symmetrical surfaces meet at the central section of the intrados whose curvature is abated by the layer of plaster.[20]

In domestic architecture of the Alentejo, domical vaults appeared first in noble residences in the earliest reform works, or as new construction, to show clear architectural intentions – such as the halls of Palácio Ficalho and Casa Gavião Peixoto in Serpa **[Fig. 17]**. They emerged much later in housing in the Algarve – from the second half of the 19th century onwards – and mostly in urban ordinary dwellings from Olhão and Fuzeta, with the same privileged position which, in this type of housing, is shared with sail vaults: as an emphasising spatial feature of the main, front façade-facing room (Pacheco 2018).

In the religious architecture of the entire South, domical vaults appear sporadically in sacristies or other flanking compartments of churches, and rarely in chancels. However, these vaults are not rare in convents and other religious houses, and are seen in the cubicles[21] of Jesuit colleges, in corridors and sometimes staircases.

[19] As Pacheco (2018, 222) elicits as the rule-of-thumb from several pre-industrial architectural treatises, depressed arches are often codified as three or five-centre composite agreeing curvatures.

[20] This is more the case for vaults with bricks assembled perpendicularly; timbrel vaults have such a smooth curvature that no creases between webs are left to be 'disguised' by the application of plaster.

[21] This is the term used within the Jesuit Congregation for *cells*.

Fig. 18 Domical vaults in 19th century domestic spaces. Living room in Quinta da Marreira, Serpa. Source: authors, 2023.

In the late 19th and early 20th centuries, the prevalence of domical vaults ballooned – especially in the Alentejo – due to the convergence of two factors: on one hand, the dissemination of timbrel vaulting as an efficiency improvement in traditional construction (Fortea Luna 2008) profited from a vaulted form whose rise is both linear and horizontal, expediting brick-setting; and on the other, housing construction in this period was marked by developments in private life that saw a specialisation of domestic spaces, resulting in the growing compartmentalisation of older multi-purpose interiors into clearly defined bedrooms, social rooms, bathrooms and subservient circulation areas **[Fig. 18]**. New buildings from this period were also conceived like this, making domical vaults almost as ubiquitous as barrel and groin vaults. Additionally, the gradual transition to timbrel vaulting lowered the average rise of practically all vaulted forms. In domical vaults, the abatement of the calottes trimmed down the re-entrant groins, merging the two pairs of webs into an almost continuous curved surface with short pleats at the corners.

All these types of vaults are composed of surfaces or calottes that can accommodate the insertion of lunettes or penetrations – small vaulted surfaces (ideally cylindrical) that interrupt the main vault. These serve as 'light channels,' drawing light from vertical windows, or are simply used as decorative elements to introduce variation or animation on an interior space, at the junction between the calottes and the walls.

As 'light channels', they are commonly found in church roofs, particularly in the nave rather than the chancel, especially toward the end of the Early Modern period. When used as decorative features, they are frequent in southern vaults and appear in all types of dwellings, applied in various ways. The malleability of brick construction and the accumulated expertise of master vault builders lent themselves well to this effort to break 'monotony' **[Fig. 19]**.

This basic morphological concept has a 'freer' variant, found in a handful of cases in the Alentejo, of a type of vault whose lunettes were enlarged to such an extent that there is no longer a main calotte or intrados. The lunettes are joined together at their edges that meet at an apical point in the vault's zenith **[Fig. 20]**. The lunettes themselves extend from the centre of the vault to the walls, intersecting them obliquely so that the separating edges vary in length: the longest edges project diagonally across the room, while the shorter ones align with its medians.

Naturally, as is often the case with vaults in general – and particularly with composite vaults – the most technically and formally elaborate examples of penetrations are found in religious buildings, despite their widespread use in domestic architecture in the South of Portugal. The repetitive use of 'decorative' penetrations produces an even greater effect in large spaces, as seen in the sacristy of the former Convent of São Paulo in Serpa **[Fig. 21]**. However, the evolution of a vault of this type into a continuous 'undulating' surface without edges (as seen in what currently is the laundry room at the former Convent of São Francisco in Serpa) or the intricate adaptation of lunettes and edges to the space and openings of the chancel in the Church of São Pedro in Moura **[Fig. 22]** evoke the greatest sense of wonder and admiration.

Ribbed vaults are also an example of composite vaulted structures, comprised of different surfaces, but they belong to an entirely different lineage, distinct from the families of vaults previously analysed.[22] Developing predominantly within learned contexts, particularly in religious architecture, they are a medieval European invention, closely tied to Gothic architecture's structural and spatial innovations, making them chronologically limited. While in some European regions late Gothic styles extended well into the 16th century – thus overlapping with the cultural context of the early Modern era – Portuguese ribbed vaults were also used in Renaissance architecture and, more broadly, in classicising architecture until the late 16th century. In such cases, either Gothic construction techniques were acclimated to a classical expression, as seen in the profiles of the ribs, the design of

[22] Although, according to various authors in the field of structural analysis, its initial conception may have been suggested based on the understanding of the unequal distribution of forces in a typical groin vault.

Fig. 19 Elaborate lunette vaults. Staircase in Grémio da Lavoura, Moura. Source: authors, 2023.

Fig. 20 Octopartite vault. House in Praça da República, Alvito. Source: authors, 2023.

Fig. 21 Penetrations in the sacristy of the Hospital (formerly convent) of Saint Paul, Serpa. Source: authors, 2022.

Fig. 22 Unconventional vault shapes. Chancel of Igreja de São Pedro, Moura. Source: authors, 2023.

supporting corbels, and the decorated keystones, or these elements ceased to serve any structural purpose, becoming merely decorative and less prominent.

The inclusion of ribbed vaults within the scope of vaulted architecture in southern Portugal is justified for both structural/material and prestige-related reasons. Many of the ribbed vaults found in the architecture of the Alentejo and the Algarve are constructed entirely from brick. This includes the surfaces of the various webs that compose the vaults and the structural ribs that join these surfaces, except for the springing corbels, which are often made of carved stone. These vaults are

Fig. 23 Ribs integrated with pictorial decorative programmes. Chancel of Igreja do Espírito Santo, Moura. Source: authors, 2023.

Fig. 24 Imitation of stonework. Sacristy of Convento do Carmo, Moura. Source: authors, 2023.

commonly found in a wide range of religious spaces, such as chancels, naves, chapels, cloisters, sacristies, and refectories (e.g., Convento do Carmo, Moura; Convento de São Francisco Serpa).

The material and prestige-related aspects of ribbed vaults are evident in religious, military, and civil architecture. In religious architecture, this is reflected in the relative complexity of the ribbed vaults, which tend to be more elaborate in areas such as chancel chapels or chapter rooms. In all architectural typologies, however, brick ribs were originally plastered and whitewashed. In cases where the intrados of the vaults feature decorative or figurative paintings, the ribs are integrated into the overall pictorial design **[Fig. 23]**. Conversely, in some instances, decorative programmes consisted only in the ribs being plastered or painted in order to mimic stonework, underscoring the connotation with the desired prestige of stone masonry construction **[Fig. 24]**.[23]

Such programmatic considerations, along with their implied technical complexity, meant that ribbed vaults (in brick) were rarely used in domestic architecture, except for some noble houses of the Alentejo. Even in these, their use was sporadic, appearing in a few late-built tower houses (16th century) commissioned by families aiming to assert their rising social status (e.g. Torre das Águias, Brotas, Mora). They are also found in the oldest surviving sections of urban noble houses, invariably on the ground floor and in spaces adjacent to the building's main façades. These spaces may have served representative functions, such as vestibules or chapels, or perhaps even shops, as the ribs were not strictly necessary to bear the weight of upper floors (e.g. Casa Rocha and Palácio Ficalho in Serpa). The simplicity of the rib sections used in these cases – often unnecessarily wide and sometimes crude in appearance – suggests a tendency toward vernacular adaptation, despite being found in the homes of privileged social groups **[Fig. 25]**.

Conclusion

It can be confirmed that vaulted construction, though by no means exclusive to the south of Portugal, has a particularly significant presence in the regions south of the Tagus River, spanning all housing types, including ordinary dwellings. Combined with the predominant use of brick, most often assembled without centering, we can affirm that, regardless of its origins, this technique has solidified into a vernacular tradition.

Although it has not yet been possible to determine a clear 'boundary' for the extent of the use of this technique in vernacular contexts – and acknowledging that such construction questions rarely have exact limits – it is possible to propose

[23] The outward expression of solidity provided by stone likely explains its selection for constructing the ribbed vaults in some of the most significant military structures in the Alentejo, such as the keep towers of the castles of Beja and Estremoz.

Fig. 25 Detail of irregular ribbed vault in Palácio Ficalho, Serpa. Source: authors, 2022.

an approximate delimitation. The area dominated by brick vaults constructed without centering corresponds to a broad swathe of territory extending from the interior of the Alentejo to the eastern Algarve. This broadly coincides with the *Sotavento Algarvio*.

However, this general constructive continuity in southeastern Portugal, encompassing the assemblage method that dispenses wooden centering, does not translate into uniformities of employed vaulted forms, functions of the spaces they cover, areas with the highest density of vaulted constructions, or even the way materials are applied.

The entire Lower Alentejo on the Left Bank of the Guadiana River, the easternmost strip of its territory, has already been highlighted as the area with the highest concentration of vaults in terms of both number and variety. In the Algarve, where vaults are even rarer in the northern mountain range (*Serra*) than in the western region (*Barlavento*), the greatest density is found in the central zone, in an arc centred on Faro and roughly defined by the urban centres of Fuzeta, Moncarapacho, São Brás de Alportel, Loulé, and Boliqueime.

Although the constructive similarities between the brick vaults of these two regions are undeniable, the mixture of stone and brick in the central Algarve produces significant differences, albeit hard to perceive when these structures are plastered. In this zone, where the Barrocal reaches its greatest width, limestone predominates – often of varying quality. The so-called *pedra caliça* (a light and easy-to-work limestone) is frequently cut into small parallelepiped blocks and mixed with brick for vault construction. Typically, the two materials are used in different parts of the same vault, though with zones of integration or at least adjacency. Moving westward, one begins to encounter vaults constructed exclusively in *pedra caliça*, albeit built using the same techniques as those employed for brick. This is not the case when moving eastward, where stone also appears in vault construction but not as an equivalent or substitute for brick. Instead, it is used as rougher, larger masonry blocks to form the starting segments of vaults with straight springing from walls.[24] In sail or groin vaults, this type of stone may also be used to form the springing points at the corners, acting as concealed corbels of considerable size.

These different combinations of stone and brick in vaulted coverings may be one of the reasons for the rare use of timbrel vaults (*abobadilhas*) in the Algarve. Stone, even when light and well-carved, was not compatible with the construction techniques of timbrel vaulting. Additionally, in the Alentejo, timbrel vaults are predominantly constructed on upper or ground floors that are not required to bear heavy loads. In the Algarve, even in single-storey houses, vaulted coverings are almost always constructed with bricks placed perpendicularly to the curved surface. In two-storey houses, vaulted ceilings are rarely found on the upper floor.

Even if, from a top-down perspective, the vaults of Alentejo and Algarve can be indistinctly grouped in the same territory of southern or Mediterranean architecture, up-close analysis of dozens of such structures demonstrates that they have developed in both regions with some degree of geographical and chronological autonomy. Furthermore, it remains clear that both of these regional constructive traditions arose mainly in the Early Modern period, making them historically separate from the attested vaulted construction of Iberian Roman Antiquity and the (so far) fictional vaulted construction of the Gharb al-Andalus.

[24] These correspond roughly to the lower thirds of a vault's curvature, known in Portuguese as *rins* and in Spanish as *riñones*.

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Abstract

Within the scope of the Vaulted South Project, an open-source platform was implemented using Omeka-S software to store and interconnect digital data and enable research and dissemination – based on the FAIR principles (Findable, Accessible, Interoperable and Reusable) – of knowledge of vernacular vaulted buildings in Southern Portugal. The corpus was generated by crossing several methodologies and interrelated heterogeneous data on vaults, covering digital transcription, digital photography, laser measurement, terrestrial laser scanning, parametric BIM modelling, and non-destructive inspection techniques such as infrared thermography. This article presents the structure of the database and reflects on the operability of the exploratory methodological approach developed in the project, which encompasses data from several fieldwork campaigns, covering a specific geographical area. It reveals the importance of using innovative methods to achieve accurate data in a more efficient and less intrusive way when dealing with unstudied current buildings. Combining traditional and digital methods of surveyance, data acquisition, data management, communication and scientific dissemination, which are often employed separately in the fields of Architecture, History of Art and Engineering, the Vaulted South Project provided opportunities to bring these scientific fields together as a common field to the History of Architecture and the Digital Humanities.

keywords

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Digital vaulted territories:

development of a cross-tool platform for vaults knowledge

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Introduction

This article aims to present and discuss the methodological approach developed in the Vaulted South Project.[1] The project combined traditional and digital methods of surveyance, data acquisition, data management and science communication and dissemination, often employed separately in research fields of Architecture, History of Art and Civil Engineering, and applied in this project to vernacular vaulted buildings knowledge, demonstrating an exploratory character in the scope of the Digital Humanities.

The Vaulted South Project had an exploratory component in the field of the History of Architecture and Construction that emerged from the need to fill in the gap in studies on vernacular vaulted houses and construction processes. In conventional historiography, methodologies have mostly been based on archival research, fieldwork case studies and comparative methods. However, this project developed research based on interdisciplinary perspectives and methods in order to intersect the study of architectural treatises and construction manuals, complemented and compared with analysis of vaulted buildings in the Portuguese regions of the Alentejo and the Algarve, as surveyed through photography, laser measurement, terrestrial laser scanning (TLS), and then inspected using non-destructive techniques such as infrared thermography.

In our interdisciplinary approach, vaults were taken as connectors between the theoretical geometry referenced in books, the built geometry of buildings, and

[1] Research undertaken as part of the FCT EXPL/ART-DAQ/0171/2021 project, 'Vaulted South – Casas vernaculas abobadadas no sul de Portugal / Vernacular vaulted houses in the south of Portugal' (DOI:10.54499/EXPL/ART-DAQ/0171/2021), coordinated by Mafalda Batista Pacheco and Margarida Tavares da Conceição, corresponding to tasks 5 and 6, and including the support of scholarship holders Teresa Marques, Sérgio Costa, Mariana Folgado and Gonçalo Duarte, and with the technical support of Joana Paulino from the DHLab – Digital Humanities Lab, FCSH NOVA, and the Laboratory of Construction, CERIS IST UL. This article had the support of CHAM (NOVA FCSH/UAc), through its strategic project, sponsored by FCT (UIDB/04666/2020, DOI10.54499/UIDB/04666/2020).

the parameterised object files of 3D models. The transition from analogue to digital and parameterised geometries through the modelling of vault types and the creation of a BIM library (a catalogue of BIM object files) enables scientific comparison between vault case studies along with their re-use in future contexts.
The main activities of the Vaulted South Project were: 1) the compilation and study of treatises and construction manuals about vaulted systems used in Portugal between the 16th and the 19th centuries; 2) the survey and study of vernacular vaulted houses in southern Portugal, namely in the regions of Baixo Alentejo and Algarve; 3) the identification and study of influential buildings in the surroundings of vernacular vaulted houses that may have served as sources of knowledge; 4) the characterisation of vault geometry, assemblage systems and materials; 5) the generation of a corpus based on written knowledge, vernacular buildings, vault typologies and geographical distribution; 6) the creation of digital, three-dimensional and parameterised data; 7) the creation of thematic routes; and 8) the storage and curation of the corpus on an open-source online platform, as a structured and georeferenced database, made available to the scholarly community and the general public.
Discussion of the Vaulted South Project methodology will be based on case studies involving different sources, scales and methods of approach, taken from 21 handwritten and printed documents, 190 buildings surveyed and georeferenced in Baixo Alentejo and Algarve, 41 representative technical drawings of them, 5 thematic optimised routes covering 35 buildings in Moura, and an in-depth study of two buildings in Serpa: the Quinta de São Brás house and Ficalho Palace.

Vaults under study: a digital methodological approach

Vernacular buildings and architectural treatises are rarely connected or even documented in the archival sources. However, to fully understand vernacular construction systems, it is necessary to study the textbooks and treatises used to instruct not only architects but also builders. The challenge of researching vaults is marked by the disparate nature of sources (oral testimonies, written documents and buildings) within specific social and geographical contexts that rarely have the opportunity to be read simultaneously with a unified scope. Many differences stand out when dealing with written documents – both handwritten and printed – and vaulted buildings, from erudite buildings to common houses. This dichotomy was stressed in the project's tasks and specific objectives.

The main goal of the task 'Learned Sources' was to research how architectural treatises and textbooks written for the master builders' instruction could provide important information about vaulted systems, with their geometry, building materials and construction techniques (Conceição and Pacheco 2023; Cardamone and Martens 2017). Previous research demonstrated that architectural writings often include prescriptions about construction techniques, namely vaulted systems, with stone vaulting being the only method usually studied (Pacheco 2021; Conceição 2020). Thus, this kind of data from architectural writings, both manuscript and in print, widespread in Portugal between the 16th and the 19th centuries, was surveyed and extracted to develop comprehensive research on vernacular vaulting and its connections with the so-called erudite or learned architecture.

The 'Cultured Buildings' task sought to understand how religious, military, infrastructural and noble buildings could work as a source of technological knowledge, formal composition and inspiration for detail. In other words, how construction sites work as places for knowledge exchange and transmission (Costa et al. 2023; Pacheco 2021). In this case, formal and constructive comparison between cultured and vernacular buildings was the method to clarify the hypothesis and to research the boundaries and contact points within architectural knowledge, which are usually perceived as opposites. It was noted that vault constructive systems are the link between cultured architecture as perceived as a reference constructional model for vernacular architecture.

In turn, 'Vernacular Buildings' explored the apparent relationship between place and form, or place and time (Joyeux-Prunel 2020), by assessing specific constructional features. This was carried out by looking at buildings as primary sources, through surveying and mapping vaulted houses still extant in the regions of the Alentejo and Algarve (south of Portugal), built between the late 18th and the early 20th century. On-site research is one of the most profitable methods of enquiry in popular architectural studies, since these vaulted houses were built thanks to the oral transmission of knowledge and technical rules, without support from educated experts and designers, nor documents.

The survey focused on vault materials and constructive systems in the Baixo Alentejo region, with the hypothesis of the predominance of brick vaults with the 'bed' face showing (*à face)* constructive system, in the West Guadiana river line (at Reguengos, Portel, Alvito and Vidigueira) and the East Guadiana river line (at Moura, Amareleja, Safara, Serpa and Vila Verde de Ficalho). In the Algarve region, with the hypothesis of the brick vaults with the 'stretcher' face showing (*ao cutelo*) constructive system predominating, surveys were conducted in the windward region west of Faro (Monchique, Silves, Paderne and Boliqueime) and the leeward region at east of Faro (Loulé, São Brás de Alportel, Estói, Olhão, Fuzeta, Moncarapacho and Tavira), among other relevant towns. This task articulated the theoretical references concerning learned written sources and references to cultured buildings with vernacular houses, which formed the basis for the study of the vault systems task.

Next, the task on 'Vault Systems and Materials' focused on the prospection and evaluation of vaulted constructive systems, which occurred during the survey of vernacular buildings. This covered the variety of systems (with and without formwork) and brick vaults with 'stretcher' or 'bed' face showing, also called timbrel vaults (locally called *abobadilha*), and materials and finishes (bricks, stones and mortars), and vault geometries from the simplest to the most complex (barrel, recessed barrel, groin, ribs, sail, domical or cloister, lunette and dome) and their variations of different generator arches, helped when possible by infrared thermography, a non-destructive prospection technique.

In the context of the fifth task, 'Learning from Vaulted South', in the field of the Digital Humanities, the corpus of knowledge on vernacular vaulted houses was fed with transcriptions, surveys, observations, analyses and reflections about the history, architectural and constructional features of such buildings. Once digitised, data was compiled, processed and stored on a database on an online platform, accompanied by photographs, technical drawings and three-dimensional digital models of buildings and parameterised models of vaults and arches, the application of which can be extended outside the project as a BIM library. The parameterisation process involved deciding what could be measured and how, according to the purpose of analysis and comparison (Drucker 2021).

Finally, besides the process of choosing the most suitable platform, the main challenges of the 'Vaulted South Platform' were structural organisation, operability workflow, and the curation of the data to provide access to stored items that were collected and processed or digitally created, in a way that facilitated the digital synthesis of collected and created knowledge about the vernacular constructive system of vaults while making it available online.

Structuring and correlating vaults

The 'Vaulted South Platform' was developed to enable the organisation, storage, categorisation, curation, visualisation and filtering of linked data of different kinds in a geo-referenced and open-access digital database. The criteria for choosing the software to create the digital platform was based on the three 'Es' – Economy, Efficiency and Effectiveness – and the FAIR principles – Findable, Accessible, Interoperable, and Reusable (EC 2016). It was essential for the platform to be open-source and freely accessible for long-term use.

The platform was implemented using Omeka-S, an open-source web-publishing and content management system (CMS) specifically designed for the Humanities (Omeka 2024), increasingly used by the scientific community to digitise galleries, libraries, archives, and museums (GLAMs). Omeka (Classic) was launched in 2008 by the Roy Rosenzweig Center for History and New Media at George Mason University (Hardesty 2014). Since 2016, the Omeka project has been developed by the non-profit Corporation for Digital Scholarship, with the release in 2017 of Omeka-S, a new version designed for institutional use, providing the capability to host multiple sites drawing from a common pool of resources. Omeka has been applied for functions such as digitisation, metadating, geolocation and online publishing per international standards (Brown 2020). One of the key strengths of Omeka as an open-source web tool is its thriving community, which contributes to the development of numerous plugins and presentation themes, enhancing the core software functionality and enabling a wide range of features. At NOVA FCSH University, the use of Omeka-S to develop research projects is increasing thanks to the support and hosting services of the Digital Humanities Lab (DHLab).
Previous experiments with the use of Omeka software applied to the Humanities with computational methods in GLAMs have demonstrated both its potential and some shortcomings and technical challenges. In 2008, the Metropolitan New York Library Council (METRO) used Omeka to create a directory of digital collections 'as a test to determine the viability of this platform for member libraries interested in using Omeka to build and deliver their own collections' (Kucsma 2010). The *Routledge Companion to Digital Humanities and Art History* reports testing of Omeka-S on the history of the Association of European Historians (AsE), a network of historians from several European and non-European countries founded in 1983, devoted to European historiography. The use of Omeka-S, in combination with traditional methodologies and network analysis, allows a more in-depth examination of the AsE network and its historiographical paradigm (Brown 2020). In another example of the implementation of Omeka, the Indiana University Libraries provided access to fragile items by making them available through online exhibition, revealing the benefits of Omeka for different types of digital library collection exhibits and different levels of technical expertise, although recognising it is 'limited in the ability to manage multiple exhibits of separate digital collections' and the need to improve tools for the GLAM community (Hardesty 2014). The adoption and implementation of metadata standards at Omeka also raises some different perspectives on what it means to 'adopt a standard' among Omeka creators and its users, insofar as 'these values are not equally shared amongst all stakeholders in a digital library ecosystem' (Maron and Feinberg 2018). Omeka-S was chosen as the platform for the project to guarantee the operation

of the project's online activities and for the long-term lifecycle of the digital work and platform. In this way, different data (images, texts, maps, three-dimensional models, and media files) have been combined and subjected to computational processing (data mining and statistical analysis).[2]

Some of the data used at the first stage of the project were collected in analogue form from manuscripts and printed architectural treatises and manual constructions, and thus needed to be digitised through a process of mediation: digitised, transcribed, sectioned, uniformised and linked (Drucker 2021). The same process was followed for the metrical measurements captured during fieldwork of the buildings that needed to be drawn, scaled, typified, uniformised and linked in digital format. Other data collected directly in digital format and similarly made uniform and linked together included photographs of buildings and houses and volumetric and thermographic prospections of selected case studies. New data was directly created in digital format through the use of software, committing to maintain uniformisation and linkage.

The design of the Vaulted South database with Omeka-S (Version 3.2.3) involved the hierarchisation and characterisation of the research items, their organisation according to topic, and their linkage according to the logic underlying the software and the implementation of the metadata standards. Five types of items were used in the research: 1) words comprising the technical vocabulary; 2) written documents comprising quotes from architectural treatises and construction manuals (handwritten and in print); 3) buildings comprising case studies of residential houses and religious buildings, through the use of photographs, drawings and coordinates; 4) drawings consisting of uniformised plan representations of buildings; and 5) parameterised 3D models of the types of vaults and buildings **[Fig. 1]**.

For the creation of these types of items, specific 'Resource Models' were developed: 'Vaulted South-Glossary', 'Vaulted South-Written Elements', 'Vaulted South-Built Elements', 'Vaulted South-Drawn Elements', 'Vaulted South-3D Elements', and finally 'Vaulted South-Vaults', which connects vaults listed in the other Resource Models. Each Resource Model is composed of a set of values with different terms that are preferably part of a metadata standard vocabulary. The most common terms used (title, author, date, quotes, type, etc.) are part of the Dublin Core vocabulary.[3] Each term is assigned an unequivocal ID and a customised label for more intuitive use when visualising. Other metadata standard vocabularies are available to combine and use in combination with DCMT to create the resource models 'Glossary', 'Written Elements' and 'Drawn Elements'. The resource model 'Built Elements' needed its own ontology to better adapt to the buildings' terminology. For that, a 'Custom Ontology' file was created and imported to the Omeka-S, being composed of terms adapted to buildings' specific needs, such as 'typology',

[2] According to Drucker (2021, 1), the components of Digital Humanities work are expressed in the sequence materials, processing and presentation, and are based on digital files and computational processes.

[3] Dublin Core vocabulary is Omeka's default vocabulary, also known as the Dublin Core Metadata Terms (DCMT).

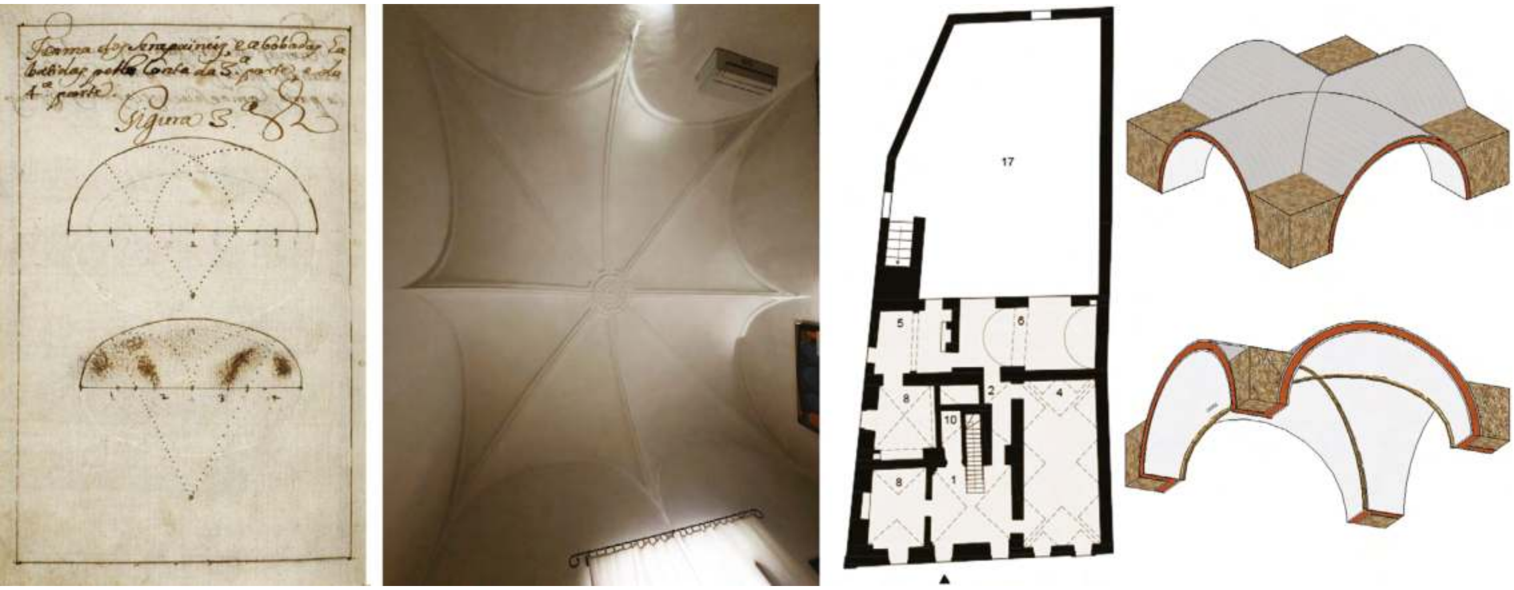


Fig. 1 Different types of items linked at the platform, from manuscripts, to photographs, architectural plans and 3D parameterised models of vaults. Source: Tinoco 1660, [fol. 43v]. BNP Cod. 5166 (left); authors, 2024 (rest).

'category', 'context', 'number of floors', 'materials', 'vault types', 'constructive systems', among others (VSEC – *Vaulted South Elementos construídos*).

Open fields include titles, authors, and quotes, while others offer predefined multiple choices to avoid errors when processing the data. In the latter cases, a list of permitted answers was created through the customised vocabularies Omeka module. Among other values, the value 'vault types' was applied, referring to items of the 'Vaulted South-Vaults' Resource Model. In addition to the values, items also have multimedia files attached (images, files, links for URL, HTML, YouTube and other digital sources), as well as location coordinates on an open source, geo-referenced and synchronised map (powered by OpenStreetMap). Therefore, the items are attached to one or more sets of items and one or more webpages.

Items were aggregated in 'Item Sets' according to type: 1) word items in 'Glossary'; 2) document items in 'Written Elements'; 3) building items in 'Built Elements'; 4) scaled drawing items in 'Drawn Elements'; and 5) 3D BIM model items in '3D Elements'. Items were linked to each other through each of the ten types of vault geometries found in the Glossary (Barrel, Recessed barrel, Groin, Ribs, Domical, Lunette, Octopartite, Reticulated, Sail, and Dome). Item Sets are part of the navigation bar on the webpage (under the same name) and allow lists with the same type of items to be visualised. The 'DigitalMuret' theme was chosen from a set of Omeka themes to give the database a visual appearance as a webpage.

A digital 'Map' was added to the navigation bar to provide a synchronised visualisation of the coordinates of the 'buildings' items in the south of Portugal, allowing users to navigate, zoom and search, and opening up 'possible encounters or proximities (…) and unsuspected connections' (Joyeux-Prunel 2020). Indeed, digital maps are a way to share findings, bridge the past and present, unlock spatial and social relations, and bring together academic and popular users (Terpstra 2016). The map visualisation is enabled by Omeka's 'Mapping Module'. Other modules were also incorporated into the Omeka-S database, such as the 'Custom Ontology', which makes it possible to create specific classes and properties to describe resources when no standard ontologies are available, the 'CSSEditor' to customise the visualisation aspects of the webpage, and the 'Bulk Export' tool to export the database in *.csv format to be processed by external software, such as ArcGIS for calculating the most efficient routes (i.e. optimised routes) and for statistical analysis.

Creating the database with Omeka allowed multiple, simultaneous users with different levels of permissions to create, modify and/or visualise contents. Mainly, three groups interacted in the database: art and architectural historians in the Glossary and Written Elements, architects and architectural historians in the Built Elements and Drawn Elements, and architects and engineers in Maps and 3D Elements. We envision the Vaulted South database and maps, which contain the corpus of the knowledge of vernacular vaulted houses, as a kind of 'Digital Vaulted Territories'.

Collecting vaults from books and buildings

The challenge of crossing information between 'written' and built vaults, coming from starkly different contexts of erudition in the vernacular setting of southern Portugal between the 16th and 19th centuries, requires an understanding of learned sources that were no strangers to the vault construction sites, and were thus likely to influence smaller-scale constructions and builders. Simultaneously, the search, identification, study and characterisation of the vernacular vaults in unexpected contexts were pivotal to assessing how far a construction system reached. Taking the most representative and better-known local buildings (religious, aristocratic, military, and infrastructural) with vaults as the starting point, the search for 'anonymous vaults' in the surrounding areas began, and so these findings were entered into the discourse of construction history. Consequently, the project compiled 21 handwritten and printed documents, surveyed 190 buildings in a georeferenced map of the Alentejo and Algarve regions, analysed routes for 35 buildings in Moura, and studied the Quinta de São Brás house and the Ficalho Palace in Serpa in depth.

From architectural writings to digital 'Written Elements'

Architectural literature frequently outlines construction methods, particularly focusing on vaulted systems, with stone vaulting being the primary technique examined. To conduct comprehensive research on vernacular vaulting and its relationship with scholarly architecture, it is essential to review the treatises and construction manuals on vaulted systems used in Portugal from the 16th to the 20th centuries. A selection was compiled of 21 architectural books and construction manuals, representative of those found in Portugal referencing vaults as a general roofing system.[4] These dataset items were selected from an initial survey within the broader scope of the so-called architectural treatises. The review was designated as 'Written Elements' to reflect the variety of texts in terms of internal consistency and cultural context.

The primary goal of the sources compilation was to investigate the origins and definitions of the vault, as a concept, focusing on both construction and cultural aspects from the scholarly sources. Starting with modern editions of Vitruvius' book and Alberti's treatise, and including the systematisation of the Encyclopedia and technical knowledge cultivated in the 19th century, the selection was based on the richness and representativeness of the content. Manuscripts and printed works were chosen for their chronological, typological, and geographical diversity, utilising resources from the National Library of Portugal and the Library of the National Palace of Mafra.

The ultimate aim of this section was to provide the material needed to explore the connection between theoretical and codified knowledge about construction techniques and vernacular vaulted constructions, and to examine the transmission of such knowledge.

Items in 'Written Elements' are composed of four sections: 1) Selected images of the document; 2) General information section identifying the book (title, author, date, editor, place, type, etc.); 3) Content section, featuring transcriptions relating to vaults followed by the list of vaults and materials mentioned in the transcriptions, linked to the Glossary; and 4) References section with the bibliography, access to the digital repository and digital images of the written sources. The Resource Model used in this Items Set mainly consists of a combination of metadata standard vocabularies from the Dublin Core (*.dcterms) and Bibliographic Ontology (.*bibo) ontologies.

Since the books are written in different languages – Portuguese, Spanish, French, Italian and Latin – the digitised pages containing quotes relating to vaults were fed into Transkribus, an AI-powered tool for text recognition, image analysis and structure recognition of historical documents, for the automated transcription of

[4] For the complete list of documents consult the section Written Elements – Vaulted South

writing and searching (Baudry 2023). Transkribus has publicly available AI models, in particular the 'Transkribus Print Multi-Language', developed by the Transkribus Team, which was applied to the printed books mentioned before. The use of Transkribus increased the accuracy of transcriptions made available on the Vaulted South platform **[Fig. 2 left]**.

From vaulted buildings to digital 'Built Elements'

Research on cultured buildings as sources for technological knowledge, formal compositions, and inspiration for details – with construction sites serving also to exchange and transmit knowledge – was essential for the formal and constructional comparison between erudite and vernacular buildings. A significant number of vaults in buildings was registered, creating a representative corpus (190 buildings: 154 residential and 36 religious). A digital collection was generated, encompassing constructional features such as the type and number of vaults in a building, constructional systems, materials, and the function of the building, among others.

Since one of the research themes was to identify the erudite sources for vaults, or at least schooled/educational/cultured sources in popular contexts, the survey of buildings began with those with an erudite character, such as palaces, noble houses, convents, monasteries, churches and chapels, more likely to have been influenced by technical knowledge from written sources, in the same way that the systematisation of current houses and the know-how of master builders of vaults, transmitted over the last centuries, were integrated.

Case studies were selected taking into account the richness of the constructions and their chronological and typological (occasionally, geographical) representativeness, bringing together erudite and popular buildings. Data acquisition methods included photographic surveying, metric laser measurement, terrestrial laser scanning, and thermographic surveying of the exterior and/or interior of the buildings, to be discussed in full in the next section.

The 'Built Elements' set is made up of 190 items, corresponding to a sample of buildings with brick vaults used for roofing or floor systems, located in south Portugal. This compilation was aimed firstly at querying the variety of vault geometries and construction systems, their geographical and chronological spans, and at further analysing their convergence with written sources. This dataset was gathered from fieldwork campaigns conducted in the Moura, Vidigueira and Serpa regions in Baixo Alentejo and in the Algarve region, consisting of an initial exploration within a broader territorial context. The designation 'Built Elements' is intended to encompass the various types of buildings, considering their uses, settings, and construction consistency, as well as their cultural context.

The 'Built Elements' set is organised around the Alentejo region (with 113 items), comprising the towns of Alvito, Amareleja, Brinches, Moura, Portel, Safara, Serpa, Vidigueira, and Vila Verde de Ficalho; and the Algarve region (with 77 items), comprising the towns of Boliqueime, Faro, Fuzeta, Loulé, Moncarapacho, Monchique, Olhão, Paderne, Portimão, São Brás de Alportel, Silves, and Tavira.

Each item in the 'Built Elements' comprises six sections: 1) Selected images of the buildings: 2) General information (e.g. title, address, place, region, coordinates, etc.); 3) Form and use of the building (e.g. type of use, category, classification, number of floors, context, allotment, building genesis, etc.); 4) Vaults (e.g. type(s), quantity, construction and decorative elements, materials, constructive techniques, interior and exterior coatings, etc.); 5) Access to buildings (type of property and access); and 6) Digital architectural drawings linked to the 'Drawn Elements' set.

The Resource Model used in this Items Set is composed of 35 terms (around half of which are mandatory), mainly from a Customised Ontology, VSEC (*Vaulted South Elementos construídos*) (*.vsec), purposely created for the project, as there was no metadata standard vocabularies suitable for the characteristics of the item.

As the Vaulted South Omeka-S database has the dual function of storing and visualising data, some of the terms attached to items were left public and others private, according to their role in research. This can mean, for instance, that some data are only stored for management and processing, such as that data used for statistical analysis or for preparing routes **[Fig. 2 centre]**.

Creating digital vaulted territories

At the core of the Vaulted South Project is the aim of transforming analogue data of knowledge about vaults into digital formats so as to enable scientific comparison between case studies and their future re-use in other research contexts. These contents were named 'Digital Vaulted Territories' to reflect the diverse and interconnected knowledge of vaults anchored in the digital domain. The digitalisation of textual elements concerning vaults – via transcribing passages from digitised documents – to a metadata standard vocabulary Resource Model, integrated into the 'Written Elements' section, was already approached in section 3. Thus, the vaults and the vaulted buildings surveyed and registered in 'Built Elements' were subjected to various digitalisation processes.

Regarding the territorial scale, coordinates data in the 'Built Elements' section were used to generate a map with the buildings geo-referenced. This composite map

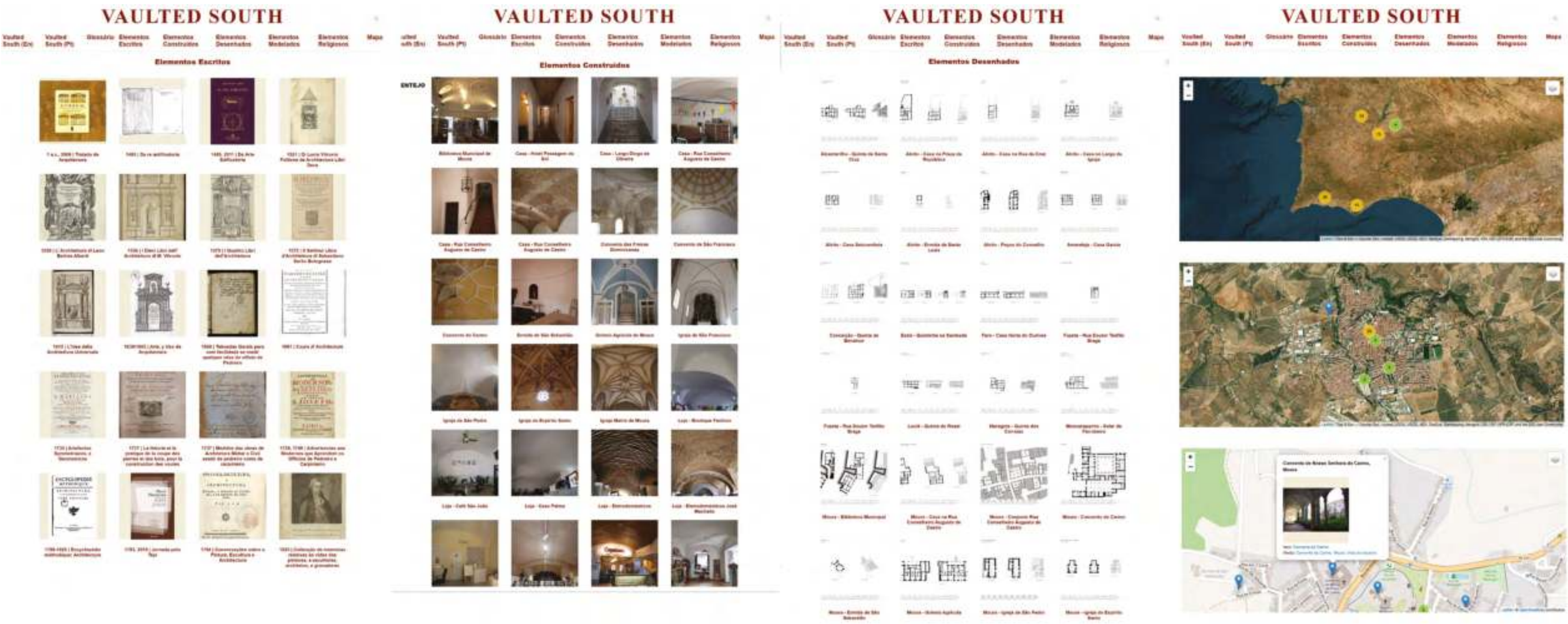


Fig. 2 Item Sets at the Vaulted South platform powered by Omeka-S: Written Elements; Built Elements; Drawn Elements; and Maps (from left to right). Source: Vaulted South Project 2024.

was added to the navigation bar of the webpage to provide a simple visualisation of the locations of the 'buildings' items in south Portugal. Although the Omeka-S does enable map visualisation through the 'Mapping Module', the map generated does not allow data manipulation for run analysis. To address this constraint, the database was exported to *.csv format and imported into Geographic Information System (GIS) software to generate virtual routes.

Creating digitally generated routes

The use of GIS tools to define virtual routes with the goal of promoting architectural knowledge has been explored by Finno et al. (2022), namely by suggesting a methodological workflow based on themed virtual tours of 360° scenes, integrating a variety of informative contents and digital products as external hotspots/switches. GIS maps should be designed for easy access online through websites and smartphone apps, allowing for their customisation and adaptation to various audiences. These maps can offer an immersive experience that engages both virtual and physical visitors, fostering universal access to knowledge and cultural heritage (Volzone et al. 2022). On the other hand, Fauzi et al. (2022) highlight the importance of Web-GIS routes in combatting over-crowding at tourist attractions. Indeed, in the

Fig. 3 Generation of optimised route in GIS environment for vaulted buildings in Moura, Alentejo. Source: authors, 2024.

scope of a public presentation of the Vaulted South Project in the European Heritage Days 2023[5] in Moura, it was understood that thematic routes could be particularly efficient in promoting and disseminating built heritage knowledge.

The automatic route generation for determining the most efficient path was made using the ESRI ArcGIS PRO Network Analyst module, considering the Dijkstra algorithm and the Euclidean distance as a cost function. For the city of Moura, four pilot optimised routes were generated, starting at the Moura City Council building [Fig. 3]:

1. The Moura Vaults Route, including the surveyed buildings in the town of Moura, covering a total distance of 3,260 km with 35 stops and informative bullet points about the buildings' uses;
2. The Religious Vaults Route, comprehending a tour across the religious buildings in Moura, such as churches, chapels and convents, at a total distance of 2,503 km with 8 stops;

[5] This public presentation at Moura European Heritage Days 2023, entitled 'The vaulted Alentejo', is available in Talking with Vault Builders, in documentary format.

3. The Vault Typologies Route, to discover the variety of vaulting types and geometries by visiting buildings with more than three different types of vaults, along 2,254 km with 8 stops;
4. The Most-Vaulted Buildings Route, featuring a short visit to three buildings with more than 10 vaults, with a distance of 1,450 km.

Creating 2D digital vaulted elements

Different scales and complexity levels of digitalisation were addressed according to the objectives, from the scale of urban blocks to the geometry of vaults. From the buildings surveyed and made available in 'Built Elements', digitally scaled architectural plans were elaborated for an urban block in the historical centre of Moura, comprising 18 buildings located on the same street, and 40 individual buildings located in 15 other towns. The process of representing the drawings was an effort to record, standardise, analyse and communicate the built vault heritage. A template layout for the drawings webpage was developed with symbols for the types of vaults, room uses, the representation of scales and building orientations to enable the categorisation of building and vaults. The drawings were digitally elaborated using Autocad 2D, a Computer-Aided Design program from Autodesk, and curated as items in the Omeka-S database in a set designated 'Drawn Elements', in line with 'Written Elements' and 'Built Elements', which were linked to the drawing plans. The Drawn Elements set reflects the need to compare different types of built vaults, construction systems and uses in a standardised way to enable research into regional trends, exceptions and similarities between erudite and popular examples.

Creating 3D digital vaulted elements

While it is well known that the digitalisation of objects, particularly buildings, is a complex task that requires considerable amounts of time and human and monetary resources, the practice does enable scientific comparison between objects and their re-use in other contexts (Drucker 2011). In this sense, two buildings particularly relevant for the study of vaults were chosen for complete three-dimensional study using Terrestrial Laser Scanning (TLS) for the acquisition of point clouds, a discrete set of data points in space positioned according to their coordinates (X, Y, Z) and later imported to be converted into a 3D model in a Building Information Model (BIM) environment using the Autodesk Revit 2024 software.

Bagnolo and Argiolas (2021) describe in detail the Scan-to-BIM workflow used to generate the vaulted system of the main body of the church of Nostra Signora della Speranza in Cagliari, Italy, emphasising the critical role of employing a TLS (Terrestrial Laser Scanning) system to guarantee precision in the structure's geometric representation. In Portugal, Trovatelli et al. (2023) proposed a parametric approach to model a lunette vault and evaluate its structural behaviour in a chamber in the National Palace of Sintra.

The Quinta de São Brás house and the Ficalho Palace, located in Serpa, were the chosen case studies for 3D modelling due to their complexity and richness of vaults and building techniques. Quinta de São Brás[6] is a rural recreational home located five kilometres south-southwest of Serpa and built after the Great Earthquake of 1755 in around 1761, the date inscribed on the iron gate of the entrance (Costa 2024). The single-floor house sits atop the sloped property and features vaulted rooms with plaster finish of different geometries, building techniques and construction periods. Access to the extrados of the vaults through the attic was relevant to the 3D modelling, as it allowed for a complete scan of the vaults, including their thickness, a fundamental feature for assessing the building process and transformations over time. Access to the vault extrados was also possible in the case of the Ficalho Palace, justifying its 3D modelling.

The Ficalho Palace[7] is an aristocratic residence dating from the second half of the 17th century and was built into the medieval wall that surrounds the historic centre of Serpa. During the 20th century, the Marquesses of Ficalho carried out restoration and rehabilitation works between 1946 and 1973. The palace is composed of two floors. Except for the entrance hall, with the stairs covered by a wooden roof, all rooms are vaulted with plaster finishing, with the ground floor having a lower ceiling and older vaults, insofar as it was constructed before the rest. In this building, different construction phases are connected to different vault geometries and building techniques. Complete 3D data acquisition of the intrados and extrados of the vaults provided insight on the variation in thickness of the materials, allowing the accuracy of the geometry and the building processes to be assessed and compared with the São Brás house.

The 3D models of the Quinta de São Brás house and the Ficalho Palace were based on a point cloud acquired through Terrestrial Laser Scanning (TLS) Faro Focus S70, with a total of 15 scans of the house and 25 of the palace, corresponding to two scans per room, merged into a single point cloud for each case study, with the support of flat paper targets placed on vertical walls **[Figs. 4 and 5]**. The Quinta de São Brás house and Ficalho Palace were 3D-modelled using Autodesk Revit 2024 software, based on the point clouds obtained from TLS. A total of 28 compartments were modelled for the house and 60 for the palace. To model the

[6] See the entry for Quinta de São Brás house on the Vaulted South Platform.

[7] See the entry for Ficalho Palace on the Vaulted South Platform.

Fig. 4 3D models of the Quinta de São Brás house in Serpa: Point clouds with TLS (left) and compatibilisation of point clouds with BIM model (centre and right). Source: Folgado 2024,34, 44.

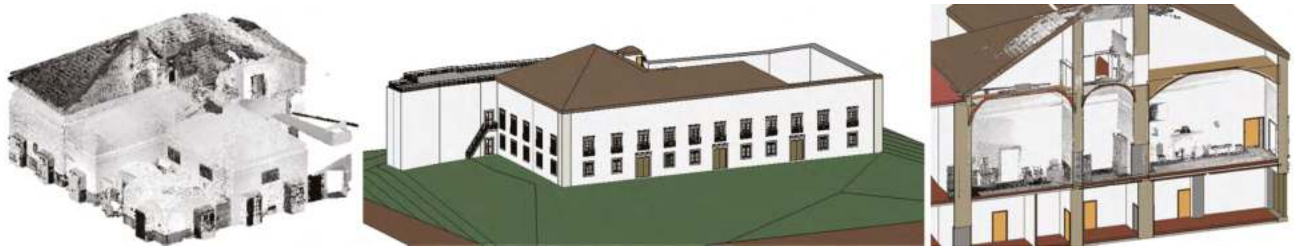


Fig. 5 3D models of the Ficalho Palace in Serpa: Point clouds with TLS (left) and compatibilization of point clouds with BIM model (centre and right). Source: Folgado 2024, 34, 48.

buildings, the various elements were divided into main and secondary elements, respectively: vaults, interior and exterior walls, floors, slabs, roof and pillars; and windows, doors, beams, railings, gates, and stairs.

In the absence of an existing BIM library for different geometries of vaults in a parameterised 3D format, one was purposely created and applied to 23 vaults in the 3D model of Quinta de São Brás house and 30 vaults in Ficalho Palace, in a process described further ahead. This BIM library is now available for public use in the '3D Elements' section of the Vaulted South webpage.

A BIM library of 3D parameterised format for different types of vaults was created to respond to a more suitable scale concerning the vaults: the analogue elements of vault geometry were digitalised through a procedure involving the parameterisation of the vaults' geometrical construction, from the trace of the arches to the generation of the volumetry of the vaults, digitally replicating the manual procedures learned from the books inscribed in 'Written Elements'. The parameterised modelling of vaults, done in Autodesk Revit 2024, created an unreleased BIM library of six vaults (barrel, sail, groin, ribs, domical and dome) and their variation according to the 3 types of arches (perfect round, elliptic, and three-centres). Each vault has four layers, the first of which is plaster, followed by the structural material, in this case brick, then mortar, and finally the filling. Vaults have different parameters according to geometry, namely the thickness of the interior plaster, the thickness of the structural material and the mortar, the height of the filling, the span, rise, length, and thickness of the ribs section [Fig. 6].

This BIM library allows users to change the parameter values according to their needs, as was done for conducting the comparison between the parametric model and the point cloud acquired. The items corresponding to the 3D digital vaults

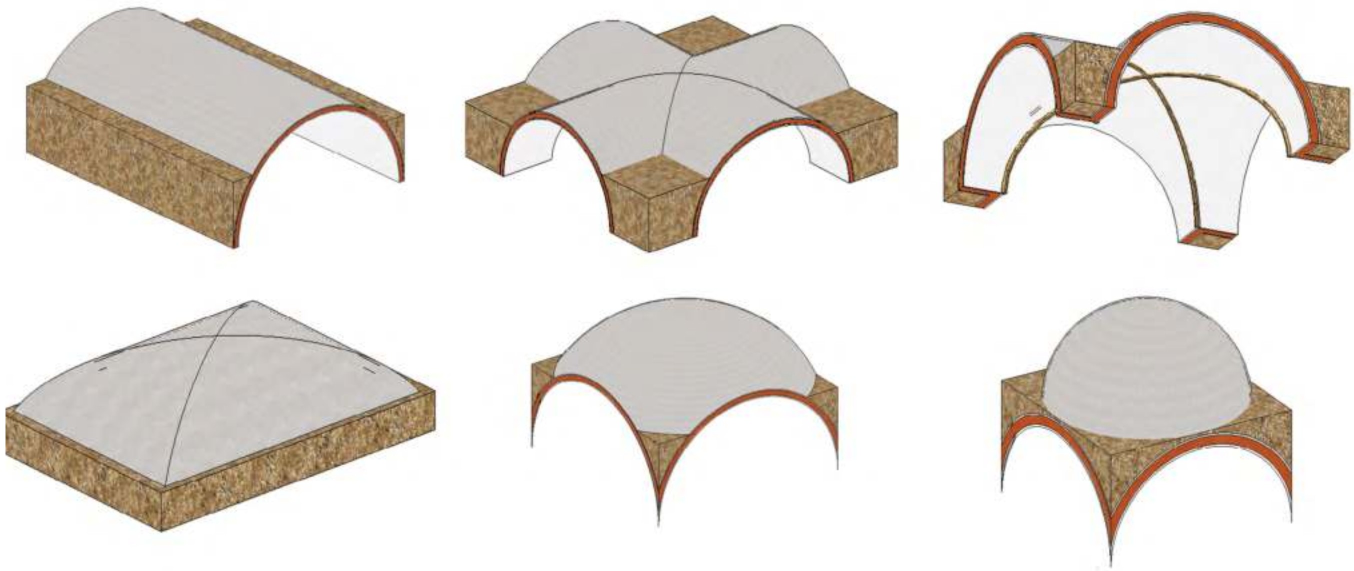


Fig. 6 3D library of parametric vaults modelled in Autodesk Revit 2024. Source: authors, 2024.

were curated at the '3D Elements' set at Omeka-S database, being linked to the 'Written' and 'Built Elements' through the 'Glossary' set.

The following procedure was adopted for modelling the remaining main elements: the slabs and floors were modelled on the boundaries created by the walls, while the pillars were modelled using the outer line and the beams were modelled using a structural beam system, delimiting their perimeter and the distance between beams. The roofs were modelled using their perimeter, with Quinta de São Brás house having a central gabled roof and pyramid hip roofs on the four corners and Ficalho Palace with two contiguous hipped roofs. As there was no BIM library corresponding doors and windows, one was created **[Fig. 4 and 5]**. Challenges have arisen when adapting BIM modelling approaches to masonry structures in ancient architectural constructions, such as arches, vaults, and domes (Ben Lashihar 2024). An automated iterative process within a scan-to-BIM methodology to support the final phase of the 3D parametric/adaptive reconstruction when applied to masonry vaulted systems was tested by Buldo et al. (2023).

Creating digital coefficients of vaults' building physics

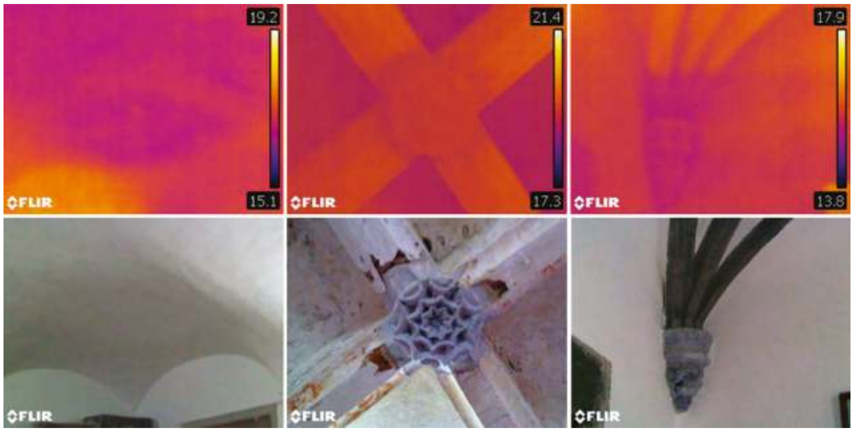
Hitherto, the study of vaults has been approached based on vault volumetry and considering geometry and tectonics, in disregard of construction materials and systems. Nevertheless, building materials have a decisive influence on constructive systems, as the sources in 'Written Elements' make clear. Two constructive procedures for brick vaults in the vernacular context of southern Portugal can be adopted, depending on the way bricks are placed side by side: either with the 'stretcher' or 'bed' face showing. In most cases, assessing the system employed is hard, even impossible, due to the plaster in the intrados surface (commonly limewashed) and to the capping and filling in the extrados with clay and lime mortar.

A non-destructive prospection technique (NDT) consisting of the capture of thermograms with the use of a thermographic camera to record heat transmission in the materials, helps assess the constructive features, simultaneously recording the different temperatures on the surface, which is crucial for determining the thermal behaviour of buildings. Infrared Thermography (IRT) makes it possible to identify constructive elements, irregularities and heterogeneity by measuring the infrared radiation emitted by different materials (brick, stone and mortar) (Gomes and Tomé 2023, Barreira and Freitas 2007), by following several standards (ASTM 2003, BSI 1999). To maximize the difference between materials, this should preferably be done during the afternoon in indirect sunlight, after the materials have absorbed solar radiation.

Indeed, all bodies emit thermal radiation at a temperature higher than 0 K, and the emitted thermal radiation will be greater for higher surface temperatures, which depends on each material's thermophysical properties. Therefore, considering that there is variation in the thermophysical properties of different zones – such as defects or construction solution heterogeneities (e.g., zones where different materials or thicknesses exist in parallel, leading to thermal bridges) – variations in surface temperature will be easily detected by thermograms. This non-destructive technique has been successfully employed in vaults made of stone masonry (Chácara et al. 2023) and timber arches, reeds, and plaster (Quagliarini et al. 2013).

The thermographic approach was used to identify constructive solutions for vaults in the intrados of different types of buildings. Prospection was carried out in the interior of the rooms without contact or mechanical iteration with the surface **[Fig. 7]**. Through this procedure, thermograms clearly show the existence of internal reinforcements in the vaulted surface **[Fig. 7 left]** and the existence of different materials in the ribs (stone and brick) **[Fig. 7 centre and right]**, hidden by the plaster which could not be detected by only examining the vault surfaces. These findings led us to understand the process of vault construction concerning assemblage, materials used, and the role materials perform in the structural and filling dimensions. Moreover, the data obtained sheds light on the distribution of temperature on vault surfaces, emphasising differences between the start and closure segments of vaults.

Fig. 7 Thermograms (above) and matching photographs (below) of the thermographic non-destructive prospection campaign to detect different materials (brick and stone) in vaults in the Convent of São Francisco, Serpa. Source: authors, 2024.



Conclusions

In the historiography of Architectural History, research methods have been mostly supported by archival research and fieldwork surveys. The Vaulted South Project has approached architectural research using innovative methodologies from related disciplines. Transposing analogue data from written sources and building records to a digital format (texts, technical drawings, and 3D models) and completing these with digitally captured data (photographs, point clouds, and thermograms) and digitally created data (3D and parameterised models) stored in an online structured database has contributed to generating new knowledge on the constructive systems of vaults. Through interdisciplinary analysis of vaults as connectors of different element collections (Written, Built, Drawn and 3D collection), we have clarified how and where vaults were built, which processes and materials were used, whether in an erudite or popular context, and whether construction processes were in alignment with written records.

This article reveals the importance of using innovative methods to achieve and manage accurate data in a more economical, efficient and effective way that is also less intrusive. Thanks to the interoperability of the platform, it was possible to identify which constructive details were traced back to scholarly sources, and those which emerged from popular contexts. In articulating vernacular vaults and codified or theorised knowledge about construction techniques, means of knowledge transmission have been questioned.

By generating these 'digital vaulted territories', the platform contributes to assessing the features and geographical extension of vaulted buildings, and to disseminating this cultural knowledge in different scientific fields, as well as standing as a collection and tool for use in future studies.

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Abstract

In this paper, we propose a methodology for documentation and geometrical analysis of vaults that relies on laser scanning, geometric analysis, three-dimensional modelling, and 3D printing. The methodology was applied to the study of three types of vaults, two of them in brick and the other, the main vault of the Arco da Rua Augusta, in stone stereotomy. Starting from a planimetric layout a geometric analysis is carried out to infer the generative geometries. This is done by exploring the point cloud data and other related outputs, like drawings or meshes. A return to three-dimensionality was achieved through digital modelling and 3D printing. Returning to physicality allows a different type of interaction where some aspects of constructive systems, like assembly hypothesis, can be tested. The proposed methodology paves the way to recognize heritage significance from direct documentation which is fundamental to support conservation studies.

keywords

VERNACULAR ARCHITECTURE
BRICK VAULT
STEREOTOMY
DESCRIPTIVE GEOMETRY
LASER SCANNING
3D PRINTING
ARCHITECTURAL HERITAGE VALUES

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From the empirical making of Alentejo vaults
to the generative geometry of the Arco da Rua Augusta vault

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Introduction

The main purpose of this paper is to show that surveying methods like photogrammetry and laser scanning, while ensuring precision and quality of geometric data acquisition allow the development of rigorous and quantitative studies which pave the way for more informed interventions in heritage. To demonstrate this statement, we present a methodology to analyse, from a geometric point of view, the vault constructive element. The methodology includes the following steps: 1) laser scanning survey and mesh modelling, 2) geometric analysis and modelling, 3) analysis of deviations between the reality of the constructed fabric, given by the surveyed data, and the idealised geometric model, and 4) 3D printing.
To apply the methodology, we have chosen three situations of vault construction that pose different challenges due to its nature an erudition level. These range from a type of vault that is constructed mainly based in empirical rules in a context of vernacular architecture, to a stereotomic vault based in a very sophisticated design process. By applying the methodology to these different types of vaults we will be able to understand different levels of depth in the use of geometry as a conceptual tool to generate the built form.
The remaining of the paper is structured as follows. In the next two sections we do a short review of the literature and an introduction to the case studies. Then, the following three sections address the application of the analysis methodology

to each of the case studies. Finally, in the last section we discuss the results and present the conclusions.

A short review of the constructive element vault and related works

A vault is a construction solution for covering a span framed by supports that can be in the form of walls or columns. It generally has a curved shape and can be simple, consisting of a single surface, or composite, consisting of multiple surfaces that connect with each other (Rodrigues et al. 2002; Escudero et al. 2014). It features a visible surface, the intrados, and a generally invisible surface, the extrados. There are exceptions to this rule, for example, in the case of some domes, which are special cases of vaults where the extrados is a visible surface. It is a construction system that, like the arch, is based on the balance generated by compressive forces resulting from its own weight and any additional loads placed on the extrados, or others, such as the bells suspended in bell towers that help balance the vault that covers them. It is present in many types of architecture, both vernacular and erudite. It can be constructed with various materials such as earth, brick masonry, and stone, and its design can be based on empirical rules, refined over years of practice and tradition, as is the case with medieval and Gothic vaults, traditional Alentejo vaults, or some types of brick vaults commonly seen in civil architecture, or it may involve a prior design, drafted, which became more common starting from the Renaissance, particularly in stone stereotomies (González 2006; Calvo-López 2020).

Stone stereotomy is the study of cutting this material for construction purposes, namely for arches, domes and vaults, primarily with a structural purpose, based on geometric rules. This construction tradition in Western Europe lasted until the end of the 19th century and tended to disappear in the beginning of the 20th century due to the use of reinforced concrete. This knowledge is preserved through architectural treatises like those of Derand (1643) or Frézier (1739), just to mention a few. On the other hand, it awaits discovery through the analysis of built structures, which are, in fact, the place placeholder of that knowledge. Recently, there have been several studies regarding stereotomy. They typically cover specific geometric types, periods, or regions (Callabria 2015; Calvo-López 2020; Delgado 2017; Díaz 1996, 2020; Genin et al. 2009; Genin 2014, 2020; Huerta 2007; Palacios 1990; Pérouse de Montclos 2001; Sakarovitch 1997; Shelby 1969). Montclos (2001) mainly studied the French case, with some forays into Spain, and briefly into Italy, Germany, and England. Regarding the Spanish case, Rabasa Díaz (2000) studied ribbed vaults from the Renaissance to the 19th century, and Palacios (1990) conducted research on the influence of Vandelvira's treatise, from 1585, on the Spanish Renaissance, where he reinterprets drawings and shows constructed examples.

The first reference to Portugal appears in Frézier's treatise, *La théorie et la pratique de coupe des pierres* (…) (1737-1739). In this work, the vaults of the Church of the Jerónimos Monastery in Belém are described as 'the most beautiful and well-executed of their kind' (Frezier 1739, vol. 3, 28). Genin (2014, 2020) and Delgado (2017), mentioned by Calvo-López (2020) and Calabria (2015), investigated the stereotomy of the 16th century. Sousa (1988) studied some examples of skew arches in tunnels and bridges in the Lisbon region. Regarding the period between the 18th century and the end of the 19th century in Portugal, there are no systematic studies. Exemplars that deserve study from the perspective of stone stereotomy include the National Palace of Mafra, the Estrela Basilica, the Church of Memory, the Galo Tower, and the Arco da Rua Augusta, all located in the Lisbon region or its vicinity.

To perform a geometric study on this, or other, historic constructive element, one must rely on a survey. The surveys can be done using a wide variety of methods and tools. These can include direct measurements, topographic surveying, photogrammetry and laser scanning. In the context of this paper, we are particularly interested in demonstrating that laser scanning as a data collection tool provides a very useful support for precise quantitative studies. The works from Genin (2009, 2014, 2020) relied on photogrammetry as the documentation method. Mateus et al. (2012) and Calabria (2015) mention the use of laser scanning as the primary method for data acquisition. Many studies report on the use of laser scanning and/or photogrammetry as the primary methods for data acquisition to support geometrical analysis of built fabric.

The motivation for such studies is varied. Banfi (2019) and Stanga et al. (2019) describe methodologies for vault modelling in the context of BIM that include in situ observation, point cloud survey, and modelling. However, the focus is placed in fitting NURBS primitives to point cloud data, to get the smaller possible deviations, rather that understanding the geometric nature of the geometries involved. Other studies are more focused on understanding and interpreting the geometric nature of the constructive elements. Capone et al. (2019), Spallone et al. (2019) and Vitali et al. (2021) developed studies about vaulted systems based on archival drawings, treatises and photogrammetric and laser scanning surveys. Scandurra et al. (2018) discuss the geometrical nature of the dome of the church of San Carlo all'Arena in Naples based in a laser scanning and photogrammetric survey. Essentially the authors experimented between oval and elliptic solutions for the planimetric shape of the dome and then used a three-axis ellipsoid as basis for the 3D model. The end purpose was to generate a BIM model of the church. In the process a reference to Serlio treatise is made, which highlights the possible importance of historical data. López González et al. (2023) present a study about the Valencia Cathedral in which, after a laser scanning is carried out, a planimetric and sectional analysis is carried out. An interesting aspect of this analysis is to consider the ancient units of measurement. By doing so, the system of proportions becomes much more apparent.

Another category of studies, like the ones developed by Agustín-Hernández et al. (2021) and López González et al. (2020) consider and underline the role of point clouds as the primary data for the geometrical interpretation and analysis. In this line, Lanzara et al. (2019) define a workflow aiming reliable reconstruction hypothesis of vaulted systems including point cloud survey, geometric modelling, considering both ideal models and models mathematically fit to the surveyed data, and comparison between the models and the survey data. Rinaudo et al. (2023) present a methodology for the interpretation of point clouds through the geometric study of key sections, leading to imposition of some theoretical models to the surveyed the data. Then these models are compared with the survey in terms of distances. The methodology includes the production of haptic models via laser cutting and 3D printing. An interesting aspect of this study is to consider geometry as a value qualifying intangible heritage. Finally, Attenni et al. (2023) present a methodology to analyse vaulted systems very similar to the one we present in this paper except for the 3D printing. They consider the following steps: analysis of planimetric configurations, analysis of the geometric components, 3D modelling on an ideal shape, evaluation of the deviations between the ideal shape and the 3D point cloud data, unfolding conic surfaces for the purpose of high quality ortho generation.

In some sense, the methodology that we propose can be viewed as a synthesis of the above presented approaches in what concerns the use of point clouds as the primary source of data for the geometrical interpretation and analysis of the vault constructive system, and as a benchmark for the qualitative and quantitative evaluation of those interpretations. The core of the methodology, corresponding to its second phase, is related to geometric analysis and modelling, and includes a few key steps that need to be highlighted in advance for the sake of clarity of reading: a) definition of the planimetric bounding geometry, b) sectioning the point clouds through key plans to extract the main profiles, c) analysis of those profiles in terms of geometric configuration, d) in the more complex cases, elaborating on the geometric nature of the geometric elements present, e) developing an idealized 3D model to be compared with the point cloud data.

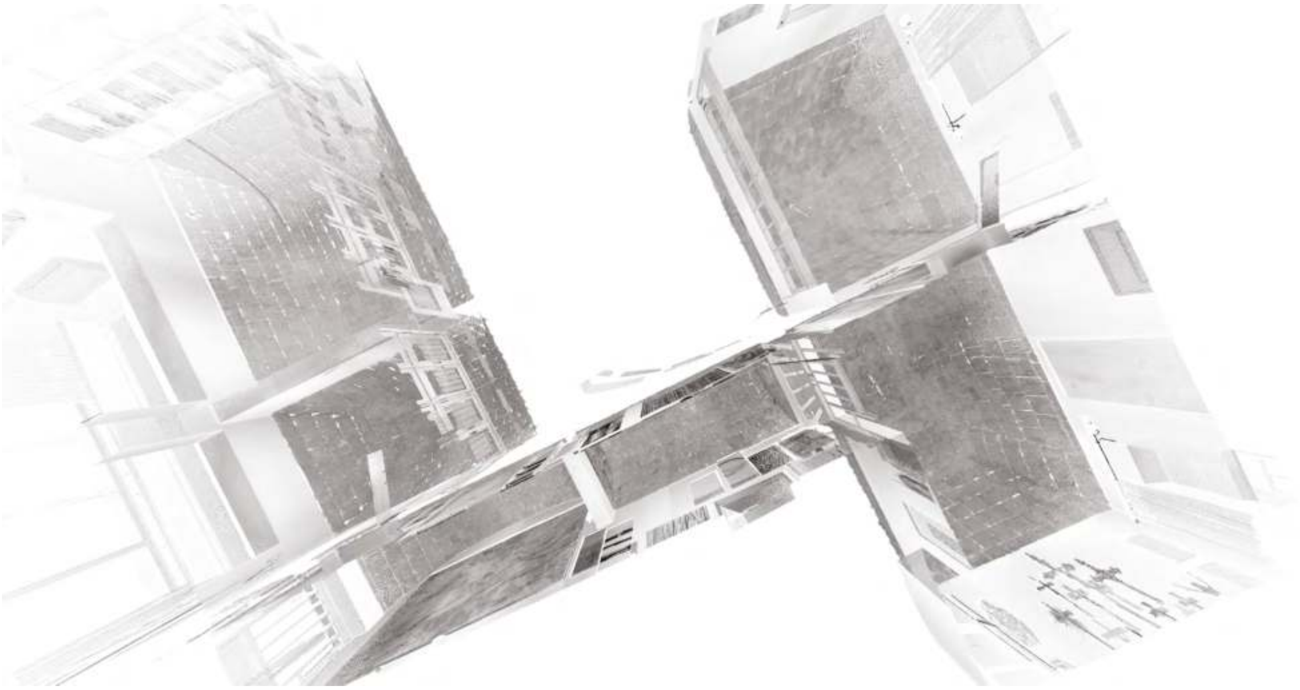


Fig. 1 Point cloud data: Inferior view of the vaults covering the spaces of a vernacular house in Alentejo. Source: author, 2024.

The case studies

To apply the methodology, we have chosen three situations of vault construction: 1) one vault of vernacular architecture in Alentejo, 2) one vault of the house of Valflores, from 16th century, in Loures, and 3) the main vault of the Arco da Rua Augusta, in Lisbon. The purpose is not to provide a historical or typological study of vaults but rather to establish a possible path for the analysis of that type of constructive element which, in turn, can bring some light on its heritage value. The reason to choose these examples is because they represent diverse approaches to conception and construction, where it is expected different levels of sophistication in the use of geometry as generative principle.

A vault from a vernacular house in Alentejo

Alentejo traditional brick vaults are a constructive system commonly used to cover the spaces of a vernacular house [Fig. 1]. They are built without any type of support and there is no prior drawn plan for their execution. Bricks are laid out one after the other, in rows, and the progress of the construction relies on empirical

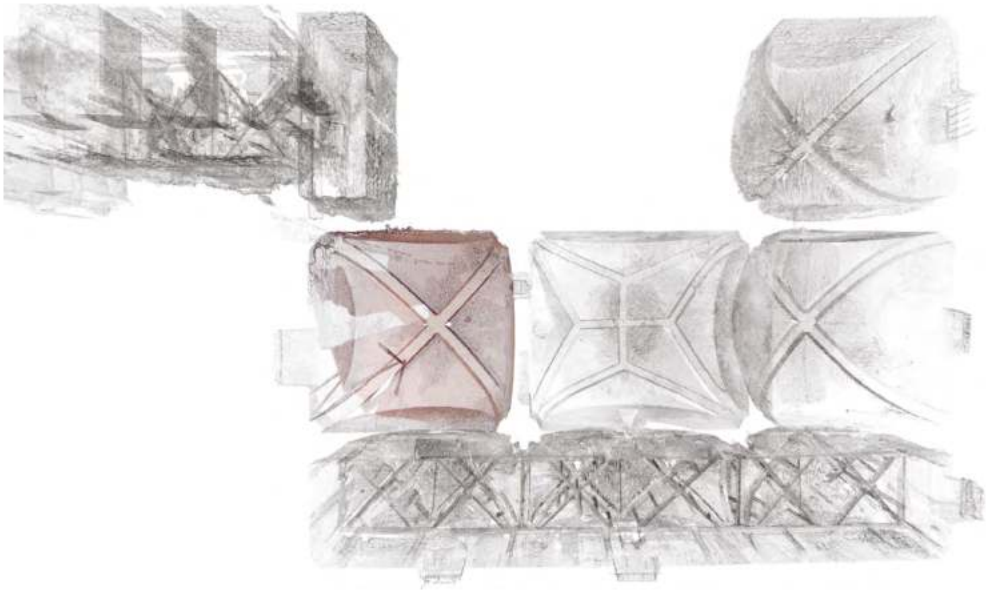


Fig. 2 Point cloud data: inferior view of the vaults covering the lower spaces of the house of Valflores. Source: author, 2024.

geometry and drying time of the mortars used. Usually, the thickness of the vault is the same as the smallest length of the bricks used, around three or four centimetres. For the application of our documentary and analytic methodology, we selected one of such vaults, commonly known as cloister vault.

A 16th century brick vault in a renaissance building in Loures

Other than the brick vaults present in vernacular architecture, one can also find this type of constructive system in more erudite buildings. The other example that we bring to our study is a vault found in the house of Valflores, a 16th century exemplar of civil architecture from renaissance in Portugal, located in Loures nearby Lisbon. This house was built by Jorge de Barros, the representative of the Portuguese king in Flanders, and one of the richest men in Portugal (Mateus 2020). In this case, the vaults are the constructive system that enables the construction of the main floor of the house [Fig. 2]. They cover the ground rooms used as warehouse. Unlike the previous type of vaults, these have a bigger thickness that corresponds to the second largest dimension of the brick, around 12cm, not considering the loads on the extrados. And they are built using brick arches as support. The data used came from the surveys done in 2016 in the context of the preparation of basis for the restoration works.

The main vault of Arco da Rua Augusta

After the earthquake of 1755, the reconstruction plan for the lower city included the construction of a large square framed by a triumphal arch aligned with Rua Augusta. The construction unfolded in two phases. In the first phase, following the building of the structures flanking the Praça do Comércio to the north, the structure was erected up to the cornice. Then, the completion was waited for several years, finally finishing in the 1870s. The complete structure is a true showroom of solutions of stone stereotomy. The constructed project is authored by the architect Veríssimo José da Costa, and the decorative program is divided between Calmels, at the top of the arch, with sculptures representing Glory crowning Genius and Valor, and Vítor Bastos, with sculptures of Nuno Álvares Pereira, Viriato, Vasco da Gama, and the Marquis of Pombal (Silva 2012). Also by this author are the statues representing the rivers Tejo and Douro. Little is known about the project's author. He was appointed as a second-class artist associated with the Civil Architecture class at the Academy of Fine Arts in Lisbon,[1] is believed to have been connected to the foundation of the Association of Portuguese Civil Architects,[2] founded in 1863, and may have served as a second lieutenant in the Portuguese navy. Thus, he is a virtually unknown figure, but given what we are about to unveil, he deserves to be highlighted and studied.

The Arco da Rua Augusta **[Fig. 3]** embodies a hybrid program of Architecture and Sculpture. It is the element that marks, to the north, the symmetry of the Praça do Comércio and serves as a backdrop for the equestrian statue of the King D. José. This building, doubly pierced by the axis of Rua Augusta and the axis of the arcade of the buildings to the north of Praça do Comércio, presents itself as a triumphal arch. At the pedestrian level, its main vault is visible, above which is the clock room. This room, also vaulted, is below the terrace roof, from which one can contemplate the entire historic Lisbon. Access to the clock room is via a spiral staircase located in one of the four corners that support the structure.

Although is a relatively recent structure, just over a century and a half old, the whereabouts of the original project drawings are unknown. The only existing documentation prior to this study consisted of a set of survey drawings made in the 1960s, found in the archive of the former Direcção Geral dos Edifícios e Monumentos Nacionais [General Directorate of National Buildings and Monuments], and a topographical survey carried out by the municipality of Lisbon. These two records did not provide any detailed information about the stone cutting layout. Under the pretext of developing a conservation project for the facade surfaces of the buildings in Praça do Comércio, a 3D laser scanning survey of the Arco da Rua Augusta was done in 2010. In addition to creating the base documentation for the

[1] ANTT, Registo Geral de Mercês, Mercês de D. Maria II, Lv. 9, fol. 11.

[2] Museu Arqueológico do Carmo, website: https://museuarqueologicodocarmo.pt/historia.html, cons. 04.02.2015.

Fig. 3 Point cloud data: Inferior view of the main vault of Arco da Rua Augusta. Source: author, 2024.

restoration project developed by Atelier 15, led by architects Alexandre Alves Costa and Sérgio Fernández, it was possible to conduct an initial study of the generative geometry of the main vault (Mateus et al. 2012), which is now deepened through a simulation of what could be the stereotomy of that structure, inferred from the visible surfaces recorded in the survey.

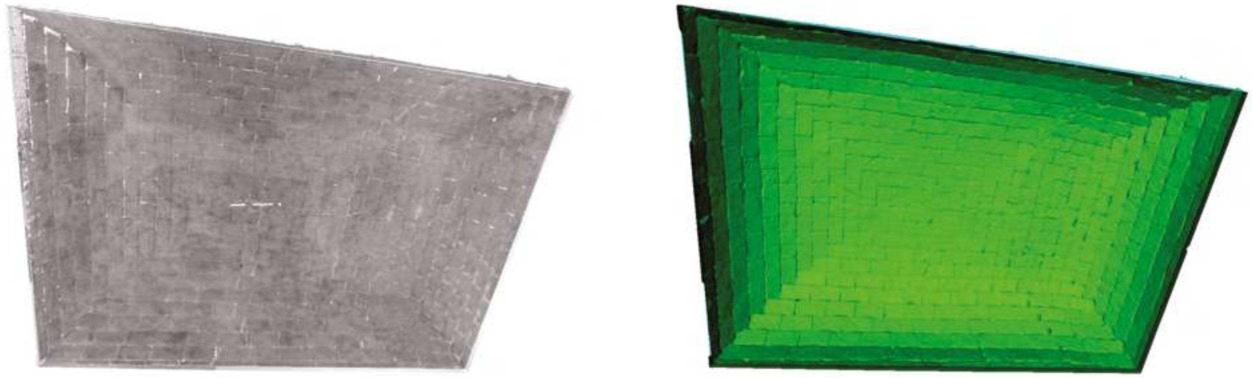
Recovering the geometry from empirical making

In this section it is presented the first case study about a vernacular brick vault.

Laser scanning survey and mesh modelling

Laser Scanning provides the raw data from which all kinds of geometrical analysis and modelling can be performed. In Fig. 4, in the left, we have an image of a point cloud, and in the right, we have its conversion to a triangulated model, commonly known as mesh.

Fig. 4 Left: point cloud. Right: mesh model.



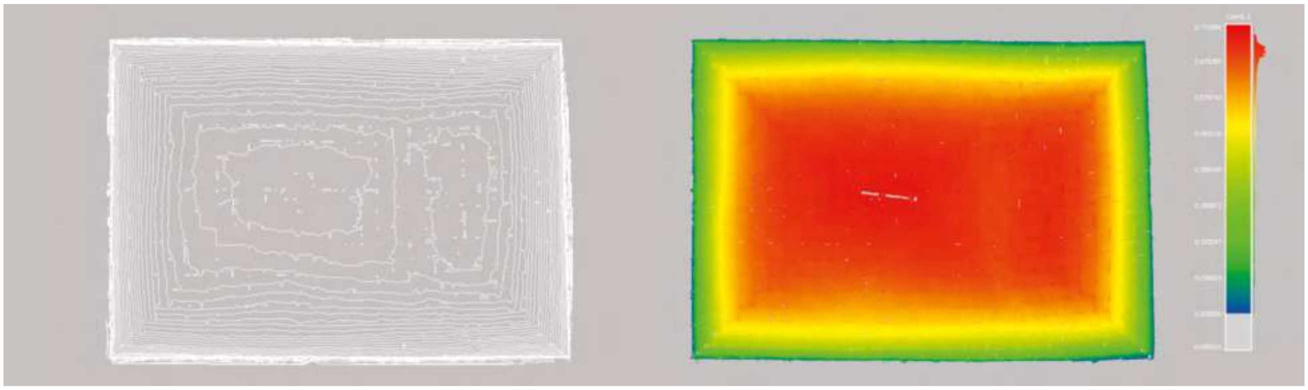


Fig. 5 Left: contours. Right: height map.
Source: author, 2024.

Both representations can be very detailed and can depict the deformations of the real objects with high precision and accuracy. They constitute the primary deliverables of a laser scanning survey. From a conservation and restoration perspective these are very important because they can document the actual state of the geometry and provide valuable information about the conservation and structural condition. So, whenever we want to extract data that represents the existing objects accurately, these types of models are the ones to be used. For example, in the images of **Fig. 5**, we can understand the deformation of the vault in two different ways. In the left side we can understand it by looking at the contours every 2.5cm, and in the right side the deformation becomes apparent when we associate each point with a colour that represents its height. These are two typical representations that we can use to show and quantify the deformation of an existing geometry.

Geometric analysis and modelling of the vault

Although the previous representations depict the actual geometry very accurately, one may be interested in understanding the geometry from a generative point of view. This means to understand what are the primitive geometric interpretations that we can associate with the built reality. Is this geometry based on rectangles, circular

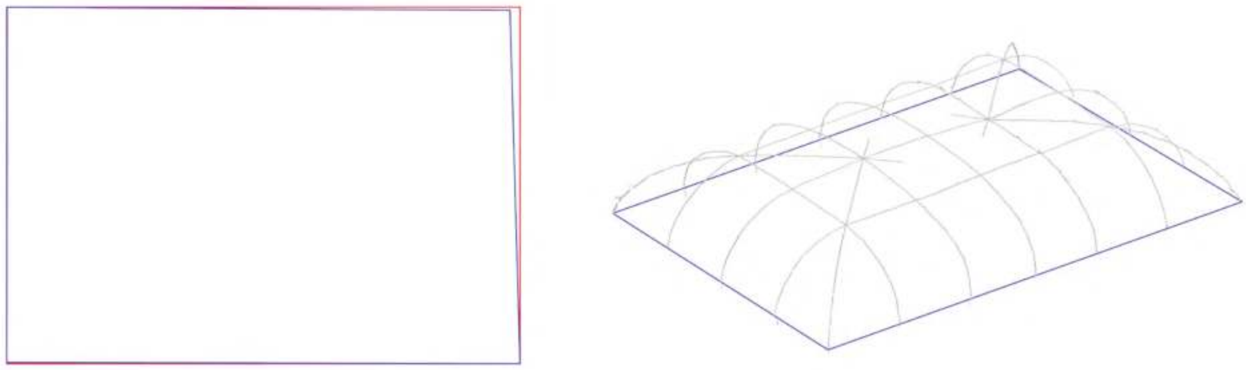


Fig. 6 Left: Difference between bounding rectangle and bounding quadrilateral. Right: Main sections extracted from the point cloud. Source: author, 2024.

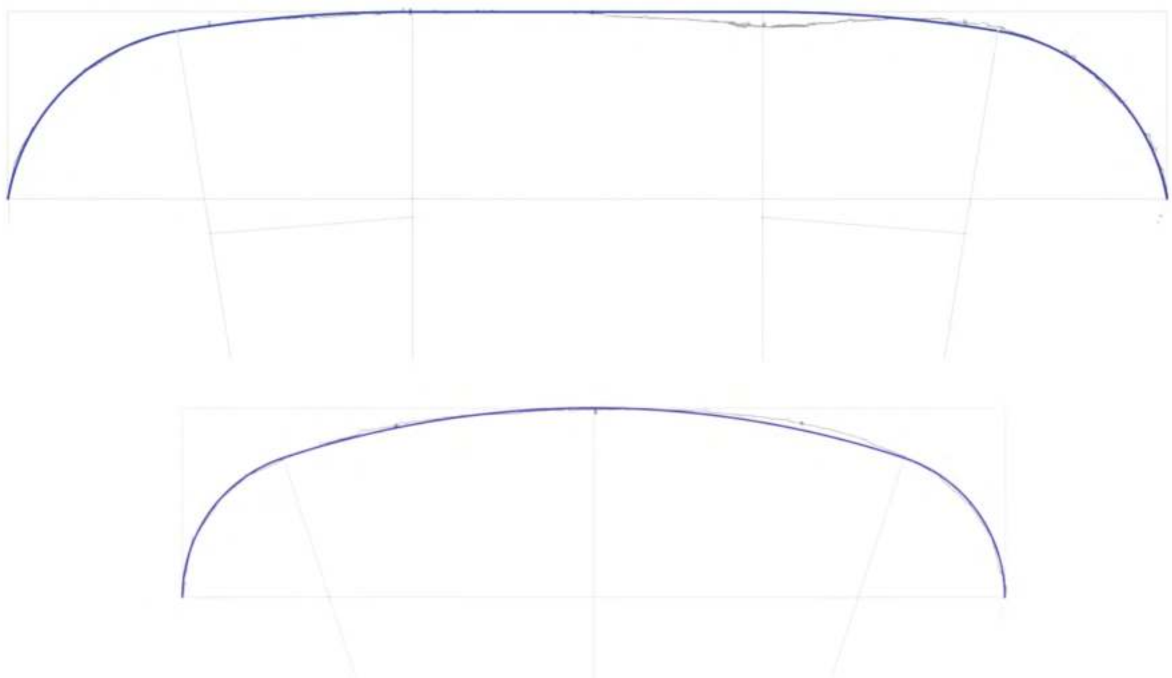


Fig. 7 Top: Longitudinal arc. Bottom: Transversal arc. Source: author, 2024.

Fig. 8 Final geometrical model.
Left: view from top. Right: view from bottom.
Source: author, 2024.

arcs, or in more complex geometries? The response to these questions usually arises with the need to model the geometry in the context of simplified representations as it can occur when developing other types of models. And it is a trade-off between considering a very idealized geometry and a geometry that fits the data up to a given threshold. For example, in this case, the most simplified geometric representation would be inscribed in rectangle, but that may not acceptable because such assumption may imply a significant deviation between the representation and the real data. This is always an issue when modelling historic constructions because they almost always present a lack of orthogonality. One approach can be to introduce small transformations to the idealized geometries to make the models fit better the existing data without introducing unnecessary complexity. In this example, in the left side of **Fig. 6**, we can appreciate the difference between a bounding rectangle (in red) and a bounding quadrilateral (in blue). The rectangle measures 4.66m x 3.24m and in the most discrepant point the difference between the rectangle and the quadrilateral reaches almost 10cm. Of course, neither the rectangle nor the quadrilateral represent exactly the bounding geometry of the vault but the second is a better approximation and does not introduce much complexity. Therefore it was adopted in this case.

Then, starting with the quadrilateral we can extract a set of key sections to be used to understand the generative geometry of the vault **[Fig. 6, right]**. Now, we need to check what is the simplest geometry that can represent those sections, and we need to decide the level to which it should fit the existing data. In **Fig. 7** we present representations for the longitudinal section of the vault (top) and transversal section of the vault.

We observe that, for each half arc, excluding deformations, the geometry can be captured using two tangent circular arcs. In the transversal section it was assumed a symmetry. It would also be reasonable to search for a better approximation to the right side of the arc. The same exercise can be done for the other sections shown in **Fig. 6**.

From these geometrized sections we can obtain a simplified, yet precise, model of the vault visible surface **[Fig. 8]**.

Deviations between the surveyed data and the idealised geometric model

One way to verify the level of compliance of the geometric model with the surveyed data is to measure the distances between both. In this case these differences will reflect both the geometrical simplification introduced and the fact that some deformations were not considered **[Fig. 9]**.

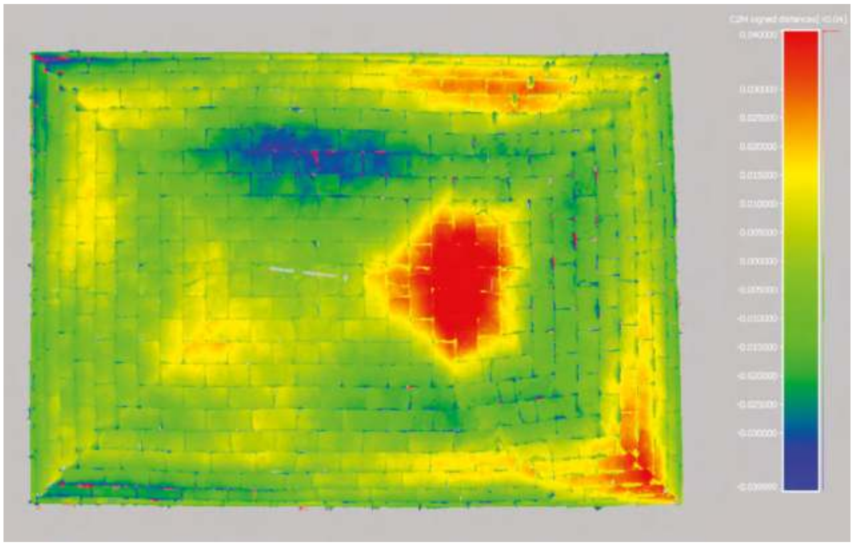


Fig. 9 Distance analysis between the modelled surface and the surveyed point cloud.
Source: author, 2024.

In **Table 1** we can see that, despite the modelled surface did not consider the structural deformations of the vault, about 50% of the points in the point cloud are within a range of 1cm to the model. This means that the approximation to this representation suits most of architectural representation purposes. On the other hand, the analysis performed makes the structural deformation of the vault very evident and quantifiable.

Point cloud	Number of points	Percentage of points
Vault base point cloud	5.280.730	100%
Segmented point cloud (± 1.5 cm)	3.824.232	72%
Segmented point cloud (± 1.0 cm)	2.803.029	53%
Segmented point cloud (± 0.5 cm)	1.510.896	29%

Table 1. Distance analysis between the geometrical model and surveyed point cloud.

3D printing as way to present a constructive detail

Finally, in this example, 3D printing was used to put in evidence some features of the constructive system that are lost in the above simplified representations. In **Fig. 10 (right)** we can see that the rows of the bricks do not align in the edge of

Fig. 10 Left: 3D printing of the vault.
Right: 3D printing of a detail.
Source: author, 2024.

the vault. This type of model can have a pedagogical role in the field of construction history. It can be used to teach about how the bricks are placed in the construction phase to ensure an equilibrium of the structure. The haptic nature of 3D printed models makes them richer tool in explaining certain geometrical configurations than drawings. For example, in this case, the way the two reference surfaces meet in the corners, without a defined curved edge, would be very difficult to convey and understand through drawings. On the other hand, the model, although being a compact one, perfectly allows one to understand how much each row of bricks must be displaced aside to enable the variation of slope for the orthogonal row.

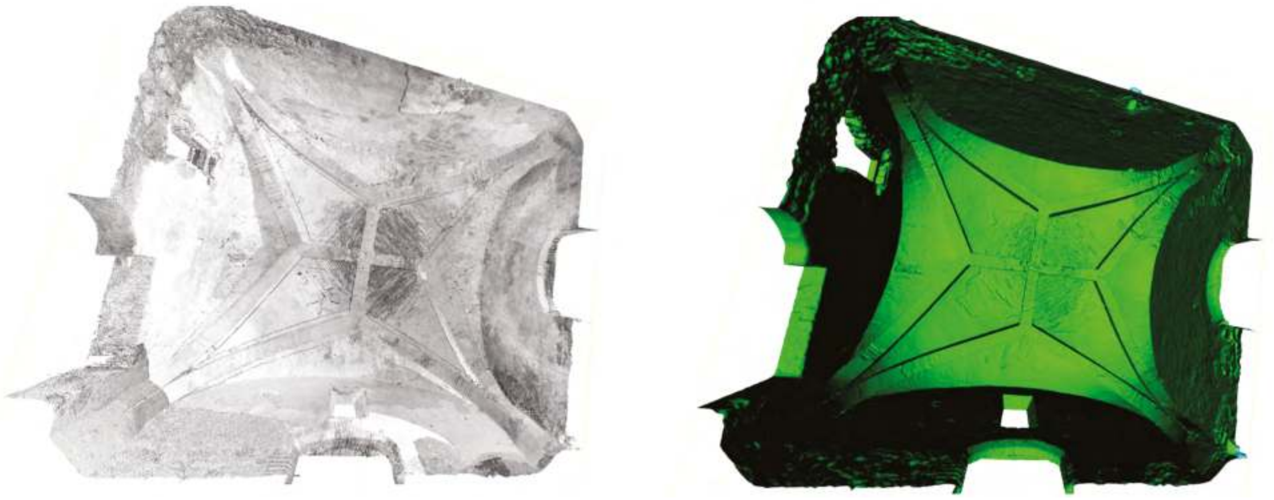
Brick vaults in a 16th century building

In this section, the second case study is presented.

Laser scanning survey and mesh modelling

Like in the previous example, the point cloud and its corresponding mesh provide a detailed description of the visible surfaces of the vault. In this case, the state of conservation of the structure becomes apparent as we can observe the lack of coating mortars, particularly in the centre of the vault. [Fig. 11]
At the naked eye, this vault appears to be perfectly symmetric. However, if we segment the height map as we can see in Fig. 12, then we can perceive that there is no perfect symmetry.

Fig. 11 Left: point cloud. Right: mesh model.



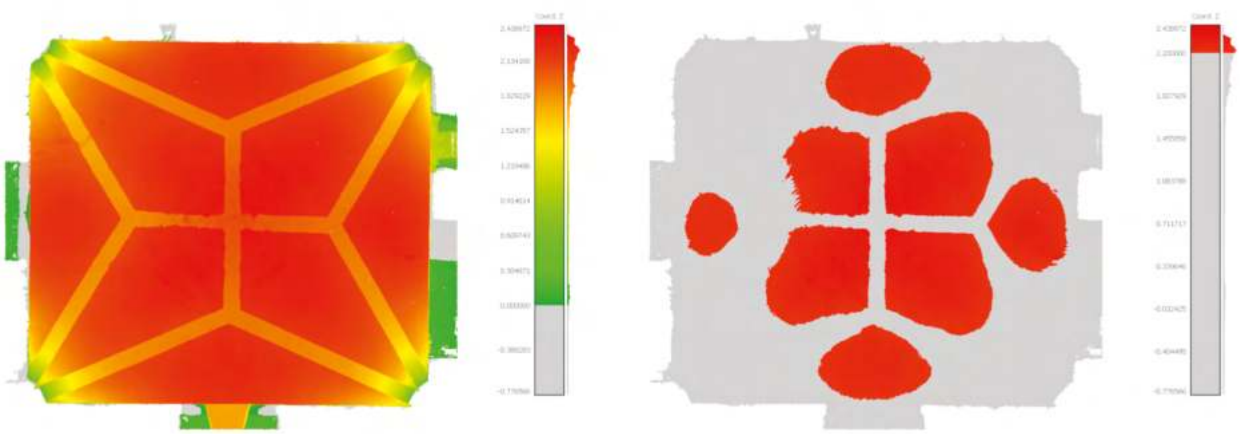


Fig. 12 Left: height map. Right: upper part of the height map. Source: author, 2024.

Geometric analysis and modelling of the vault

Like in the previous example, we propose that the geometric analysis starts with extracting the polygon corresponding to the room where the vault is located. If the polygon is similar to a rectangle within a few centimetres, one can consider the rectangle as good representation of the room, otherwise, the polygon configuration should prevail. There is no universal rule to justify this decision. What should be considered is the purpose for which the analysis is being conducted. From a modelling point of view, both options should be possible. What we mean is that a simpler representation should not be justified just because there is a limitation of the modelling tool. In our example, although the symmetry of the vault is not perfect, the room can be well represented by a rectangle with 6.18m x 5.56m.

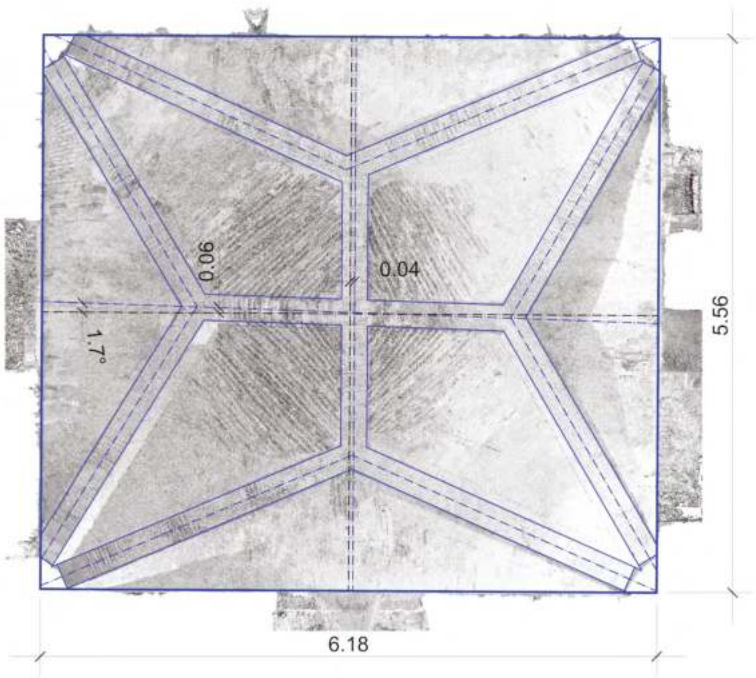


Fig. 13 Room axes (in black) and ribs axes (in blue). Source: author, 2024.

The deviations from this geometry are due to the irregularities of the walls and do not exceed 3cm. Although the room can be considered symmetrical, the main ribs axes (blue) have some deviations from the room axes (black), both in location as in orientation, as it can be seen in Fig. 13.

Again, one should ask if it is admissible to model the vault fitting the room as if it was symmetrical or should consider these deviations. As previously mentioned, there is no universal rule to make this choice. Our option was to consider these deviations. However, we opted to model the surfaces of the ribs as if there was not any lack of coating mortars. The next step in the modelling process is to see what geometry best represents the arcs of the ribs. To do so, we sectioned the point cloud through vertical planes containing the axes. Then we fitted primitive geometries. This was a progressive process. This means that, within the desired level of approximation, if a simpler geometry can be used, that should be preferred to a more complex one. For example, if possible, a circular arc is preferable to an elliptical arc. The exception to this rule exists if we have reasons to believe that, from a conceptual and generative point of view, the more complicated geometry represents better the existing configuration. If we conclude that there is enough repetition or that all geometry is from the same family, we can use parametric modelling to facilitate the process. The two central arcs can be correctly represented

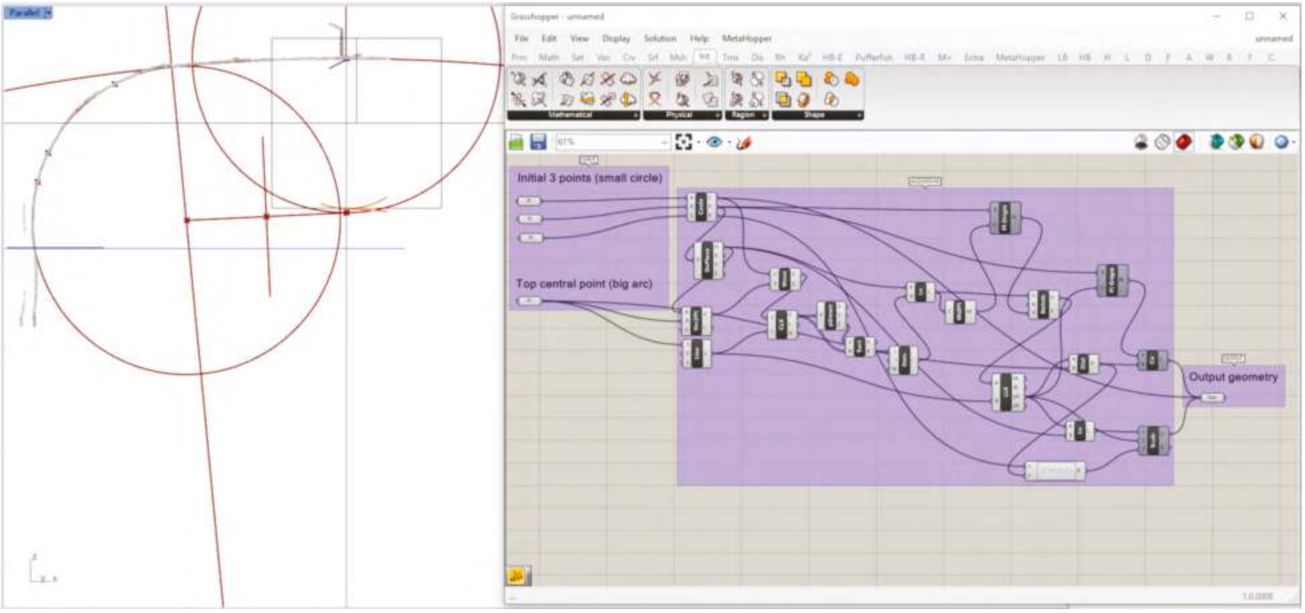


Fig. 14 Parametric model of the corner ribs arcs. Source: author, 2024.

by circular arcs. The other eight arcs that start in the corners of the room can be correctly represented by two circular tangent arcs. For these we used parametric modelling [Fig. 14].

The advantage of parametric modelling is the possibility of repetition within the family of geometries to be modelled. Small changes in the input parameters become easily reflected in the output models. And that comes with considerable savings in modelling time.

Deviations between the surveyed data and the idealised geometric model

Since we modelled the ribs and the spans of the vault as if there was not any lack of coating mortars, the deviations obtained with this analysis reflect more the quantity of missing mortars than the geometric quality of the model. In Fig. 15 that effect is clearly seen in the central area of the vault, where the texture caused by the bricks is also visible. If needed, the difference between the point cloud and the model could be used to estimate the volume of missing mortars. This could be relevant in case of restoration works.

In the table below, we can see that 61% of the points in point cloud are within a range of 1cm to the geometric model.

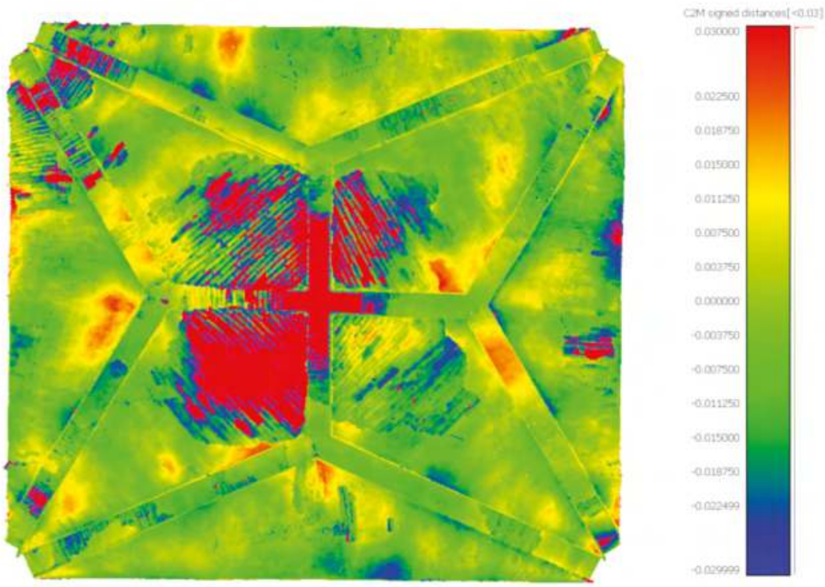


Fig. 15 Distance analysis between the modelled surface and the surveyed point cloud. Source: author, 2024.

Point cloud	Number of points	Percentage of points
Vault base point cloud	480.008	100%
Segmented point cloud (± 1.5 cm)	373.384	78%
Segmented point cloud (± 1.0 cm)	294.698	61%
Segmented point cloud (± 0.5 cm)	161.827	34%

Table 2. Distance analysis between the geometrical model and surveyed point cloud.

3D printing to convey a volumetric idea

3D printing can be used for many purposes like showing a general view of the geometry, illustrating a constructive principle, or put in evidence a particular part of the object. With this example, our intention was to show a global view of vault [Fig. 16]. It can be argued that a simple visualisation of a 3D model can play a similar role. And that is true to some extent. However, there are features that are easier to understand by handling a physical model. For example, subtle discontinuities in surfaces, like the ones that happen in this case in the transitions between ribs, are easier to see in a scaled physical model than in a digital model. Additionally, we can also think about these models as medium to make heritage accessible to impaired people or other audiences, or even construction sites, without being dependent on digital representations.

Fig. 16 3D printing of the ribs and spans of the vault. Source: author, 2024.

Geometry as the base for stereotomy

Finally, in this section it is presented the last case study.

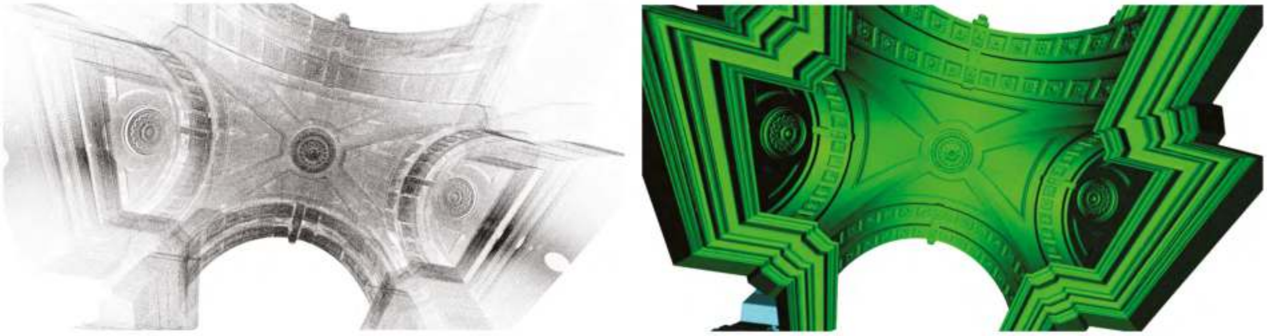
Laser scanning survey and mesh modelling

The laser scanning survey initially conducted in the context of the preparation of conservation works included the recording of the building's exterior and interior surfaces in the form of point clouds **[Fig. 17 left]** and allowed for its graphical representation through floor plans, sections, and elevations, enriched by orthoimages. These elements proved to be fundamental for the analysis presented. From a 3D modelling point of view, the point cloud is a base to produce several types of models. These can depict all the details **[Fig. 17 right]** or can be more idealized. If the purpose is to get other types of models, like CAD or BIM, it is mandatory a trade-off between full accuracy and efficiency of the model.

Geometric analysis and modelling of the vault

The layout defined by the relationship between floor plan, section, and elevation in some way reflects the operational setup of the 19th century architect. In this

Fig. 17 Left: point cloud. Right: mesh model.



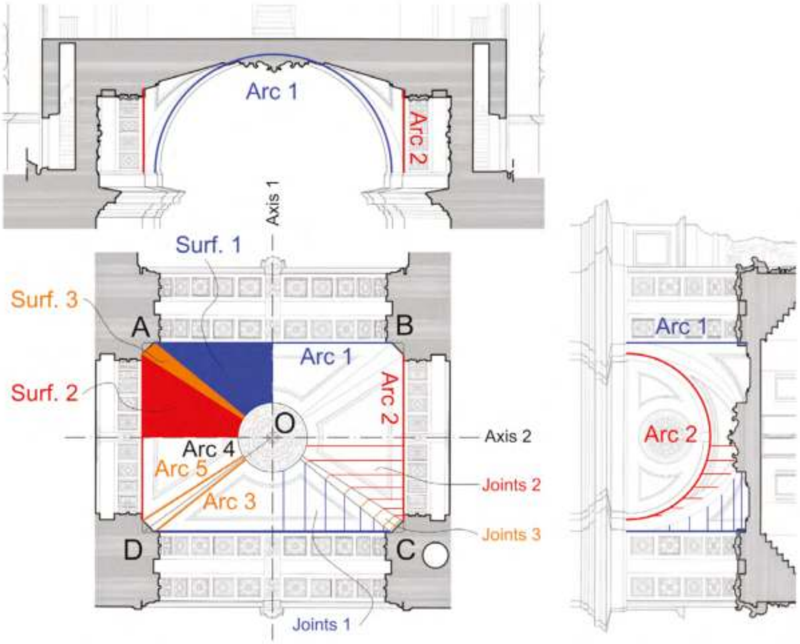


Fig. 18 Recapturing the operative layout of the architect through plan and sections. Source: author, 2024.

sense, it is more significant for understanding the generation of form than an exclusive reading of the three-dimensional data resulting from the survey.

By doing this kind of reverse engineering of the design project, a set of geometric relationships, that would otherwise remain hidden, is revealed [Fig. 18].

Through Fig. 18, it becomes evident that the geometric structure of the vault has two axes of symmetry: one transversal (axis 1), aligned with Rua Augusta, and another longitudinal (axis 2), aligned with the arcades. The area of the vault corresponds to the rectangle [ABCD], with centre O. Axis 1 contains the centres of arcs of type 1, and axis 2 contains the centres of arcs of type 2. These arcs correspond to semicircles contained in vertical planes, with the radius of arc type 1 being greater than the radius of arc type 2. It is then observed that arcs of type 1 give rise to surfaces of type 1 through extrusion. Thus, surfaces of type 1 are cylindrical, which is also confirmed by the drawing of joints 1, parallel to axis 1. The cylindrical surfaces, in turn, are bounded by vertical planes according to arches of type 3. Consequently, arcs of type 3 are elliptical.

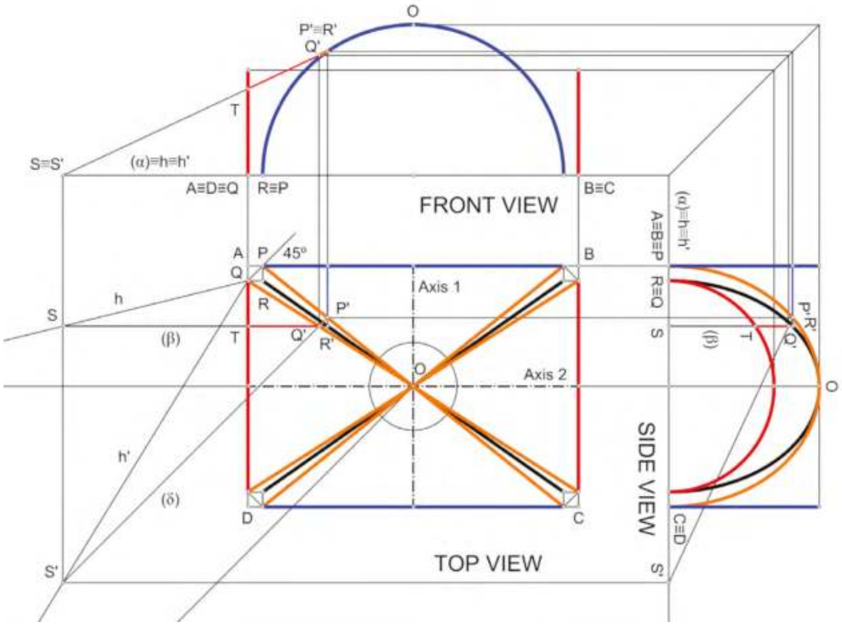


Fig. 19 Geometric analysis of surfaces 2 and 3. Source: author, 2024.

Next, we postulate the consideration of arcs of type 4, which also result from the intersections of the cylindrical surfaces with diagonal vertical planes of the rectangle [ABCD]. In a manner like what occurs with arcs of type 3, the arcs of type 4, which do not correspond to any edges of the vault, are also elliptical. These arcs of type 4, together with arcs of type 2, support the generation of surfaces of type 2. In these surfaces, it is observed in the ceiling plan and in the side view that joints 2 are parallel to the vertical plane of axis 2. Considering this observation, at first glance, we are led to conclude that surfaces of type 2 are cylindroids, that is, ruled surfaces, with a directing plane, whose generatrices rest on two curved directrices.

Subsequently, the surfaces of type 2 are bounded by the arcs of type 2 and type 5, whose geometric nature remains to be clarified, contained in vertical planes. Finally, the arcs of type 3 and 5 bound the surfaces of type 3, which, due to having the joints 3 parallel in the plan view, are also supposed be cylindroids.

However, deepening the geometric analysis of surfaces of type 2 and 3, it is verified that they are not cylindroids, as we initially supposed, but rather conoids **[Fig. 19]**.

Let us begin with surfaces of type 2. A surface of this type is guided by one arc of type 2 and one arc of type 4, and a directrix plane. The directrix plane is vertical with an orientation β parallel to axis 2, which means that all the generatrices of this surface, [R′T], will be parallel to axis 2 in the plan view. Since arc 2 and arc 4 are conic curves, specifically a circle and an ellipse, in the side view they are related by an affinity of axis h. That is, for any generatrix [R′T] of this surface, the ratio R′T/TS is constant, as manifested in the side view, in the plan view, and also in the front view. This means that, in the top view, the lines representing the arcs 4 and 2 are also related through an affinity of axis h. In fact, line h is the trace of surface 2 in plane α, which is the horizontal plane above which the vault rises. Therefore, it follows that although we started with two curved directrices, surface 2 also contains a straight one, line h, which makes it a conoid.

Regarding surfaces of type 3, it is noted that they result from the chamfering the corners of rectangle [ABCD] at 45º in relation to its sides. That is, surfaces of type 3 connect cylindrical surfaces of type 1 to conoid surfaces of type 2. These surfaces have a vertical directrix plane with orientation δ at 45º in relation to axes 1 and 2. The directrices of these surfaces are arcs of type 3, which are elliptical, and arcs of type 5, whose nature is unspecified. For example, the arc 5, contained in the vertical plane passing through points Q and O, results from the intersection of this plane with the corresponding conoid surface of type 2. For a generatrix [TQ′] of the conoid surface of type 2, there corresponds a generatrix [P′Q′] of a surface of type 3. It is verified that these two generatrices and the generatrix of the cylindrical surface of type 1, which passes through point P′, are coplanar. For this reason, the trace of the generatrix [P′Q′] in plane α, line S.S′, has the direction of axis 1. Now, note that all the triangles of type [Q′SS′], in the plan view, must all be homothetic with respect to point Q. Hence, all points of type S′ must be located on a line h′ passing through point Q. This line h′ is the trace of the surface of type 3 in plane α. Thus, by considerations analogous to those made above, surfaces of type 3 are also conoids.

If we proceed with a first modelling attempt of the vault based on this analysis, we will see what can be observed in **Fig. 20**.

In this model, the appearance of two vertices, X and Y, is observed, which are the ends of the junction edges of surfaces of type 2. However, these edges are incompatible with the data from the survey. This means that there should exist new surfaces ensuring a smooth transition between the two surfaces of type 2. Geometrically, the connection between the two surfaces of type 2 should be made through tangency with another surface. Our hypothesis consists in assuming that this new surface is also a conoid.

Since surfaces 2 are warped, the transition to other surfaces, which is assumed to be along a straight generatrix, must consider an auxiliary quadric, a hyperbolic paraboloid, or a scalene warped hyperboloid, simultaneously tangent with the surface of type 2 and with the new surface, which is also ruled, along the common straight generatrix. The new surface is also a conoid with directrix plane β. Furthermore, this new surface must be symmetrical with respect to axis 2. We will

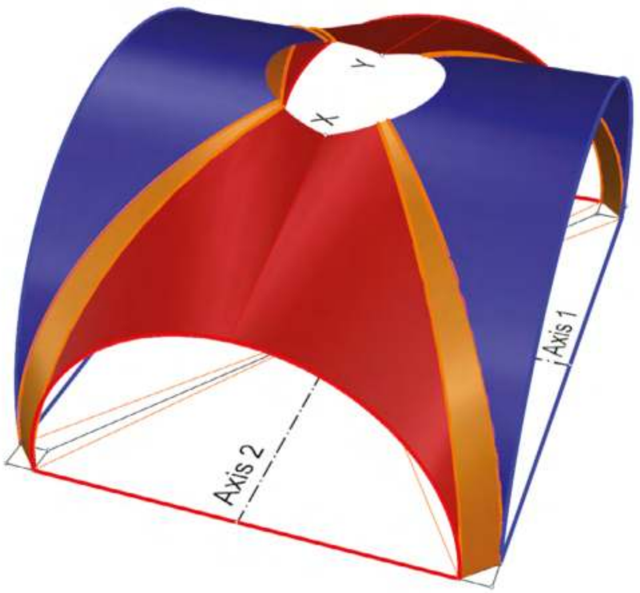


Fig. 20 First model of the vault where it is perceived an edge between surfaces 2. Source: author, 2024.

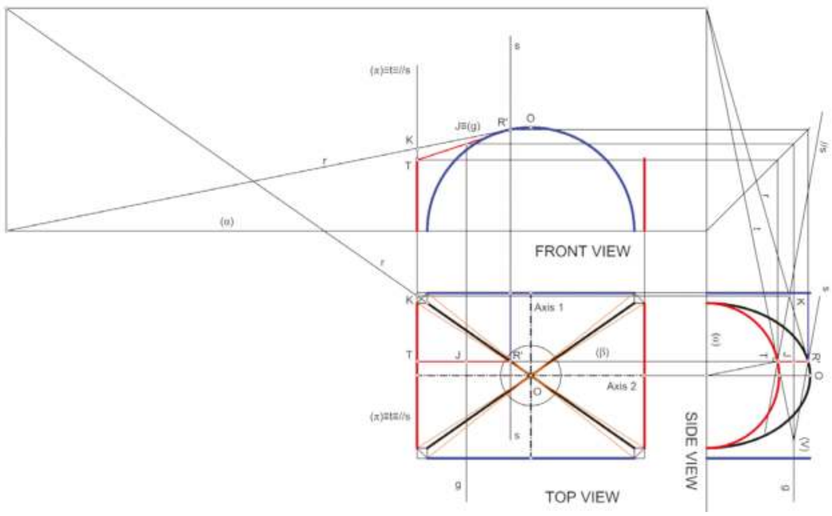


Fig. 21 Smoothing the edge between surfaces 2 through the tangency with another surface. Source: author, 2024.

now return to the representation of Fig. 19 to resolve the tangency we just mentioned. The drawing is what is shown in Fig. 21.

The first step is to select the generatrix of tangency, in this case, line T.R′, which is done analysing the surveyed data. This line intersects arcs 2 and 4 at points T and R′, respectively. The tangent plane to conoid 2 at point T is defined by line t, tangent to arc 2 at point T, and by line T.R′. The tangent plane to the conoid at R′ is defined by line r, tangent to arc 4 at point R′, and by line T.R′. These two planes will be tangent to the conoid surface that we intend to define, as well as

Fig. 22 Final geometrical model.
Left: view from top. Right: view from bottom.
Source: author, 2024.

to the auxiliary quadric that needs to be considered, in this case, a hyperbolic paraboloid with directrix planes β and π. Orientation π is chosen because this is the only orientation that ensures a symmetry regarding the axis 2.
The tangent plane to the conoid 2 at point R′ intersects plane π along line //s, defined by points K and T. This line gives us the direction of generatrix s of the hyperbolic paraboloid passing through R′, the straight line s. Since there is a family of generatrices of the hyperbolic paraboloid parallel to β, this gives rise to the point of divergence V, in the side view, through which the generatrix g of the hyperbolic paraboloid can be drawn, horizontal and parallel to π. This generatrix g is also be common to the transitional conoid between the two surfaces of type 2. Thus, the transitional conoid between surfaces 2 will have β as the directrix plane and arcs 2 and line g as its directrices.
The modelling of the vault, taking into account this new surface, and refined by considering surfaces parallel to those studied to accommodate the profiles and the trimming in the stone cutting, can be seen in Fig. 22.

Deviations between the surveyed data and the idealised geometric model

The final test of the hypothesis regarding the generative geometry of the vault was conducted by analysing the distances between the point cloud from the survey and the model resulting from the previous stage [Fig. 23].

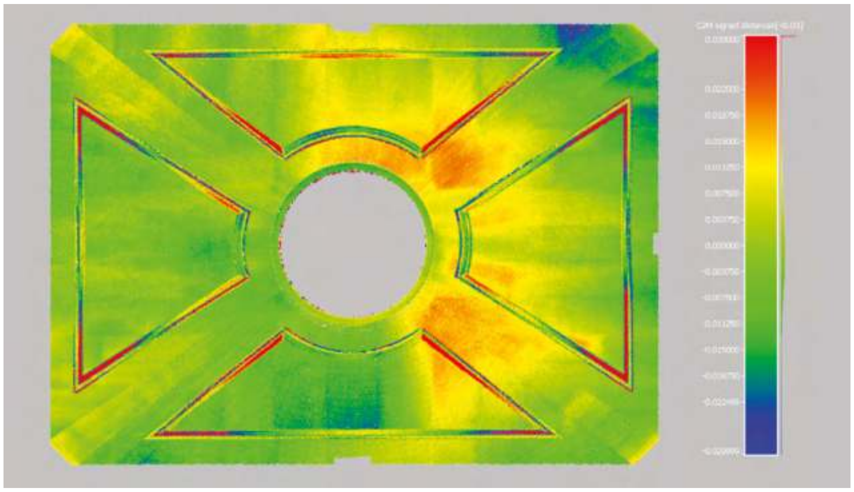


Fig. 23 Distance analysis between the modelled surface and the surveyed point cloud.
Source: author, 2024.

Table 3 shows that there is a high degree of congruence between the produced model and the survey data. It is observed that about 71% of the points in the point cloud are within a distance less than 1 cm from the produced model. These results are even more significant regarding the quality of the construction when considering that the adjustment was made between a geometrically idealized and perfectly symmetrical model and real data, which naturally reflect the asymmetries and imperfections inherent to the construction process, as well as slight deformations resulting from the passage of time.

Point cloud	Number of points	Percentage of points
Vault base point cloud	719.529	100%
Segmented point cloud (± 1.5 cm)	624.552	87%
Segmented point cloud (± 1.0 cm)	509.077	71%
Segmented point cloud (± 0.5 cm)	312.408	43%

Table 3. Distance analysis between the geometrical model and surveyed point cloud.

Modelling and 3D printing of a stereotomic hypothesis

Based on the model of the visible surfaces of the vault, and taking into account the joints between the voussoirs visible in the point cloud from the survey, a hypoth-

Fig. 24 Stereotomic hypothesis.
Left: view from top. Right: view from bottom.
Source: author, 2024.

Fig. 25 Process of assembly of the voussoirs
after 3D printing. Source: author, 2024.

esis of stereotomy was modelled, estimating the thicknesses and the geometry of the contact surfaces between the stone blocks, as can be seen in Fig. 24.
Regarding the thickness, an average value of 30 cm was considered, from which the lower trimming of 14 cm was subtracted. As for the non-visible joints between stones, it was assumed that they are flat and convergent along axes 1 and 2. A total of 70 voussoirs were modelled, including four that form the closure of the vault (not represented in Fig. 24). Assuming a specific weight of 2500 kg/m³ for the limestone from which the vault is constructed, the weight of the voussoirs varies between half a ton and two tons. Each of the closure voussoirs of the vault weights approximately three and a half tons.
Finally, each of the modelled voussoirs was 3D printed at a scale of 1/20 and assembled with the help of a cardboard structure that reproduces the boundary conditions of the constructed vault, restricting the sliding movement of the pieces. To simulate the friction between the pieces and any metallic elements that may exist, adhesive tape was used. It was observed [Fig. 25] that during the assembly process, the structure immediately began to behave like an arch and vault. Note that even before it was completely assembled, the pieces were already self-supporting. When the pieces corresponding to the closure were added to the assembly, the final model became stable and capable of withstanding some pressure.
This type of physical model can be used to gain insights about the actual behaviour of a vault structure and to simulate collapsing mechanisms.

Discussion and conclusions

In this article, we presented a methodology for the documentation and geometrical analysis of the constructive system named vault. We applied it to the study of three examples of vaults representing different types of architecture, namely a traditional brick vault in a vernacular house, a brick vault in a renaissance house, and the main vault of the Arco da Rua Augusta, a remarkable example of stone stereotomy. The methodology included the phases of surveying, geometric analysis, three-dimensional modelling, comparison of the generative geometry with the surveyed data, and 3D printing. Documentation and recording methods such as laser scanning and photogrammetry are increasingly established as the standard that ensures the precision and quality of data, enabling the development of more rigorous quantitative studies which are fundamental to inform intervention actions.
Since a vault is used to cover a given space, the geometric analysis started from a planimetric view to define the bounding polygon representing that space. In the

case studies of the brick vaults we observed that the actual bounding polygons may deviate significantly from a rectangle (vernacular vault), and, when that happened, they were chosen to represent the space being covered by the vaults. In the cases of Valflores and Arco da Rua Augusta those differences were negligible and, therefore, a rectangle was considered. Then, in the cases of the brick vaults, the inference of the generative geometry was done by slicing strategically the point cloud to retrieve the curves that structure the geometry of the vault. Whenever possible, the curves were represented as circular arcs or combinations of circular arcs. Only, if circular arcs did not represent the curves correctly, other geometries were adopted, which did not happen in these cases. For the Arco da Rua Augusta it was followed a different approach. We laid out a two-dimensional layout that related the plan and two sections, one transverse and the other longitudinal. In this way, the typical operational setup of a 19th century architect was recovered, as it is the case with Architect Veríssimo José da Costa, author of the constructed project. The geometric analysis carried out highlighted the high level of sophistication in descriptive geometry knowledge possessed by the author of the project. In particular, the use of tangent conoid surfaces in the design of the vault stood out. It is important to note that ensuring the tangency between the surfaces is not trivial and involves the use of doubly ruled quadrics as auxiliary surfaces. The knowledge necessary to pursue this task was being developed in the 19th century, enhanced by the Descriptive Geometry that Gaspard Monge published at the end of the 18th century, and which others, such as Hachette, Olivier, Poncelet, Chasles, and Plücker, further developed during the 19th century. This architect was, therefore, well-informed about these developments, as evidenced by the analysis we conducted. From this perspective, the Arco da Rua Augusta is a testimony of the scientific value in that it reflects the most advanced studies of geometric surfaces existing at the time and the results obtained with this case study constitute, themselves, a contribution to the study of stereotomy in Portugal in the 19th century, period for which there is no research developed.

Considering the comparison made between the produced models and the surveyed data, it was found that the accordance between the geometric models and the surveyed data, expressed by the distances between both, showed that the percentage of points that range within a distance less than one centimetre is 53%, 61% and 71%, for case studies 1, 2 and 3. These results should be read carefully because they have various meanings. For example, if an object is very deformed and deviates from the idealized geometry, this is expressed in the distances found. The same happens when there is lack of material. However, the case of Arco da Rua Augusta is remarkable when considering that this is the biggest of the three and it is about a century and a half old. We can say that the deformations in relation to the idealized model are minimal. This reflects the enormous quality of the construction, which would had only been possible with the careful design of the construction solution that must have included a planning for the stone cutting. The modelling of a hypothesis about stereotomy allowed us to provide some insights into the physicality of the object. By individualizing each of the voussoirs, it was possible to estimate their mass. This parameter can impact future studies aimed at exploring the logistics of a construction site of this type, as well as estimating what resources would be necessary to carry it out.

On the other hand, 3D printing allows physical simulations of the models. This is an important aspect from many perspectives. Printed models allow a direct physical interaction which can be used to enhance pedagogical strategies in educational contexts. These types of models can be used to improve accessibility, for example for people with impaired vision. In the case of Arco da Rua Augusta it was possible a scaled simulation of the assembly process of the voussoirs, thereby reinforcing the understanding of the tectonics of the solution. This physical model also allowed for the verification of the structural equilibrium logics of the vault. In addition to this aspect, the educational potential of this type of model for the study of historical constructive systems stands out.

This is a study that considers the built reality as a primary source of information and, therefore, intentionally does not rely on modelling solutions documented in treatises that often merely typify some standard solutions without exhausting the richness of the built reality.

Now, since the validity of the methodology is demonstrated, future work on this topic includes the analysis of other buildings from 18th and19th century Portuguese architecture. This should be a two-fold approach. On the one hand it must rely on visual analysis of the geometries to infer the generative principles but on the other hand it would be beneficial to introduce some automation to the repetitive parts of the process, which can, eventually be done by integration of artificial intelligence tools.

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Interview with Manuel Fortea Luna

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Manuel Fortea Luna is an architect and holds a Doctorate in Art History from the Universidade de Coimbra (2002) and a Doctorate in Graphic Engineering, Geometry, and Projects from the Universidad de Extremadura (2013). He served as the Dean of the College of Architects of Extremadura from 2003 to 2005 and is a specialist in vaulted structures. He is passionate about the recovery and teaching of traditional vault construction techniques in the Iberian Peninsula, focusing on their contemporary significance.

Manuel Fortea Luna has coordinated various workshops and courses on vaults in Spain and Portugal. He is the author of several books and articles on vaults, particularly timbrel vaults in the Extremadura region of Spain. His most notable works include the book *Bóvedas Extremeñas. Proceso constructivo y análisis estructural de bóvedas de arista* (Colegio Oficial de Arquitectos de Extremadura, 1998) and articles such as *Análisis comparativo en base a la sostenibilidad ambiental entre bóvedas de albañilería y estructuras de hormigón* (2012), *Bóvedas tabicadas. Tradición y oportunidad* (2015), *Bóvedas tabicadas: ¿Artesanía o punto de partida?* (2019), *La bóveda de escalera tabicada* (2020), *Método, gestión y tutela* (2023), and *The vault of Room H-100 at the site of Casas del Turuñuelo (Guareña, Badajoz, Spain). Hypotheses and interpretations based on archaeological evidence* (2024).

Between May 2022 and December 2023, Manuel Fortea Luna played a significant role as a scientific consultant for the project Vaulted South – Vernacular Houses in the South of Portugal. He organised a technical visit on vaulted constructions for the project members in Zafra, Spain, in June 2023.

Manuel Fortea Luna was interviewed by Mafalda Batista Pacheco and João Vieira Caldas during the forum Vaulted South – Vernacular Construction Knowledge and Brick Vaults, held at the Colégio Almada Negreiros, FCSH NOVA University, Lisbon, on November 16-18, 2023. During this event, he delivered a lecture entitled 'Vaults: A Historical Technique with a Future' at the headquarters of the Ordem dos Arquitectos, also in Lisbon. [Fig. 1]

Fig. 1 Manuel Fortea Luna during the forum Vaulted South – Vernacular Construction Knowledge and Brick Vaults, held at the Colégio Almada Negreiros, FCSH NOVA University, Lisbon, on November 17, 2023. Soure: Mafalda Batista Pacheco, 2023.

RHA: For decades, you have been researching vault construction systems, primarily the brick vaults in Extremadura, Spain, and also in Portugal, near the border. You were also a consultant for the Vaulted South project, which aimed to explore the current vaulted houses in Alentejo and Algarve, Portugal. What is unique about these vaults?

Manuel Fortea Luna: In the south-east of Portugal, there is a very particular kind of vault, a brick vault, constructed without centering. This type of vault is also found in parts of western Spain. Culture, technique, and knowledge, in general, do not align with administrative borders; they flow through the territory and are limited by other conditions.

These vaults are constructed with bricks, a masonry technique with its own rules and characteristics. The other construction technique for vaults is stonework, which has different features. Masonry vaults require two main elements: bricks and the mortar to bind them. Bricks are found in all places where the art of ceramics is mastered. The mortar traditionally used is lime mortar.

Brick is one of the oldest construction materials known. At its most rudimentary, manufacture consists of simply kneaded clay, dried in the sun and baked in kilns stacked with fuel. One of the earliest places where we find brick is in the paving and vault construction of the tombs of the 3rd Ur dynasty, in Ancient Mesopotamia.

The brick vaults in Spain and Portugal are constructed without centering, meaning without any auxiliary structure during their execution. This gives them both an advantage and a disadvantage. The advantage is that dispensing with the centering lowers costs. The disadvantage is the vaults must be stable at every moment of their construction; that is, they must be stable in all situations during the process. This presents a challenge for their builders. [Fig. 2]

RHA: Portuguese houses with vaults in the south were first made public in the book *Arquitectura Popular em Portugal* (Portuguese Popular Architecture, 1961), published by the National Union of Architects as a result of an inquiry into Portuguese rural architecture. That book led to further studies on vaults. In Spain, a decade later, compilations also appeared, such as *Arquitectura Popular Española* (Spanish Popular Architecture) by Carlos Flores (1973) and *Itinerarios de Arqui-*

Fig. 2 Technical visit of the Vaulted South Project team with Manuel Fortea Luna in Zafra, Spain. Source: Mafalda Batista Pacheco, 2023.

tectura Popular Española (Itineraries of Spanish Popular Architecture) by Luis Feduchi (1974-1984), among others. Were these a turning point in Spain?

MFL: In Spain, some authors had already noticed these unique vaults. Feduchi highlights the importance of the vault in Extremadura, describing it as the most distinctly Extremaduran [architectural] element, capable of individualising an architectural work and qualifying the skills of builders. He traces its origin to the preservation of techniques introduced and mastered by the Romans, and more specifically, perhaps, those developed during the Byzantine Empire (Feduchi 1984, 22).
García Mercadal (1981, 67-68) had already observed that from the Tagus to the Guadiana rivers, there was hardly a single horizontal wooden framework to be found, and that all the floor divisions in this area were composed of vaults, sometimes even roofs. He defined the vault as an essential element of the Extremaduran house, referring to the Byzantine term for vaults built without centering.
Albarrán (1885, 3) wrote a report aimed at promoting knowledge of the construction and execution of brick vaults in the province of Extremadura, about which works about classical construction said nothing. In Extremadura, all vaults are built

without centering, covering basements, cisterns, ground floor rooms, and farmhouses where the upper floor is used as a granary. These vaults are made in different spans and shapes, with beautiful and varied decorations.

Other authors could be cited, but they all agree on the unique importance of vaults in Lower Extremadura, noting a special characteristic, which is that all of them are built without centering. Some justify that by the supposed lack of wood in the region, which is a weak argument considering that in the same region, north of the Tagus, timber-framed architecture proliferates (Pizarro Gómez 1983, 51), while, with a few exceptions aside, vaulted constructions are topped with wooden roofs. In my book *Bóvedas Extremeñas* with Vicente Lopez Bernal (1998), we already noted their existence on both sides of the border and called them Extremaduran vaults. We can describe the Extremaduran vaults as a highly refined technical, constructive, and structural solution, with great economy of means and great versatility in their function.

RHA: You just mentioned they are built without centering. What does that mean? What are the differences between construction with and without centering?

MFL: Construction with centering involves creating two structures: one supporting and the other supported. As a consequence, this approach doubles the cost, since most of the time the auxiliary structure is more expensive than the permanent one. Construction without centering implies a very advanced technology to control gravity, with far-reaching repercussions on execution, costs, deadlines, safety, the guarantee of the work itself, and of course, the final result. It is approached uniquely from its conception, requiring its own specific design, calculation, planning, and execution, which is different from a [type of] construction requiring auxiliary means of support during execution. A construction without centering is constantly fighting for itself against the constant, stubborn action of gravity and represents significant savings by dispensing with an auxiliary structure. In addition to cutting costs, there is the advantage of reduced execution time, which sometimes can be more valuable than monetary costs.

Solving several problems at once with a single gesture is not the result of chance or luck, but of analysis, reflection, experience, and ingenuity. **[Fig. 3]**

RHA: Is this kind of brick vault, constructed without the use of centering, found in other areas of the Iberian Peninsula? Are there similar references to this technique being used elsewhere?

MFL: There are no references to this type of vault in the rest of the Iberian Peninsula, including during the Roman period, so we can rule out a Roman origin. To find refer-

Fig. 3 Vaulted South Project team meeting about types of vaults in Portugal and Spain, with Manuel Fortea Luna in Zafra, Spain. Source: Mafalda Batista Pacheco, 2023.

ences of this type, we really have to move to the Middle East. We find vaults of this type in Hagia Sophia in Istanbul, completed in the year 537 AD. But the oldest ones have been found south-west of ancient Nineveh, at Tell Rimah, the ancient Karana, a site built around 1800 BC, during the time of Shamshi-Adad I of Assyria. The entire complex is built with mud bricks and bricks and corresponds to a monumental building following the Babylonian tradition. It has brick vaults with a conical row arrangement, which is outstanding. This is a unique technique of construction without centering that would become popular 2000 years later in the Byzantine Empire.

In Egypt, the funerary temple of Ramses II, who ruled from 1289 to 1222 BC, located in the necropolis of Thebes, on the west bank of the Nile River opposite the city of Luxor, has warehouses surrounding the temple under vaults too. The warehouses were large and give us an idea of the huge amount of products stored in them. These are barrel vaults with a non-circular section (apparently an elliptical or catenary arch) composed of four brick layers. The rows are conical, meaning the bricks are inclined at an angle. This technique is clearly of Mesopotamian origin. Some authors doubt the origin of these vaults built between Egypt and Mesopotamia without centering. It is evident that they appear earlier in Mesopotamia (we already mentioned Karana), and it is also evident that they are found sporadically in Egypt.

This vault system was not used by the Western Romans in the Iberian Peninsula; so I believe it is a technology imported from the Near East, of unknown date and itinerary.

RHA: Does this construction technique with conical rows without centering appear in the Iberian Peninsula?

MFL: The secret of this system lies in tilting the rows without exceeding their angle of attrition, thus ensuring their stability without any other support. In a barrel vault with a circular section, the inclined rows are ellipses, and the construction begins from two opposite ends simultaneously until they meet at the closure. These vaults and the ones described by the mentioned authors are found in Extremadura and are still seen relatively frequently today.
Auguste Choisy ([1899], 335-336), in his *History of Architecture*, explains the technique of conical rows, mentioning that Byzantine vaults, like Persian vaults, are executed, as far as possible, without auxiliary supports. In Syria and Armenia, vaults were almost exclusively built of stone, and the advantages of construction without centering were limited to the domes. But the Byzantine building tradition, which systematically used brick, built its vaults 'directly in space', and the new types of vaults added to the ancient Persian repertoire are the groin vault, which the Persians never practised, and the dome on spherical triangles instead of the dome on squinches, the only one known to the Persians. In the method of conical rows, the rows are constructed in order from the walls towards the centre, successively overlapping.

RHA: Another technique to build vaults in the south of Portugal and Spain is characterised by placing bricks with the underside showing, known as *abobadilha alentejana* and *bóveda tabicada* (timbrel vault), also without centering. What is the difference from the ones we were speaking about previously?

MFL: There are only two known techniques for constructing vaults without centering in the world: one is what I call Byzantine construction, and the other is the timbrel vault. The Byzantine vault is made of brick masonry in a single layer, held together with lime mortar, with a thickness of no less than half a foot. The timbrel vault is a mechanism made of a thin layer of brick, no thicker than the edge of the brick, held together with gypsum plaster and other materials.
Neither of them requires centering. The Byzantine vault is supported during construction by the skilful placement of the pieces. The timbrel vault is supported by quickly setting the gypsum plaster. The timbrel vault is a refined evolution of the Byzantine vault with the incorporation of a new material into the process, the gypsum plaster.
The timbrel vault cannot be understood without crossing the borders of the medieval Christian kingdoms of the Iberian Peninsula. It is necessary to delve into Muslim Spain to deepen its origin, knowledge, and evolution. In a place where knowledge and mastery of gypsum plaster existed, it is easy to imagine the advantages of this material being exploited to save resources, both human (by requiring less labour time) and material (by requiring fewer bricks). That is to say, the tim-

brel vault emerged as the optimised version of the brick vault, called *bóveda de rosca* ('screw' vault). In Extremadura, we can find the same vault geometries built into the brick masonry version and the timbrel vault version.
In the west of the Peninsula, there are no gypsum quarries, so its use has been very restricted historically. On the contrary, gypsum is abundant in the eastern part, and consequently its use was very widespread. We can see that the timbrel vault emerged there. The area is rich in lime, but not so much in gypsum. The proliferation of timbrel vaults came with the railway, when transporting a material like gypsum from other regions became cheaper. The construction process of timbrel vaults is simpler, as gypsum allows for quick setting and therefore makes the process simpler. It is no longer necessary to use the technique of conical rows of circular and inclined planes.

RHA: You mentioned the 'Lusitanian vault' in a recent talk, 'Vaults: A Historical Technique with a Future'. What makes it stand out?

MFL: In eastern Portugal and western Spain there exists a unique geometry in vaults, sitting between the sail vault and the groin vault. Its first characteristic is composite geometry, formed by the intersection of several simple geometric figures or surfaces composing it, which gives it a double curvature.
That no breath-taking works have made use of this type of vault may justify the lack of detailed studies about it. Be that as it may, the fact is that this geometric pattern has not received much attention and has simply been defined as groin, lunettes, or other names of standardised geometry. These vaults have also been called *bóvedas peraltadas* (stilted vaults). We can find them in Gothic architecture. They are truly double-curvature vaults. They can be classified as such, but they do have a subtle difference that, while not easily noticeable, is crucial for their performance, which is the double curvature.
So, the 'Lusitanian vaults' have a very unique geometry. They are groin vaults with one singularity, which is that the keystone of the vault sits higher than the keystones of the perimeter arches. The groin vault is the intersection of two straight semi-cylinders. The 'Lusitanian vault' becomes the intersection of two semi-toroids. Since the structural behaviour of the vaults depends fundamentally on geometry, and not so much on materials, we can conclude that the 'Lusitanian vault' behaves structurally between the groin vault and the sail vault, since its geometry is at the intersection of both.
The second characteristic is that they are executed 'above in the air'. This means that a complete centering of the entire surface of the vault is not required, although it may be used occasionally to execute the auxiliary arches. **[Figs. 4 and 5]**

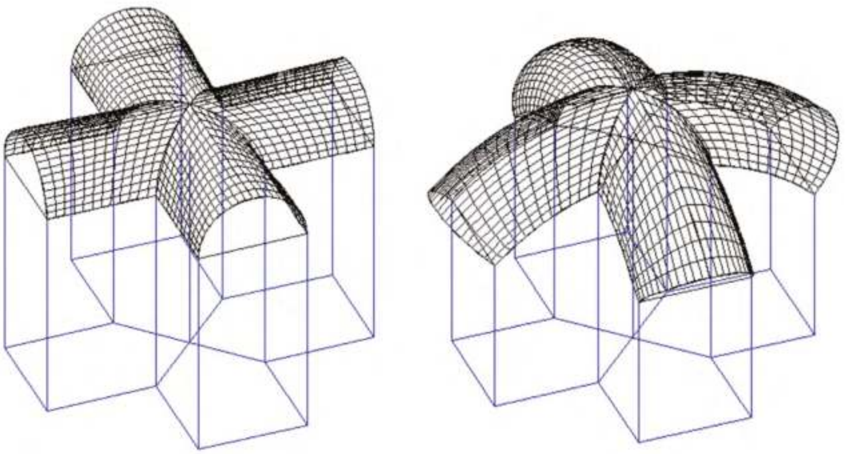

Fig. 4 Geometries of vaults: groin vault (left) and 'Lusitanian vault' (right). Source: Manuel Fortea Luna, 2023.

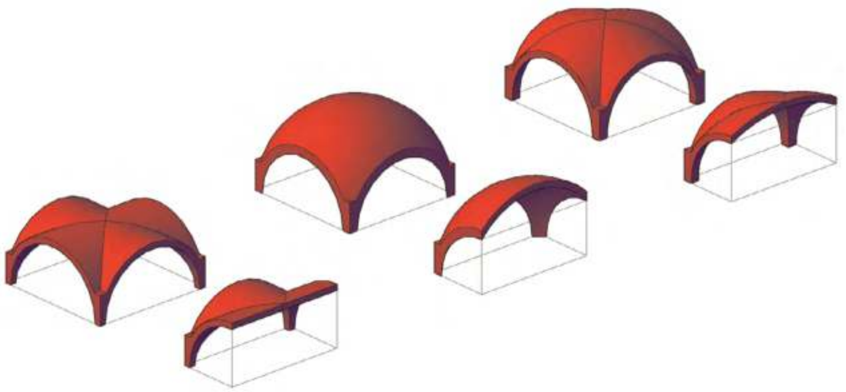

Fig. 5 Tri-dimensional models of vaults: groin vault (left), sail vault (centre), and 'Lusitanian vault' (right). Source: Manuel Fortea Luna, 2023.

RHA: What does the construction process of 'Lusitanian vaults' consist of?

MFL: These vaults are constructed using the conical rows technique. They are usually built on four existing perimeter walls, determined by the starting points and the height difference between the starting points and the keystone of the lateral arches, called the *punto* (point). With these references, the four arches that will form the sides of the vault are drawn up. Once the arches are marked on the walls, two perpendicular strings are placed, connecting the keystones of the opposite arches. The crossing point is raised by a few centimetres (this is called *retumbo* in Spanish), and from this point, a plumb line is hung to serve as a reference for the builder. The 'point' plus the *retumbo*, that is, the rise (the height between the starting points of the vault and the central keystone), should not exceed approximately 1,50 meters, so that all operations can be carried out with a single scaffold, keeping the work plane at an accessible height for the worker standing on it.

With the four former arches in place, four holes are made in the corners, where the pendentives will be put in place. These are the four corner pieces where the vault starts. They are really part of the wall from a construction point of view, so for their correct execution, a hole is opened in the wall, and the bricks are interlocked with the wall. These pieces support themselves without the need for centering, with the bricks overlapping each other. The pendentives are made in brick and lime mortar, with 4 to 6 horizontal rows. The lie down of the brick, or wedge, shapes the angle between the horizontal and the tangent to the arch where the first row of the vault will be placed.

The vault is constructed in a circle with rows supported on the pendentives and the perimeter walls. The rows are circular and inclined at an angle, resembling an oven, where the edge is produced as a result of the intersection of the rows from the four sides.

A groove is made in the arch drawn on the wall, and then an arch consisting of one row of brick is executed, slightly embedded in it and supported on the pendentive. The bonding mortar is lime, which is slower to harden. The stability of the bricks in each row during execution lies in the inclination. Once each row is complete, it supports itself. This construction technique without centering is also known as 'building on air', reminding one of a void, with no support or attachment, as if the vault were a balancing on a trapeze.

Without centering and with no other [architectural] reference besides the four lateral arches, the builder uses a plumb line, called *pesillo*, located in the centre of the vault. The vault is then closed with consecutive rows on all four sides. Great skill is required for this, as there are no auxiliary means for the correct placement other than using your eyes and hands. Obviously, these rows are applied using plaster, and each brick must be held by hand until the gypsum plaster makes it hold.

Once the vault is closed, the cavities are filled up to approximately half the height with heavy material (usually soil and stones). This operation of loading the extrados of the vault is called *hombrear la bóveda* ('shouldering the vault'). Until the load is completed, it has no resistance. At this point, the vault offers a flat surface at the extrados, except for the central part, where an almost spherical bulge stands out. To achieve a walkable surface, it is necessary to fill up to the level of the central keystone. This filling uses lightweight material, to avoid overloading the vault. Since the appearance of the railway, soot has been used in this place. **[Fig. 6]**

RHA: The 'Lusitanian vault' structurally behaves between a groin vault and a sail vault as a result of geometry. Does this have an impact on structural behaviour? What are the mechanical properties of these vaults?

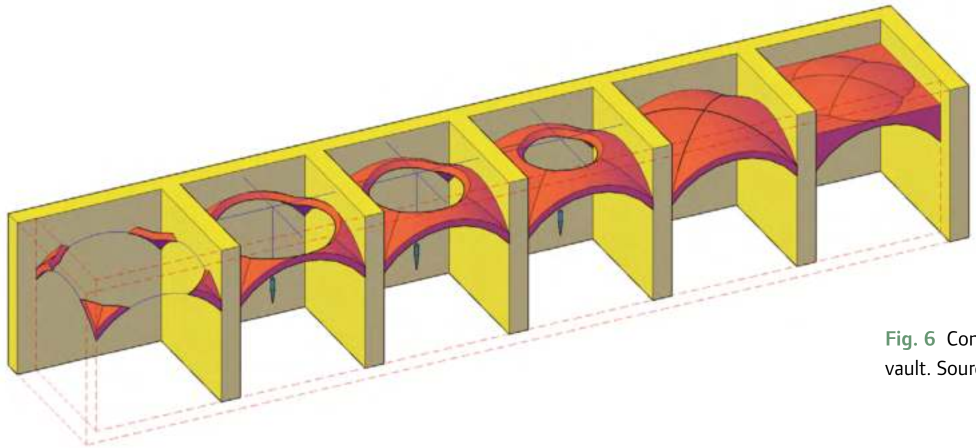

Fig. 6 Construction process of a ''Lusitanian vault. Source: Manuel Fortea Luna, 2023.

MFL: This means that when needed, the 'Lusitanian vault' will work as a sail vault, which is essentially a dome sectioned by four vertical planes, and when needed it can also work as a groin vault. This gives it great versatility as the push can be directed in different directions. Its geometry allows it to behave in very versatile ways. The most convenient mode will be used according to need, depending on the loads and the capacity of the supports, following a basic principle of entropy. The thrusts of a sail vault are distributed around the entire perimeter; in a groin vault, they are concentrated in the corners, and in a 'Lusitanian vault', they work in an intermediate position. **[Fig. 7]**

RHA: If the geometry of the 'Lusitanian vaults' is in between geometries, what is its structural behaviour? Is there any tendency for structural problems?

MFL: As a result of its geometry, the 'Lusitanian vaults' structural behaviour sits between groin and sail vaults. Its pathology is also between the two. These characteristics affect its mechanics, way of working, and the system of transmitting the forces from the vault to the wall, offering multiple possibilities, and allowing it to choose the most convenient according to the applied loads and conditions. The fact that the forces from the construction's weight and the overloads, which must reach the ground without violence to achieve permanent stability, have multiple paths, gives it an added safety coefficient that is difficult to surpass unless a major mistake is committed.
A double-curvature vault like the 'Lusitanian vault' can be considered under two assumptions regarding behaviour: 1) That it works like a groin vault, that is, considering that we divide each panel into independent arches that rest on the groins, transmitting to them the thrusts, both vertical and horizontal, running along them

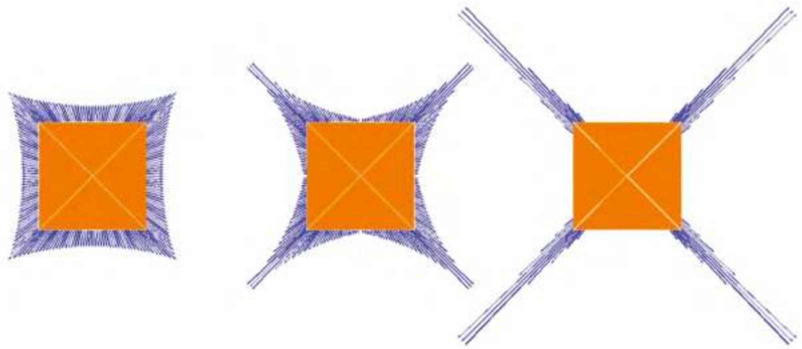

Fig. 7 Different behaviours of the horizontal thrusts in vaults: sail vault with evenly distributed thrusts (left); groin vault with heterogeneous thrusts concentrated in the corners (right); and 'Lusitanian vault' with an intermediate behaviour (centre). Source: Manuel Fortea Luna, 2023.

to the starts, where all the force is pushed to; 2) That it works like a dome, that is, if we divided the vault into radial segments, transmitting force to each base, some on the perimeter wall and others on the starts. Logically, the dimension of the thrusts depends on the dimension of the spherical cap to which it belongs.

RHA: In a 2012 article, 'Comparative Analysis Based on Sustainability Between Masonry Vaults and Concrete Structures', with Justo García and Antonio Reys, you approached vaulted construction from the point of view of sustainability. What are the advantages and disadvantages of using vaults compared to concrete construction?

MFL: In that study, we compared from a sustainability perspective the environmental impact of a horizontal masonry structure using a groin vault and a structural reinforced concrete slab of the waffle type, using Life Cycle Analysis techniques to quantify the energy consumed in the process of manufacturing the materials and erecting the structure. Generally speaking, it was found that the vault uses 75% less energy than concrete in the construction process, emits 69% less CO2 into the atmosphere, and has an average manufacturing cost for small spans – similar to that of a conventional slab and lower when it comes to large spans. It generates 171% less packaging waste on-site, although it requires more labour, and that labour is specialised.

The manufacture of construction materials causes environmental impact due to the extraction of natural resources and energy consumption. The resulting toxic emissions into the atmosphere are polluting, corrosive, and harmful to health. Vaulted structures use less energy than waffle concrete slab structures. For a 6x6 structural module, a vault consumes 10,914 MJ, while a waffle concrete slab consumes 48,655 MJ for the manufacturing and construction. As the distance between slab pillars increases, the energy required for vaulted structures decreases proportionally compared to waffle concrete slabs. It has been found that, from the perspective of environmental sustainability, the use of vaults becomes more interesting the larger the spans that need covering.

Gas emissions into the atmosphere, measured in kilograms of CO2 equivalent emissions, indicate the global warming potential (GWP) of the planet due to various gases being emitted during the production and construction of greenhouse gas (GHG) generating materials: carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), ozone (O_3), sulphur dioxide (SO_2), and chlorofluorocarbons (CFC). In vaulted structures, CO2 emissions during the manufacturing process of materials, transportation, placement, and handling are lower than in waffle concrete slab structures. Emissions of other greenhouse gases such as NOx, SOx, and CO were also analysed and found to be lower in vaulted construction compared to waffle concrete slabs. Also, waste from constructing vaulted structures is lower than from waffle concrete slabs structures, mainly due to packaging waste (which is 177.78% [higher]) and the construction process. This is because part of the recycled debris from ceramic materials, being inert materials, can be used to fill in the cavities of the vaulted extrados.

Regarding the energy used in the vaulting construction process, the energy required – including that used in manufacturing the materials – more than meets current sustainability demands, CO2 emissions, and waste production. Not all countries have the same regulations in this matter, and in some the negative effects on the environment attract higher penalties than in others.

As to insulation, it has been found that vaults with filled cavities in the extrados corners provide excellent thermal insulation when compared to other structural systems due to their mass. Additionally, thermal insulation increases with the number of layers and their thickness. Similarly, vaults offer excellent acoustic insulation compared to other structural systems for two reasons. Firstly, because the vault is composed of discontinuous elements that stop sound waves from propagating, especially those produced by impact. Secondly, because their mass is greater than in any other structural system.

RHA: But there is still more to consider than environmental sustainability. What about the economic factor of vault construction?

MFL: The cost of executing the structures is the variable that indicates the economic viability of their use. The cost of the construction process, known as the Project Execution Model (PEM), includes the labour required for its execution, the cost of materials, and the auxiliary means used.

When vaulted structures are compared to waffle concrete slab structures based on modulation, the labour hours required in the construction process are higher in all cases analysed. Additionally, it has been shown that the labour required to build vaults must be more specialised than that for the waffle concrete slab. Highly skilled labour reduces execution time, while unskilled labour substantially increases it, and untrained labour would never be able to do the work.

On the other hand, constructing the vault without centering elements increases the risk of building accidents, so safety and surveillance measures must be enhanced during this phase, especially until the first layer of the vault has been finished. In contrast, the materials that make up the vault consume less energy in their manufacturing and assembly process, with lower emissions of greenhouse gases into the atmosphere and less acidifying effect.

The construction cost of vaulted structures is lower than that for waffle concrete slab structures, due to the lower price of the materials used, such as lime, plaster, and masonry, compared to cement and steel. The value corresponds to the Spanish market, although data will obviously vary depending on the location where the structure is built, mainly due to the impact of labour costs, as more labour is required for the vaults. Functionally, both structures are equivalent in terms of their load-bearing capacity, but quantitatively they are not homogeneous in terms of environmental balance.

We demonstrated that vaulted construction more than meets current demands in terms of sustainability, and this construction technique can coexist with the technology of modern society, resulting in a product with high economic, functional, and energy performance.

RHA: Coming back to your talk in Lisbon, how do you see the future of this 'historical technique'?

MFL: New construction methods are so overwhelmingly imposed on us that traditional techniques have been relegated to oblivion, as if they belonged to a distant past, when in reality they have been applied in some areas of our region well past the post-war period, that is, in the context of modern economic development.

Let us approach these pieces of architecture with respect and admiration, aware of the value and knowledge held in them, which has been so often left in the shadows, at times due to a lack of concern with cultural transmission, and at others due to arrogance, where one's own work is the only work valued, disdaining what is foreign, spatially and temporally.

The Alentejo and Extremadura regions are rich in vaults and domes, to the point of having their own technology of great scientific and cultural value, which has not been sufficiently disseminated and exploited.

The loss of knowledge is always regrettable as it represents a [form of] cultural amputation, the denial of the past, and making additional efforts in the future.

Therefore, our main endeavour is to ensure that knowledge of these techniques does not disappear, regardless of their utilitarian value today. No construction or structural system is the ultimate solution for global building. Each of them has its merits and limitations, making them more suitable in some cases and less in others.
In the course of my research, I came to the conclusion that the use of vaults, as masonry structures, is to be advised except for in high-rise buildings. This construction technique can even coexist with the high technology of modern society, resulting in a product with high economic, functional, and energy performance, and it is possible to replace conventional slab structures with vaulted ones.

Transcribed and translated from Spanish by Mafalda Batista Pacheco,
revised by Tiago Viúla de Faria.[1]

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[1] This interview had the support of CHAM (NOVA FCSH/UAc), through its strategic project, sponsored by FCT (UIDB/04666/2020, DOI10.54499/UIDB/04666/2020).

Essay

Talking with Vault Builders: a documentary

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The process of building a vault requires mastering knowledge of construction, technique and materials. It requires a learning process that mostly takes place at the work site, and which is then transferred from one generation to the next, mainly within the family. Building a vault poses several challenges, depending on the geometry, use and finish of the vault. Thus, it is a process which goes through several phases. The main character in the Portuguese historical novel *A Abóbada* (The Vault), by Alexandre Herculano (1851), was a blind, old master builder, who remained under the stone vault in the founder's chapel at the Monastery of Batalha for three days and nights after its centering (a provisional support structure used during the construction process) had been removed.

That character – Afonso Domingues – was inspired by a real master builder who had worked in that monastery at the turn of the 14th century, and whose action was proof of his trust placed in the structural stability of the stone vault as it had been conceived, after an acquired body of construction knowledge. The scene was based on a tragic episode which had taken place in the Monastery's chapter room: the collapse of the stone vault immediately after removing the centering, under the supervision of a foreign master builder, David Huguet. **[Fig. 1]**

This episode will raise questions to any reader curious about the subject at hand. How is a vault built? What causes it to collapse? Are vaults still built? As part of understanding the process and the technical issues surrounding the construction of vaults under the scope of the Vaulted South Project – Vaulted vernacular houses in the South of Portugal, two team members interviewed several *mestres aboba-*

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Fig. 1 Drawings of the vaults in the Monastery of Batalha, Portugal. Source: James Cavanah Murphy, 1795.

deiros (vault master builders) from the eastern Alentejo region heirs of the local understanding of brick vaulting, a particular construction system that goes without the use of centering for their construction, and which has been applied in thousands of houses in south Portugal in a vernacular context, very different from the Monastery of Batalha.

The interviews were conducted by João Vieira Caldas and Mafalda Batista Pacheco in the scope of the *Jornadas Europeias do Património* (European Heritage Days), held in the Igreja do Espírito Santo, in Moura, on 23 September 2023, and promoted by the Câmara Municipal de Moura. They also took place at the worksite of a domical vault, in a house located in the surroundings of Baleizão, on 15 December 2023. The interviews were recorded and two documentaries created.[1]

The documentary *À conversa com os mestres abobadeiros* (Talking with Vault Builders) is based on the round-table talk during the European Heritage Days in Moura. It features the vault master builders Manuel Fialho (b. Vidigueira, 1952) and Joaquim Agulhas (b. Amareleja, 1975), who, among other topics, addressed the building context, details of the construction process, nomenclature, and knowledge transfer and rehabilitation.

The partner documentary, *Na obra com os mestres abobadeiros* (On the Work Site with Vault Builders) resulted from monitoring the building of a domical vault in a house in Baleizão by master builders Antônio Galamba (b. Serpa, 1960) and Hélder Ferreira (b. Serpa, 1958). The topics addressed were the same as with the other masters, but this documentary also focuses on the process of vault building step-

[1] Documentaries undertaken as part of the FCT EXPL/ART-DAQ/0171/2021 project, 'Vaulted South – Casas vernáculas abobadadas no sul de Portugal / Vernacular vaulted houses in the south of Portugal' (DOI:10.54499/EXPL/ART-DAQ/0171/2021), coordinated by Mafalda Batista Pacheco and Margarida Tavares da Conceição with the support of CHAM (NOVA FCSH/UAc), through its strategic project, sponsored by FCT (UIDB/04666/2020, DOI10.54499/UIDB/04666/2020).

Fig. 2 A master builder at work during the construction of a vault in Baleizão. Source: Mafalda Batista Pacheco, 2023.

Fig. 3 A master builder restoring the vault of a house in Serpa. Source: Mafalda Batista Pacheco, 2022.

by-step, the materials used, the differences between two main brick vault building techniques without centering, and the way bricks are assembled. **[Fig. 2]**

This topic's cultural and emotional depth can be felt from the testimonials of the master builders, covering how they learned the trade from their relatives, how they built with their descendants in mind, and how they bemoan the imminent loss of their almost timeless know-how.

A five-minute teaser, **'Talking with Vault Builders'**, was also created to promote these fascinating contents, allowing prospective viewers to catch a glimpse of the ambience surrounding vault construction, while serving as an introduction to the mastery of vault-making and some of its technicalities. The first minutes are dedicated to the testimony of two builders from Amareleja and Vidigueira, during the round-table in Moura. At the end of the teaser, a 'choreography' of brick assembling shows two builders from Serpa carrying out the construction of a vault, combining gestures and the handling of tools and materials, in a scene full of textures, colours and sounds.

These documentaries aim to record the living memory of the art and knowledge of building brick vaults, to promote conservation and rehabilitation, and to draw attention to a specific architectural and cultural heritage about to be lost. **[Fig. 3]**

Contributors

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