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

ARCHITECTURAL CULTURE
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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.

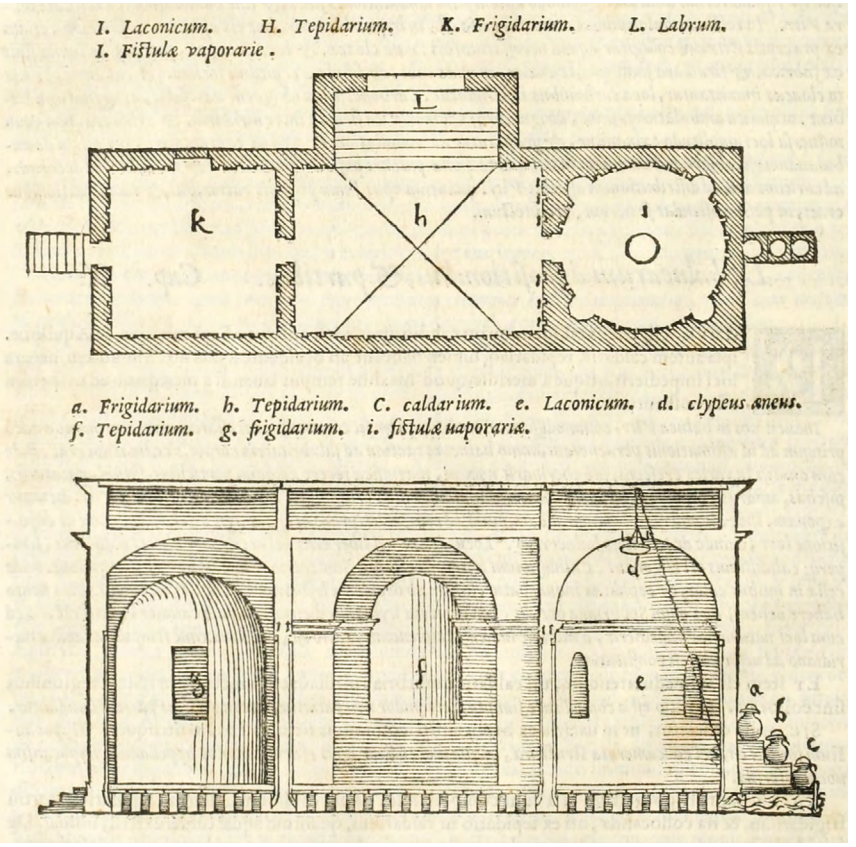


Fig. 1 Vitruvius, ed. Barbaro 1567, 198. BNP BA 259 V.

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].

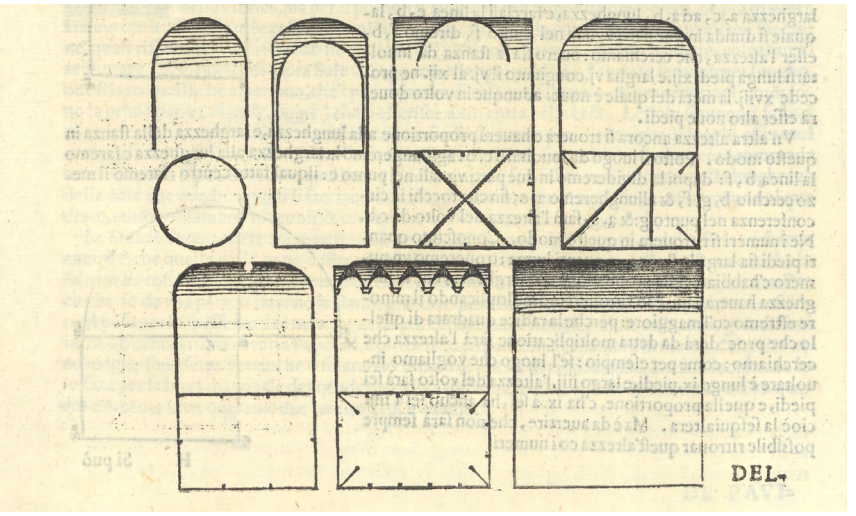


Fig. 2 Palladio 1581, 1.24. BNP Res. 2817 A.

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

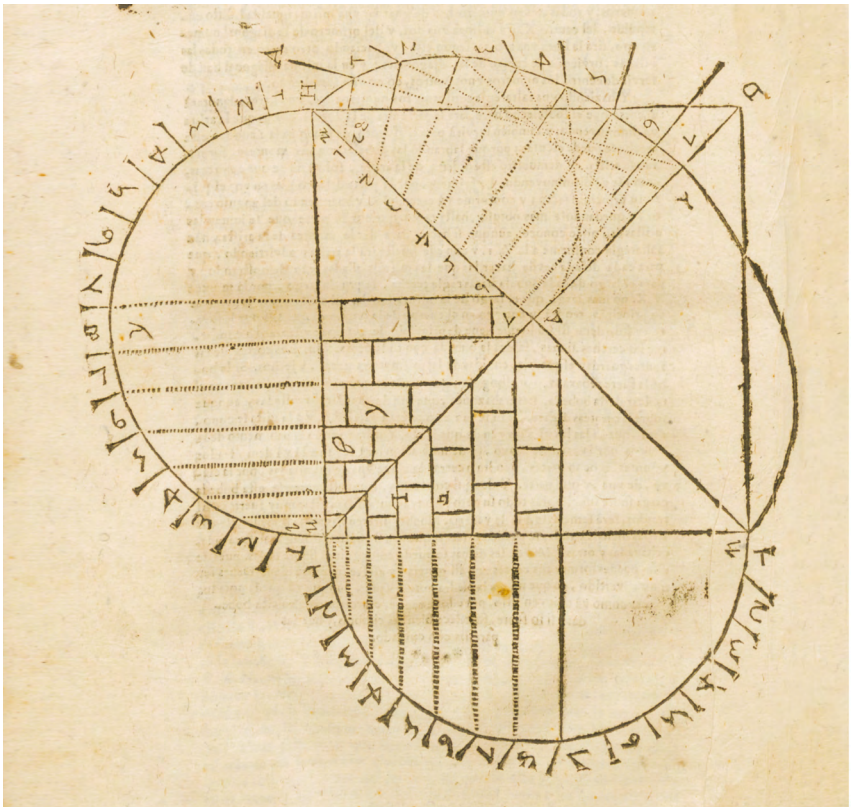


Fig. 3 Geometric diagram for the calculation and construction of timbrel vaults. San Nicolás (1639) 1736, 172. BNP 236 V.

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.

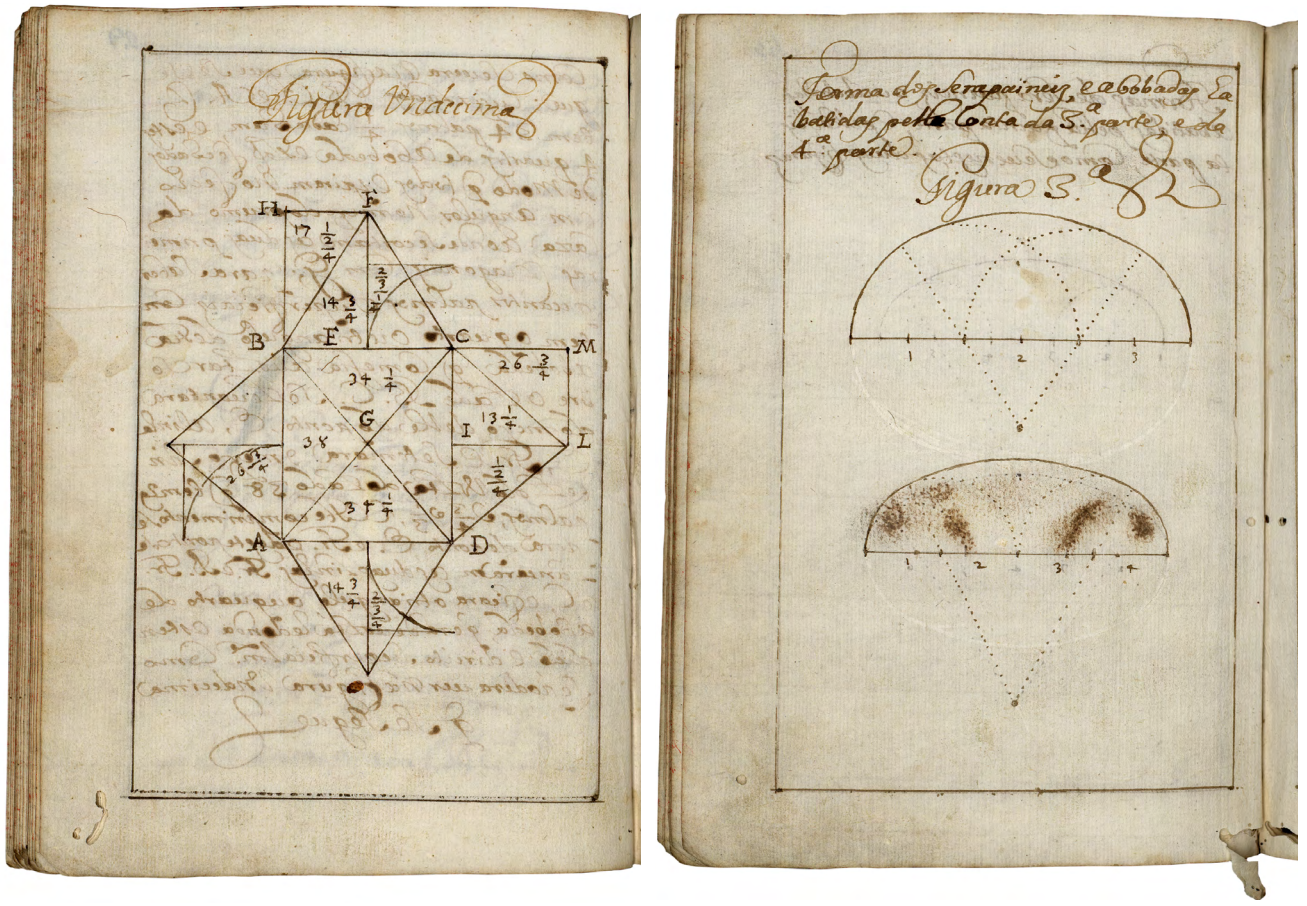


Fig. 4 'Figura Undecima', Tinoco 1660 [fol. 29v]. BNP Cod. 5166.

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]**

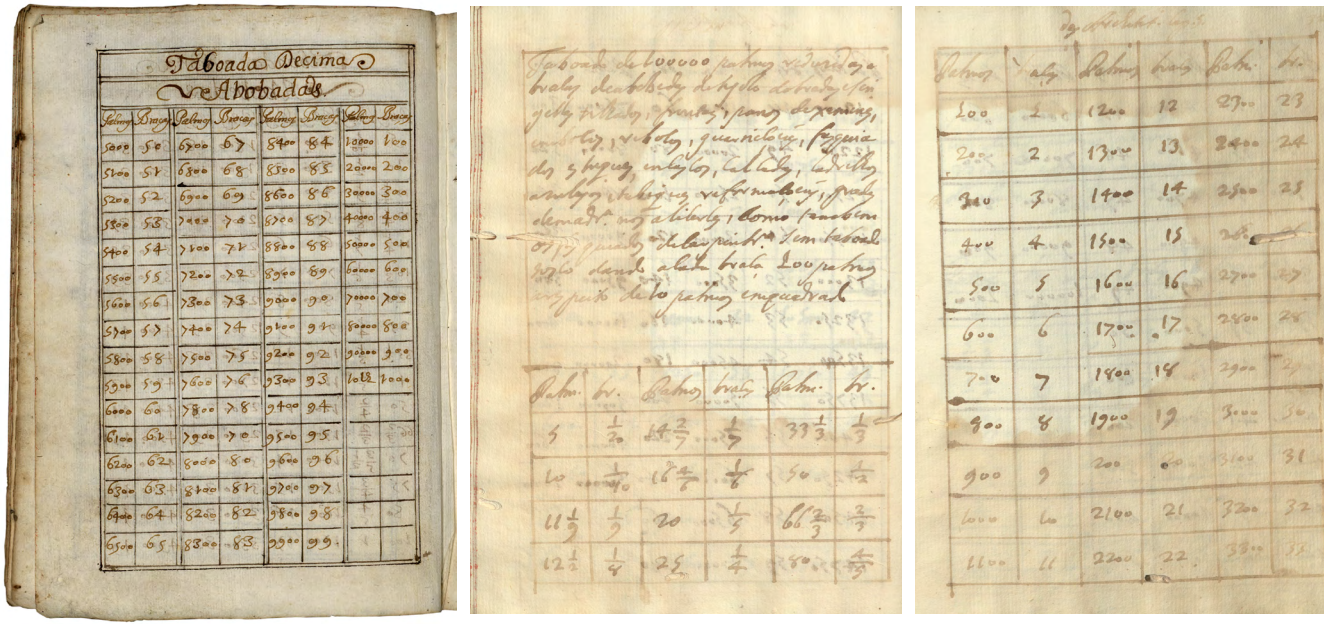


Fig. 6 'Taboada Decima, Abóbadas', Tinoco 1660, [fol. 9v]. BNP Cod. 5166.

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'

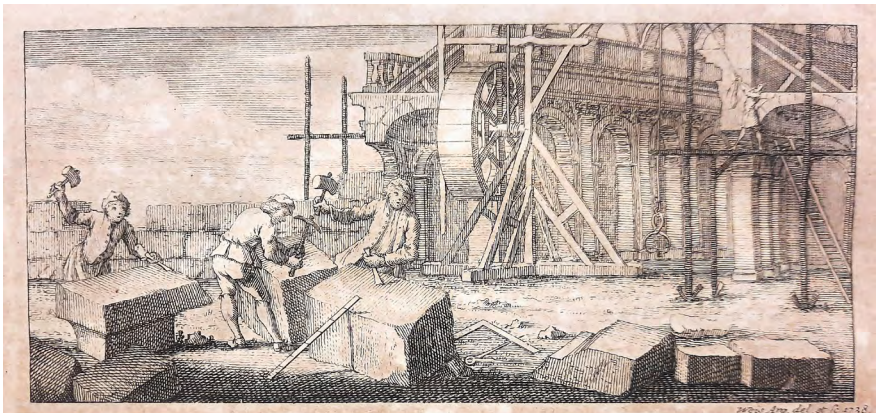
This text represents a leap forward from Portuguese fragments containing pragmatic approaches to vault construction, in which knowledge based on an oral and practical tradition prevailed. This is not so much a chronological leap as a scientific and methodological one, with a move away from geometry towards 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.]).



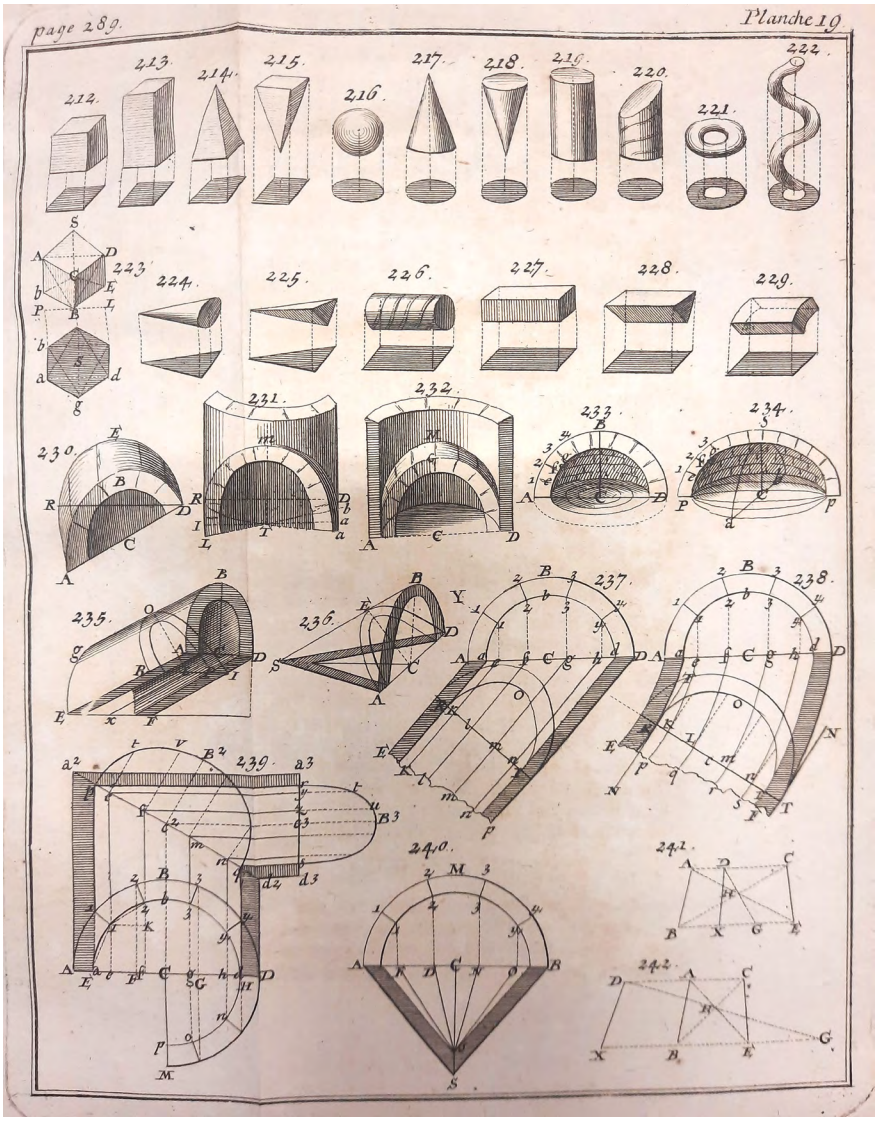


Fig. 8 Detail of the Third Book of the 'Treatise on Stereotomy'. Frézier 1739, vol. 3, 1. BNPM.

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

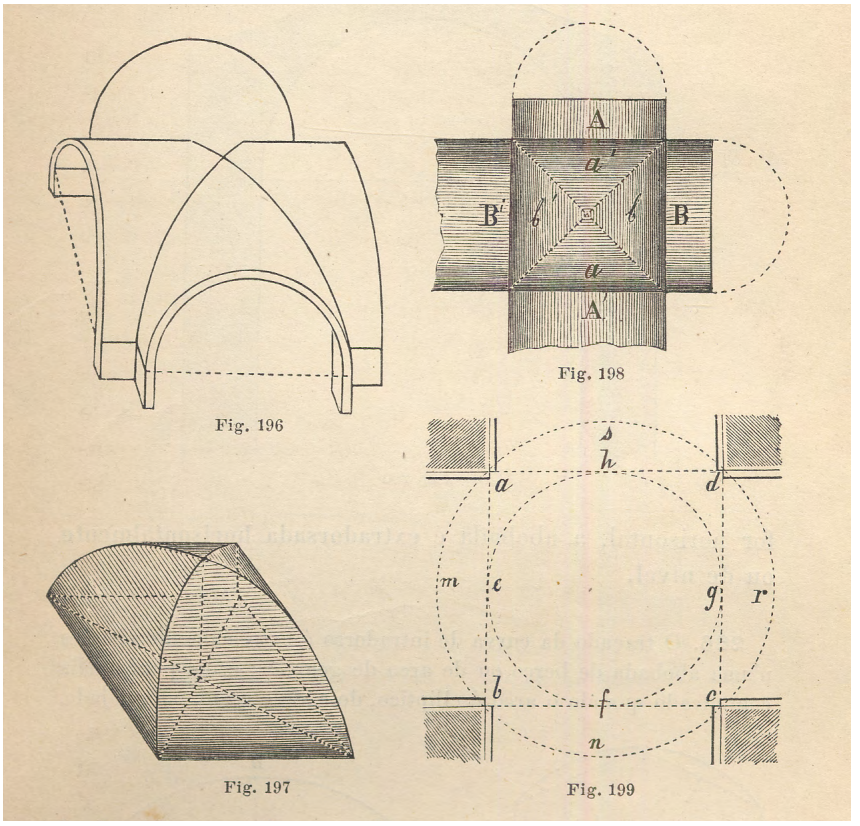


Fig. 10 Some types of vaults: axonometry of a groin vault (top left), plan of both groin and domical vaults (top right), axonometry of a domical vault (bottom left), and plan of a spherical vault with slopes applicable to the coverage of square or polygonal spaces. Leitão 1896, 255. BNP SA 5045 V.

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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