CONSTRUCTION HISTORY

International Journal of the Construction History Society

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Editorial

Sadly, we must start this editorial with news of the death in March 2014 of Joël Sakarovitch, the president of the French Construction History Society. Following this editorial we offer a tribute to Joël written by three of his close colleagues.

2014 is a year rich in anniversaries in the history of structures. We celebrate the 450th birthday of Galileo Galilei whose book Two New Sciences (1638) marks the beginning of the science of strength of materials; it is 250 years since the birth of Johann Eytelwein (1764-1849) author of arguably the first modern book on structural mechanics;[1] 1814 saw the publication of the first 4 volumes of the seven-volume treatise on the Art of Building by Jean-Baptiste Rondelet;[2] 1864 saw the death of Benoît-Pierre-Emile Clapeyron who first analysed bending moments in continuous beams,[3] and the publication of James Clark Maxwell's paper on reciprocal diagrams[4], Rankine's note on forces in frameworks[5] and the first of Karl Culmann's books on graphical statics.[6]

1864 also saw the publication of the third edition of Navier's lectures on structures and strength of materials[7] with a forward written by his pupil Barré de Saint-Venant (1797-1886). This great book is seen as a milestone in the analysis and understanding of elastic behaviour of materials and the deformation of structures loaded in bending, and contained the first exposition of Saint-Venant's ground-breaking principles. With regard to history, the book also contained the first history of the science of structures and has formed the basis of many more studies of the history of structures.[8] In 2014 we also celebrate the centenary of the birth of Charles Massonnet (1914-96), the great Belgian engineer and theoretician.[9]

While these may not be more anniversaries than we find in other years, they serve to focus our attention on the historical dimension of structural analysis, theory of strength of materials, and the development of structures, all of which form an important part of construction history.

Construction history studies any man-made structure in the built environment that was created with the aid of science and practical skills, especially from the point of view of materials and stability – but without losing sight of functional and artistic aspects. So often, these form the starting points for the construction history of a building's realisation and the associated construction processes. Research in construction history concerns the people participating in architectural and construction achievements and the era-specific processes, ideas, knowledge inventories, skills, and representation techniques, as well as the social, legal or economic circumstances surrounding the creation of the built environment. A key aim of construction history is to develop an understanding of the what, how and why of historic buildings, to re-enact the thinking and actions of the protagonists who created them and, more generally, to understand the building culture of an epoch.[10] The anniversaries mentioned above celebrate landmarks in the history of ideas (physics, structural analysis, calculus) represented through key treatises or scientific discussions and their interaction with design and construction practices which are central to our discipline.

It is well-known that the interest of natural philosophers in the knowledge and world views of craftsmen was one of the main starting points of modern science. Craft techniques – and very often those from the building sector – were regarded as a pool of every-day experiments with nature, and questioning them and analysing how they worked was a key to understand the laws of nature. Galileo, who himself had, among other things, dwelt on the knowledge of craftsmen from the Venetian arsenal, was a principal protagonist of this empirical approach. He managed to integrate the conclusions of his predecessors with his interrogation of the knowledge of craftsmen to create *Due nuove scienze*, published in 1638, which is commonly seen as the point of departure for the science of the strength of materials.[11] While Galileo's classic work has attracted the attention of historians of science,[12] it has not been the subject of recent study by historians of construction or structural mechanics.

2014 also sees the 300th anniversary of the death of Carlo Fontana (1634/38-1714). In many ways he was one of the last of the great pre-scientific engineers. In 1694 he proposed a standard cross-section for a masonry dome that was based on rules of geometry and proportion and builders' experience.[13] The section was intended to serve as standard design solution for any dome and indeed it was used with great success all over eighteenth-century Europe through Fontana's pupils and his book. On the occasion of the 300th anniversary of his death, there will be a conference in Rome on Fontana (22-24 October 2014), where the construction issues will be an important topic. A few years earlier Christopher Wren and Robert Hooke had begun to use mechanics as a basis for designing a dome and in 1712 La Hire published the first memoir on the mechanics of arches.

The interaction between modern science and building shifted the knowledge about materials and building stability away from the experience of building practitioners and authors such as Vitruvius, Alberti and Carlo Fontana and towards the mathematical modelling of physical phenomena which enabled engineering scientists to precalculate structural behaviour and to define minimum sections necessary to prevent failure. This meant that, for the first time, designers were able to calculate individual building components and their bespoke combination in each unique building *before the construction process started.* Today this seems to be the only possible approach, but it was the result of many enormous intellectual achievements over around 300 years.

The role of mathematics and science in building design developed from being based on proportion systems which had served mankind well from Antiquity to the 17th century, to become the new basis of knowledge about materials and structural mechanics from the 16th century. It is, however, not sufficient to regard mathematics as a new way of representing technical and scientific knowledge, to see it as the background of a new culture and epistemology of technology or to study it indirectly from a cultural history point of view and in the realm of discourse theory.[14] These external approaches to Construction History are important and necessary contributions, but in order to understand mathematics and scientific ideas thoroughly from the inside perspective of scientific and technological thought, they have to be studied in their own right (and not as a symbol for something else) and in great detail, as Jacques Heyman or Edoardo Benvenuto and others have shown us[15] and as, of course, occurs in the field of Construction History.[16] Over the last 10-15 years, however, research interest in these mathematical and scientific aspects of the history of structures and design has been in decline. There is still room for detailed studies which show how mathematics (and mathematical-based science) on the one hand, and building technology on the other hand, interact. Of particular interest is how mathematics enables the control of construction phenomena and can upgrade artistic and architectural design opportunities and how, the other way round, specific problems in the building sector fostered the advancement of mathematics and created new ideas in physics and mechanics.

We hope that more researchers will write about this historic dimension of structural analysis and engineering science in other branches of building such as heating and ventilation, acoustics and mechanics; this might be in the form of case studies or as part of the history of ideas, or with regard to the interaction between mechanics and other branches of physics and construction design practices.

Papers in this volume

This volume begins with a paper by Josep Lluís i Ginovart and Agustí Costa Jover on the design and construction of Tortosa cathedral in the Catalan region of Spain at the height of the Gothic era. The authors precisely compare the building as it stands today with contemporary accounts of its design and construction as well as a rare drawing on parchment on which traces of the compass used to create the drawing have allowed a reconstruction of the sequence of steps taken to set out the cathedral plan, including the seven-bay apse.

Domenica Sutera was also able to draw upon contemporary accounts of building to reconstruct events sorrounding the design and construction of the church of San Giuseppe dei Teatini in Palermo between about 1615 and 1645. This church was the culmination point for the structural and artistic use of Billiemi stone, which had been found shortly before near Palermo. Billiemi stone's strength and high density allowed it to be used for tall monolithic column shafts which were able to support heavy domes and vaults. The structural possibilities of the material led to a renewal of the architectural concept of the columnar basilica at an unprecedented monumental scale and to link Sicilian Baroque architecture to Palermo's Genius Loci, and thus to the Normannic architectural culture. It was only by emphasising that he would employ equipment and methods based on those used by Domenico Fontana to move the Vatican obelisk in 1586, that the engineer and architect Giacomo Besio managed to persuade the sceptical client to allow his scheme, which included 80 monolithic columns, some as tall as 10 metres, to be built.

We move forward to the turn of the twentieth century in Edwin Trout's paper in which he traces the origins and early work of the Deutscher Ausschuß für Eisenbeton (German Committee for Reinforced Concrete). More than any other organisation, it established the robust foundation of materials testing, standards, performance specification and design methods which enabled reinforced-concrete construction to blossom and quickly become a dominant influence on the work of the greatest architects.

Andrew Saint offers us a portrait of Samuel James Waring, an almost forgotten entrepreneur who had a significant impact on the design and construction of department stores in early-twentieth-century London. Although working mainly as a contractor for the interiors of stores, as well as hotels, theatres, ocean liners and the homes of the rich, he was also the first major contractor to bring American management methods into building projects in London and beyond.

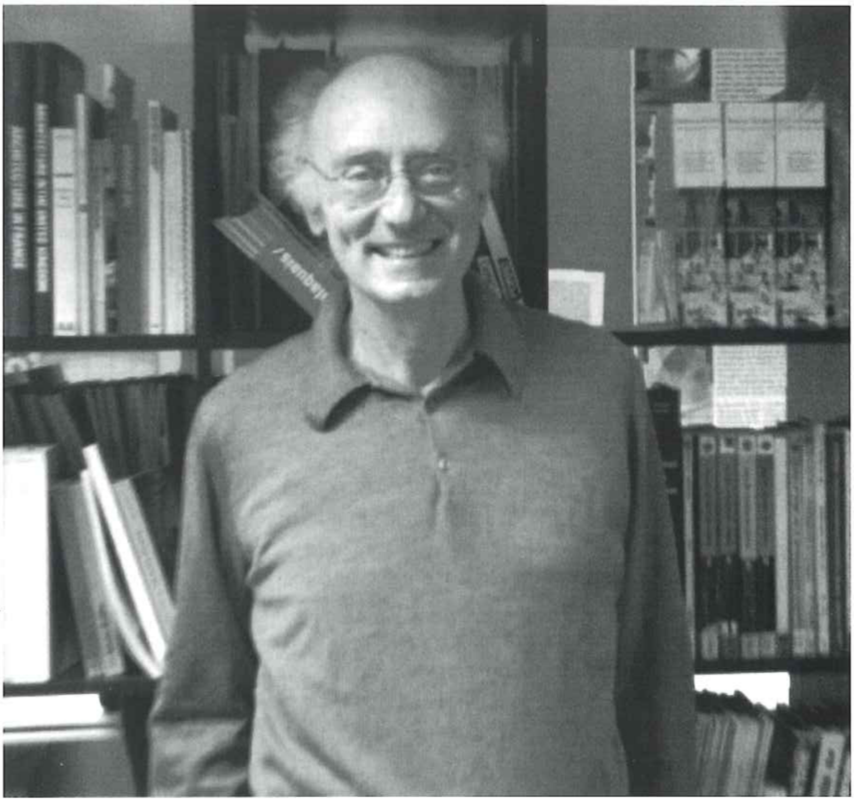
This volume ends with a little-studied aspect – the building services and internal environment – of a very well-known building – Charles Rennie Mackintosh's Glasgow School of Art. Ranald Lawrence argues convincingly that one of the greatest exponents of 'total design' not only embraced the architecture and interior design in ways characteristic of the Arts and Crafts movement, but was also strikingly innovative in his scientific approach to lighting the studios both in daytime and at night, and providing a comfortable indoor climate for the students in the early days of fan-assisted ventilation and heating. A sad footnote to this paper is that, as the present volume goes to press, this superb building was severely damaged by fire; we can only hope that it can be saved and returned to the function it has provided for over a century, as an art college.

Bill Addis
Hermann Schlimme
May 2014

1. J A Eytelwein, *Handbuch der Mechankik fester Körper und der Hydraulik* (Berlin, 1801) and *Handbuch der Statik fester Körper* (Berlin, 1808).
2. J.-B. Rondelet, *Traité théoretique et pratique de l'art de bâtir*, 7 vol., Paris: 1802-1817.
3. See K.-E. Kurrer, *The History of the Theory of Structures. From Arch Analysis to Computational Mechanics*. Berlin: Ernst und Sohn 2008, p. 722. (German edition: K.-E. Kurrer, *Geschichte der Baustatik*, Berlin: Ernst und Sohn, 2002, p. 466).
4. J. C. Maxwell, "On reciprocal figures and diagrams of forces". *Philos Mag* 26, 1864. pp. 250–61
5. W. J. M. Rankine, "Principle of the equilibrium of polyhedral frames". *Philos Mag* 27, 1864. p. 92.
6. K. Culmann, *Die graphische Statik*, Zurich: Meyer & Zeller, 1864-66.
7. A.J.C.B. de Saint-Venant [C.L.M.H. Navier], *Résumé des Leçons données à l'Ecole des Ponts et Chaussées sur l'application de la Mécanique à l'établissement des constructions et des machines, avec des Notes et des Appendices par M.Barré de Saint-Venant*, Paris, 1864.
8. J. Heyman, *Coulomb's Memoir on Statics. An Essay in the History of Civil Engineering*, Cambridge: Cambridge University Press, 1972, p. 109, W. Addis, *Structural Engineering. The Nature of Theory and Design*, New York et. al.: Ellis Horwood, 1990, pp. 91, 95; A. Becchi, 'I criteri di plasticità: Cento anni di dibattito (1864-1964)' (Ph.D. thesis, Università degli Studi di Firenze, 1994), available online, website http://www.bma.arch.unige.it/pdf/Becchi.pdf (Consulted on 30th April 2014); F. Foce, "Same Title, New Contents: Saint-Venant's Revised Edition [1864] of Navier's *Résumé Des Leçons Sur L'application De La Mécanique* [1826, 1833], in R. Carvais, A. Guillerme, V. Nègre and J. Sakarovitch (Eds.), *Nuts & Bolts of Construction History*, vol. 1, Paris: Picard, 2012, pp. 271-280.
9. C. Massonnet and M. Save, *Calcul plastique des constructions, vol. 1: Structural planes*, Brussels/New York: CBLIA and Blaisdell, 1961; C. Massonnet and M. Save, *Calcul plastique des constructions, vol. 2: Structures spatiales*, Brussels: CBLIA, 1963. In honour of Massonet there is the Charles Massonnet Award presented by the European Convention for Constructional Steelwork (ECCS).
10. Indeed, this effectively defines the scope of the Construction History journal.
11. G. Galilei, *Discorsi e dimostrazioni matematiche, intorno a due nuoue scienze attenenti alla mecanica & i mouimenti locali*. Leiden: Elsevir, 1638; K.-E. Kurrer, "Die Anfänge der Festigkeitslehre bei Galilei", in *momentum Magazin*, 2014, website http://momentum-magazin.de/de/die-anfange-der-festigkeitslehre-bei-galilei/ (Consulted on 30th April 2014).
12. For example in Matteo Valleriani, *Galileo Engineer*. Dordrecht: Springer, 2010.
13. C. Fontana, *Templum Vaticanum et ipsius origo,* Rome: Buagni, 1694.
14. In his book on the Machine de Marly, Brandstetter analyses scientific and technical knowledge at the basis of and stemming from the machine in this sense: T. Brandstetter, *Kräfte messen. Die Maschine von Marly und die Kultur der Technik*, Berlin: Kadmos, 2008.
15. Heyman, *Coulomb*, (Note 8); E. Benvenuto, *An Introduction to the History of Structural Mechanics*, New York/Berlin: Springer, 1991.
16. There were sections on these topics at all past ICCH. To just cite one of the most recent publications: A. Becchi, H. Rousteau-Chambon and J. Sakarovitch, (Eds.), *Philippe de La Hire (1640-1718). Entre architecture et sciences*, Paris: Picard, 2013 ; an overview of this research field and its publications is in the *Bibliotheca Mechanico-Architectonica*. An Open Source *Digital Library Between Mechanics and Architecture,* website http://www.bma.arch.unige.it/ (consulted on 28th April 2014).

Joël Sakarovitch

Born Paris, 10th August 1949; died Paris, 20th March 2014



In March 2014 Joël Sakarovitch, President of the Association Francophone d'Histoire de la Construction (the French Construction History Society) died at the age of 64. This is a great loss to his family, his friends, his work colleagues at Ecole Nationale Supérieure d'Architecture Paris Malaquais, and to the world of Construction History.

I first met Joël about a decade ago and am aware of his great contribution to our field of interest, not least his helping to organise the first Francophone Congress on Construction History in Paris in June 2008 and the 4th Internation Congress on Construction History, also in Paris, in 2012. He was always incredibly enthusiastic in his conversations and discussions about the subject that was his passion, and he conveyed this enthusiasm to everyone around him. I last saw him at the second Francophone Congress on Construction History in Lyon in January 2014 where he seemed to be his usual lively self. It was a great shock when news of his untimely death came.

We print below three tributes to Joel by colleagues who know him well and for many years – Robert Carvais, Anne Coste, Philippe Potié and Antonio Becchi. In this issue of Construction History we print the tributes in their original French; we will print a translation in English in the next issue.

Bill Addis

Tribute from Robert Carvais

Treasurer of the Association francophone de l'histoire de la construction

---

Funeral blues

Stop all the clocks, cut off the telephone,
Prevent the dog from barking with a juicy bone,
Silence the pianos and with muffled drum
Bring out the coffin, let the mourners come.

Let aeroplanes circle moaning overhead
Scribbling on the sky the message He Is Dead,
Put crepe bows round the white necks of public doves,
Let the traffic policemen wear black cotton gloves.

He was my North, my South, My East and West,
My working week and my Sunday rest,
My noon, my midnight, my talk, my song;
I thought that love would last for ever: I was wrong.

The stars are not wanted now: put out every one;
Pack up the moon and dismantle the sun;
Pour away the ocean and sweep up the wood.
For nothing now can ever come to any good.

Wystan Hugh Auden, *Another Time*, 1940

Mon ami, Joël,

Je veux m'adresser à toi pour te dire combien tu m'as impressionné durant toutes ces années que nous avons partagées ensemble à mettre en place ce réseau d'histoire de la construction que ce soit alors que nous organisions les deux congrès réussis l'un francophone, l'autre international - avec Valérie et André - ou bien lorsque nous préparions notre séminaire - avec Philippe - et évoquions l'idée de créer une revue - avec l'association. Tu sentais que tu n'aurais pas la force de la voir paraître. Je te promets que nous y parviendrons avec toi à nos côtés dans nos cœurs et nos esprits. Si toutes nos entreprises ont été des réussites, tu y es pour beaucoup, toi qui étais présent et discret à la fois, vigilant et bienveillant. Tu peux en être sûr. L'association francophone d'histoire de la construction vivra avec les préceptes que tu as définis et exercés pour la présider.

Au début tu m'as introduit dans le cénacle des historiens de la construction à Madrid lors du premier congrès international en janvier 2003. Je m'étais obstiné à contribuer à cette manifestation même si j'étais hors délai. Tu m'avais accueilli dans ta session avec énormément de gentillesse, me mettant à l'aise tout de suite – vu d'une part que j'étais un inscrit de dernière minute et que d'autre part je n'étais qu'un historien du droit. Que pouvais-je venir faire avec des historiens des techniques et des sciences ?

Nous avons alors beaucoup discuté. Tu as finalement compris ma présence et l'intérêt que je pouvais porter à tes travaux. Tout cela s'est poursuivi à Gênes. Tu entendais bien le rôle des artisans maçons dans le fonctionnement et la transmission des savoirs pratiques de l'art de bâtir. Je m'initiais à la géométrie et aux tracés d'épures d'architecture. Ta thèse me troublait car elle me faisait comprendre des pratiques que la lecture des archives judiciaires ne m'avait même pas permis d'apercevoir – et pour cause, je n'empruntais pas la bonne démarche. Il fallait pénétrer la littérature scientifique et technique du XVIIe siècle et tu nous en donnais les clés. C'est sur cet échange qu'a débuté notre travail. Je pouvais discuter avec tes thésards et leur expliquer le pouvoir de certains maçons et nous troquions des informations. Tu savais avec facilité et aisance nous expliquer une loi de mécanique et très simplement tu parvenais à nous en démontrer les effets pratiques. C'est véritablement ton trait de génie : passer de la théorie à la pratique. Je sais le plaisir que tu prenais aux Grands Ateliers de l'Isle d'Abeau, comme le rappellent tes amis de Craterre avec qui tu les as fondés Patrice Doat et Hubert Guillaud. Je regrette de ne pas y avoir participé, ne serais-ce qu'une seule fois ? Mais je me souviens encore du moment où tu m'as expliqué la règle de Derand. Lumineux!

Si tu m'as surpris quant à l'espace phénoménal des cultures que tu maitrisais - avec beaucoup de modestie d'ailleurs - (je pense que tu as eu plusieurs vies. Tu étais mathématicien, architecte, savant, constructeur, expérimentateur, historien), je fus aussi fortement ému par ton courage face au mal qui t'as atteint. Lorsque tu me dévoilais avec beaucoup de pudeur comme tu étais touché, je décidais bien qu'anéanti par la nouvelle, de tout faire pour avancer avec détermination et conviction dans nos projets. J'ai sciemment - je le reconnais maintenant - accéléré notre activité de travail pour te faire penser à autre chose. Cela a été difficile pour moi mais il me semblait qu'il le fallait pour t'aider. J'espère que tu n'en as pas trop souffert. Alors combien de fois nous sommes nous écrit, nous sommes nous appelés par jour pour avancer, régler les problèmes qui se posaient, détourner les obstacles qui s'interposaient, visiter les uns, convaincre les autres pour le moindre détail afin que tout se déroule parfaitement et que nos hôtes soient le plus satisfaits possible. Comme tu étais content à l'issu du Congrès que tout se soit bien passé! Quel bonheur tu affichais! Ce fut notre récompense et je t'en remercie profondément car je sais que tu étais déjà fatigué.

Les vacances passées, nous allons t'acheter ensemble de nouveaux ordinateurs. De PC tu passais à Apple. Tu allais devenir un vrai geek. Comme nous riions de cela. J'ai cru pouvoir reprendre de plus bel avec la suite : l'association, la création de la revue, le bilan international, le séminaire, les nouveaux congrès en France, à l'étranger. J'ai senti que tu étais très fatigué mais tu as fait bonne figure. Tu as toujours répondu présent jusqu'au denier moment. Tu rédiges pour moi un article sur Desgodets que tu peaufines, m'envoyant plusieurs versions des textes avec des corrections. Je te remplace à Berlin pour la naissance de l'inauguration de l'association sœur allemande d'histoire de la construction. Tu descends faire une expertise de la charpente de l'Eglise de Bédoin il y a à peine quelques mois. Tu participes au rapport sur cette controverse que je rédige pour le CNRS. Tu penses à faire réaliser deux maquettes pour une exposition à venir. Tu écris l'introduction de la publication des keynotes du Congrès. Tu prépares un powerpoint avec moi sur l'analyse des illustrations du traité d'architecture inédit de D'Alleman pour notre séminaire il y a à peine quelques semaines. Tu continues de faire soutenir thèses et HDR. Tu donnes tes derniers cours alors que tu ne tiens plus debout jusqu'à l'épuisement. Comme a écrit Joelle Trouvé, ce n'est pas une vie, mais c'est la vie que tu as choisie. Et cela mérite plus que du respect.

Je suis bouleversé c'est vrai. Je suis devant toi incapable de te dire adieu car je sais qu'un jour ou l'autre nous continuerons nos conversations, nous continuerons de penser ensemble aux stratégies du monde, à l'avenir de nos enfants et de nos petits-enfants, toi qui venait de recevoir avec une immense joie la venue de Gabriel, d'essayer de comprendre comment tout cela pouvait fonctionner, de rire aussi à des blagues yiddish comme tu les aimais tant, bref de refaire le monde avec une douceur extrême de vivre. Nous nous retrouverons à Saint-Hugues ou à Flandrin. Nous nous promènerons dans les alpages frais ou dans le maquis des Cévennes à la tombée du soleil – car tu n'aimes pas trop la chaleur étouffante du soleil. C'est vrai que tu es ashkénaze et que je suis séfarade. Mais nous nous accommoderons de nos différences. Nous échafauderons des milliers de plans et de projets que nous réaliserons avec ceux qui nous sont chers.

Je ne peux pas te dire adieu mais simplement à plus tard.

Penses-y et dis-moi.

Robert
Paris, le 20 mars 2014, premier jour du printemps
Cimetière de Bagneux, le 25 mars 2014

Tribute from Anne Coste and Philippe Potié

Brillant et modeste, Joël Sakarovitch

Avec la disparition de Joël, notre petit club des historiens de la construction de Saint-Pierre de Chartreuse perd un tiers de ses membres. Quel hasard a conduit à ce que ce petit village d'un millier d'habitants compte parmi ses résidents (permanents pour nous, saisonniers pour Joël et sa famille) trois membres du réseau Cultures constructives, trois professeurs des ENSA, historiens de la construction ? Nous perdons tous les deux un complice chartroussin mais aussi un collègue respecté qui a accompagné nos propres parcours professionnels.

Nous avons d'abord connu Joël Sakarovitch dans les colloques : Gênes (à plusieurs reprises), Madrid, Paris, etc. Nous l'avons côtoyé au sein du réseau Cultures constructives dans les années 1990 puis des Grands Ateliers de l'Isle-d'Abeau depuis 2002.

En Chartreuse, chaque fois que l'un ou l'autre passe à proximité de la maison des Sakarovitch, en voiture, à pied, en vélo, en ski de fond, il jette un coup d'œil pour voir « si c'est ouvert ». Sais-tu si Joël et Régine viennent pour les vacances ? Cette maison, c'est le frère de Joël qui en avait fait l'acquisition, il y a bien longtemps, lorsqu'il travaillait à Grenoble. Lorsqu'il a décidé de la revendre, Joël et Régine ont pris le relai.

Existe-t-il un mot en français pour dire « malice bienveillante » ? Joël avait cet œil malicieux pour cacher son angoisse lorsque l'on mettait à l'épreuve la résistance des ses voûtes plates adorées. Il ressentait dans sa chair les pressions infernales auxquelles on soumettait sa progéniture, et que dire du moment crucial du point de rupture. Il était un grand professionnel, avait la générosité des vrais pédagogues, une culture infinie et faisait montre d'une modestie déconcertante.

Il y a eu l'histoire de la terrasse de la maison de Saint-Hugues, en plusieurs épisodes! Ce fut le grand œuvre des dernières années en Chartreuse. Conciliabule de constructeurs un peu théoriciens (ah! la main à la pâte...) : quel bois ? quelle technique ? et la balustrade ? Joël, il nous aura tenu en haleine ton chantier de terrasse et nous pensons pouvoir dire qu'il t'aura aussi bien amusé.

Il y eut l'époque où nous ne retrouvions Joël que dans les colloques de nos amis espagnols, italiens, anglais et allemands, envieux de ces communautés scientifiques qui savaient faire vivre l'histoire de la construction comme discipline. Il n'y avait alors que quelques français parmi les communicants. Puis, avec ses proches collègues, Robert Carvais, André Guillerme, Valérie Nègre (et d'autres), Joël a créé l'association francophone d'histoire de la construction et les premiers congrès se sont tenus, à Paris puis à Lyon. Grâce à vous tous cette communauté existe aujourd'hui et nous savons que nous le devons en grande partie à la volonté, au travail, à l'implication de Joël.

Pour toutes ces raisons, nous voulions apporter notre témoignage maintenant que Joël nous a quittés. Beaucoup d'autres auraient pu le faire. De plus proches collaborateurs, de plus intimes amis. Nous avons perdu un grand scientifique et un membre très aimé de notre petit club local. Joël ne sera plus au rendez-vous en Chartreuse, nous espérons de tout cœur que les fenêtres de la maison de Saint-Hugues s'ouvriront encore de temps en temps par la grâce de Régine et de leurs enfants.
Saint-Pierre de Chartreuse, le 20 avril 2014.
Anne Coste
AE&CC, ENSA Grenoble
Et
Philippe Potié
LEAV, ENSA Versailles

Tribute from Antonio Becchi

A Joël, le juste[1]

Quand bien même la rédemption ne devrait pas venir,
je veux à tout instant être digne d'elle.
Franz Kafka, *Journal*, le 25 février 1912

Maintenant je peux le dire. Le sujet de la communication que j'ai présentée au 4e Congrès International d'Histoire de la Construction (Paris, 3-7 Juillet 2012), puis publiée dans ce journal[2], avait été défini le 18 novembre 2011, dans un bistrot de Paris, place Denfert-Rochereau. J'étais là avec Joël, nous venions de quitter l'ami Werner Oechslin, après avoir visité ensemble l'exposition *Mathématiques : un dépaysement soudain* à la Fondation Cartier pour l'art contemporain. L'exposition nous avait profondément déçus, Joël m'avait proposé de discuter encore un peu, avant de nous séparer.

La conversation avec lui, au bistro, je ne l'oublierai jamais. On sait que la vie est brève, mais dans certains moments on le flaire davantage. On le perçoit. Nous, Joël et moi, ce jour là, l'avons ressenti au plus profond de nos êtres, l'avons vu comme dans un miroir sur nos visages. Nos confiances nous rapprochaient encore plus, nos vies et nos songes étaient soudain devenus plus concrets et, en même temps, terriblement fragiles. Au bout de deux heures j'ai quitté Joël en sachant ce que j'allais dire au congrès : ma contribution devait être un hommage à l'esprit Saka. Je ne savais pas encore qu'elle devait croiser une autre amitié, celle avec Werner Oechslin, qui recevait la Gauß-Medaille au cours du séminaire *Architektur-Wissenschaft* (Braunschweig, 11 Mai 2012). Joël, comme Werner, était un talent hors de l'ordinaire, mais surtout, comme lui, un esprit qui m'avait avant tout foudroyé par l'honnêteté de la pensée, la clarté de la passion, la générosité de l'amitié.

Deux ans et demi après celle conversation d'hiver j'étais à Londres dans un jardin, avec mes enfants, quand Régine m'a appelé pour me dire que Joël était mort, qu'il était parti. J'ai commencé à pleurer et j'ai tout de suite pensé à une image décrite par Dante dans *La divine comédie*. Nous sommes dans le *Purgatoire* (chant XXII) et Stace, le poète latin, parle de Virgile. Il dit :

> *Oui, tu fis comme ceux qui portent un flambeau derrière eux, dans la nuit,*
> *et n'en profitent pas, mais montrent le chemin à celui qui les suit.*

Quand j'ai rencontré Joël pour la première fois, il y a plus de vingt ans, j'ai compris immédiatement qu'il y avait une affinité d'esprit, une syntonie entre nous. Mais j'étais jeune et impatient, certains traits de son caractère je ne les ai pas compris au premier regard. Je voyais le flambeau, mais je pensais qu'il le portait derrière lui par une sorte de distraction, d'esprit rêveur. Par hasard, peut-être.

Je n'avais rien compris. Le flambeau porté derrière était en effet un style de vie pour Joël. Il était extrêmement compétent et professionnel, mais le flambeau était là parce qu'il était gentil et généreux. Il ne voyait aucune contradiction entre talent et gentillesse, entre compétence et générosité. Il savait qu'on peut avoir passion sans arrogance, calme sans paresse.

Joël était un homme de science qui aimait l'architecture, la construction et comme homme de science il savait parfaitement que la balance peut avoir bras égaux ou inégaux, que les poids dans un état d'équilibre peuvent être les mêmes ou très différents entre eux. On pourrait imaginer une sorte de balance posée sur l'épaule, avec deux flambeaux aux extrémités. On pourrait avoir dans la main la balance de la justice et on pourrait se bander les yeux, comme parfois sont bandés ceux de la déesse de la justice. Mais Joël ne voulait pas cela. Il savait que dans la vie les poids et les mesures réglés et conservés à Sèvres ne sont pas de mise.

La vie, comme l'art de la stéréotomie (pour laquelle il était l'expert, admiré au niveau mondial), est différente, doit être différente. Joël savait que les pierres peuvent rester suspendues dans l'air, comme l'enseignent la stéréotomie et l'art du trait, que la gravité n'oblige pas à être et paraître lourd. Joël avait choisi d'être miséricordieux avec les collègues, avec les amis, avec le monde.

Ce trait de son caractère lui avait fait gagner le respect et l'admiration de la communauté scientifique internationale. C'est la raison pour laquelle nous avons reçu ce week-end des dizaines de messages du monde entier, des collègues allemands, anglais, italiens, belges, suisses, espagnols etc.

L'homme extrêmement compétent, l'homme qui avait changé notre conception de l'histoire de la construction, était celui qui avait aussi changé nos vies. En rencontrant Joël nous avons rencontré un homme rare que le destin à mis sur notre chemin pour nous faire comprendre que les choses peuvent être différentes dans la famille, dans l'Université, dans le quartier, dans la communauté scientifique, dans les rapports humains en général. Nous pleurons, aujourd'hui, un homme juste.

J'avais fait lire à Joël, il y a vingt ans, un écrit de Borges qu'il avait beaucoup aimé. Aujourd'hui cet écrit lui est dédié, à lui et à tous les justes, ils ne sont pas nombreux, que nous avons rencontrés dans notre vie :

Un homme qui est reconnaissant à la musique d'exister.
Celui qui découvre avec bonheur une étymologie.
Deux employés qui dans un café du Sud jouent en silence une partie d'échecs.
Le céramiste qui médite une couleur et une forme.
Le typographe qui compose bien cette page, qui peut-être ne lui plaît pas.
Une femme et un homme qui lisent les derniers tercets d'un chant.
Celui qui caresse un animal endormi.
Celui qui justifie ou cherche à justifier le mal qu'on lui a fait.
Celui qui est reconnaissant à Stevenson d'exister.
Celui qui préfère que les autres aient raison.
Tous ceux-là, qui s'ignorent, sauvent le monde.

(tiré de Jorge Luis Borges, *Los justos*, 1981)

Joël, le juste, nous a enseigné à mourir et, en faisant ça, à vivre. Mais il nous a fait un double cadeau. En effet il avait commencé à nous enseigner à vivre bien avant d'être malade. Il n'a pas eu besoin de la maladie pour décider de porter le flambeau derrière lui. Maintenant nous avons une responsabilité exceptionnelle devant nous : de donner l'exemple au petit Gabriel et à tous les petits ou grands Gabriels que nous rencontrerons sur notre chemin. Tous ceux qu'on pourrait décrire avec les mots que Joël avait choisi pour *son* Gabriel :

Deux kilos six, il est pas gras,
Mais dans nos cœurs on lui accorde
Toute la place de la Concorde.

Heiner Müller, grand dramaturge allemand, disait que la réalité n'est pas constituée seulement des vivants. La réalité, selon lui, est divisée en deux : d'un coté il y a les vivants, de l'autre ceux qui sont partis, les absents. Les morts, nos morts, sont doués de gravité et occupent, comme les vivants, un espace dans la réalité, dans notre vie. L'espace est unique et les vivants le partagent avec les absents : l'espace à disposition des vivants dépend de celui occupé par ceux qui sont partis d'ici, mais qui sont encore là. Joël, après le 20 Mars 2014, restera pour toujours partie fondamentale de cette réalité duale.

Au revoir, cher ami, je penserai à toi, reconnaissant, chaque jour, d'ici à la prochaine rencontre.

Absence
plus aigue présence.
Vague pensée de toi
vagues souvenirs
troublent l'heure calme
et le doux soleil.
Douloureux le cœur,
te porte
comme une pierre
legère.

(Attilio Bertolucci, *Assenza*, dans le recueil *Sirio*, 1929)

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1. Cet écrit est basé sur le discours prononcé aux obsèques de Joël Sakarovitch mardi le 25 Mars 2014 (cimetière de Bagneux, Paris).
2. Antonio Becchi, *Looking for an equilibrium point: Wilson, Machiavelli and the King of Siam,* «Construction History», vol. 28, n. 3, 2013, p. 1-19.

Design and medieval construction: The case of Tortosa cathedral (1345-1441)

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Abstract

Gothic design and construction was generally dependent on the knowledge of the magister operis but, in the case of cathedrals, it was finally determined by the influence of the Chapter. The knowledge of these two protagonists and the transfer of their learning suggest that the construction of certain buildings were, effectively, based on experimental designs. The remarkable Archivo Capitular (Chapter Archive) of the Cathedral of Tortosa preserves not only the masonry books but also the designs of Antoni Guarc (c.1345-80) and the scientific texts of the canons. These sources have facilitated an epistemological study of the knowledge that enabled the building's designer to meet the challenge set by the Chapter to build the ideal of the City of God.

The construction of the apse of Tortosa cathedral (1345-1441) was an experiment aimed at the total elimination of the wall from the radial chapels, using a cross section with a very low span-to-rise ratio (9/5). When its stability was confirmed, the ratio was increased in the construction of the ambulatory (9/6). The builder then provided a design solution on site of the enigmatic heptagon, based on a proportional theory (9/8). The methodology used by the designer was inspired by a Neoplatonic proportional theory, founded on the scientific texts of the library of the canons.

Keywords

Cathedral, medieval geometry, design, heptagon, Tortosa Cathedral.

Introduction: Previous studies of the Cathedral of Tortosa

The first assessment of the Cathedral of Tortosa, which appears in the codex *Notas antiguas de esta catedral,* written by the canon Manuel Macip (c.1645) is a compilation of several notes regarding the various stages of construction. The first publication about the building and its archive was in 1890 by Ramon O' Callaghan.[1]Wider international awareness of the cathedral is due to the work of José Matamoros,[2] whose work was given recognition by Pierre Lavedan in 1935.[3]

It is only since the historiographical work of Victoria Almuni in 2007 that it has been possible to understand the chronological evolution of the construction of the apse of the cathedral. [4] Her investigation is based on two main documentary resources: the notarial records of the Chapter Archive of Tortosa (ACTo) which contain the records of the business of the Chapter and the *Llibres d'Obra* (masonry books). The assessment of the 41 volumes about the main stages of the Gothic work between 1345 and 1463 revealed much information from primary sources about the construction of the cathedral. The combined assessment of the constructional matters appearing in the masonry books and the masonry of the built structure, reveal to us a good understanding of the evolution and the organization of the works from a technical point of view. It should be noted that the Chapter Archive is an unusual case since almost all the documents remain intact.

Another main source is the first geometrical survey of the Cathedral of Tortosa, made by computer between 1995 and 2000 for the *Pla Director Sancta Maria Dertosae,* by Josep Lluis i Ginovart.[5] Most of the dimensions for the plan view were taken by direct measurement, while the section relied on indirect measurement techniques. The accuracy of the planimetry is better than 1%.

The combined sources of data from the primary sources and the palaeography of the masonry itself have enabled an assessment of the construction history of apse of the Cathedral to be undertaken. As a result of these investigations, some of the conclusions about the construction of the apse have already been published: the first was a study of the evolution of the shape of the columns of the radial chapels from a structural point of view by Josep Lluis i Ginovart.[6] More recently, the joint work of Almuni and Lluis considers the setting of the main keystone of the presbytery, and explains the construction sequence of the apse.[7]

In 2012 Universitat Rovira i Virgili performed a photogrammetric survey of the vaulting of the apse and created a 3D model. The data is obtained using a total station Topcon Imaging Station 203, with a precision of 0.2 mm/1 mm ± (5 mm), which will be combined with the photographs taken with a calibrated camera Nikon D7000+Tokina 12-24, using full magnification of the zoom lens.[8] The results of the earlier geometrical survey have been revised using the new data, parameterizing the geometrical models with an accuracy of about ±30mm.

The geometrical survey of the oldest Gothic building plan in Spain, , has enabled a comparison between the building, as constructed, and the intended design, as shown in the mediaeval parchment attributed to Antoni Guarc (c.1345-80), known as the *Traça de Guarc*. The measurements published in this paper and the geometrical assessment, are obtained by superimposing the setting out lines of Guarc onto the elevation of the cathedral. Some of the key points are not accessible, as they are within the columns and walls, so the dimensions given have a deviation of around 1%. Also, the deviations between the theoretical design and the building due to the building process itself must be taken into account.

The sequence of the layout made by Guarc is similar to the construction of the apse: radial chapel, ambulatory, main keystone and presbytery, which enables us to understand the geometrical knowledge of the builders of the cathedral, especially the layout of the heptagon and octagon.

Moreover, it is performed an assessment, from the point of view of the proportion, of the primary sources available for the promoters of the cathedral. It revealed some authors like Calcidius (fol. 350), Macrobius (fol. 400) or Marciano Capella (fol. 430), who are the main transmitters of the Neoplatonic culture, and which proportional theory prevails in the general order of the heading of the Cathedral of Tortosa.

The figures of the medieval architect and the Chapter represent medieval building and Neoplatonic order, and attempted to create a city of God built by men engender in their imaginations. From this perspective, Tortosa Cathedral may be the mirror image of ideas proposed by Otto von Simson.[9]The proposals of Nigel Hiscock[10] and Robert Bork[11] are further testimony to the renewed research interest in the Gothic canons in the Platonic geometry.

The masonry construction and the codices in the Chapter's Archive,[12] enable us to relate the knowledge of the medieval masters and that of those commissioning their work.[13] This paper presents a complete view of the results obtained with the transversal assessment of the apse.

The origins of Gothic design and construction

The construction of the Gothic cathedral in Tortosa was completed under the Catalan-Aragonese Crown and had to replace the old Romanesque building (1178), the *ecclesiam vetulam*. It was commissioned in 1345 and work began in 1377. (Fig. 1) The apse was designed and built between 1345-1441. The construction of the new gothic cathedral began with the radial chapels of the heptagonal apse. The Romanesque cathedral was still in use during the first steps of the works, but its demolition began with the works of the ambulatory. There are two hypotheses about the location and orientation of the Romanesque cathedral. The canon J. Matamoros, according to the historiographical tradition, placed it perpendicular to the current main axis, with a North-South orientation, over the Chapel of *Santa Cinta.*[14] On the other hand, Monsignor A. Querol[15] and V. Almuni[16] placed it on a similar axis to the Gothic cathedral, orientated East-West. A drawing by Antoon van den Wyngaerde (1525-71), who visited the city in 1563,[17] shows the façade of the Romanesque cathedral, and it is possible to imagine the orientation of the new Gothic cathedral, taller than the Romanesque, along the same axis.

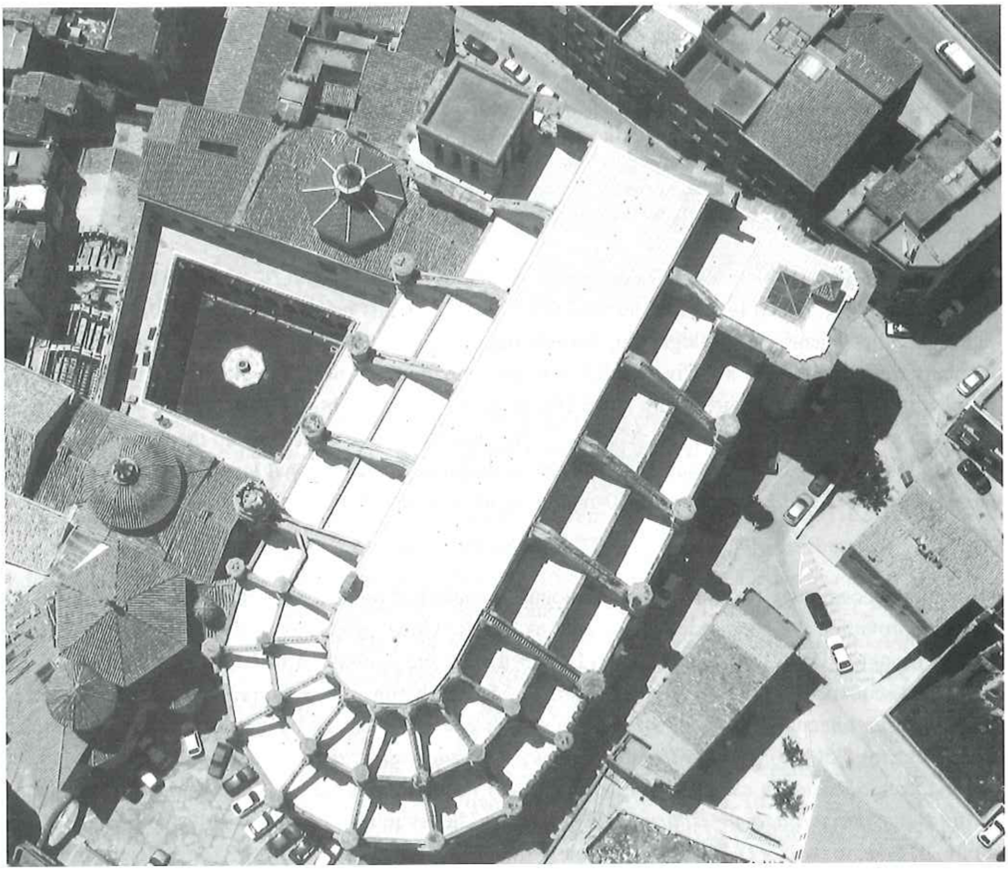

Figure 1. Santa María Cathedral, Tortosa - aerial view

Before the construction of the new cathedral started, the master Bernat Dalguaire was hired. He travelled to the city of Avignon in France, following orders from the Chapter, to observe the construction works there, *e uietes e cercades d-aquells treslasts e mostres a portar* (ACTo No.2. fol. 5r). After the journey, the master was instructed to build a model, *degues fer e mostra. I. eligiment de la seu* (ACTo No.2. fol. 5v). The first stone of the new cathedral was placed the third Sunday of May in 1347 (ACTo No.2. fol. 21v). The works were complex and involved processes of both deconstruction and construction. Thus there was a transfer of knowledge between the Chapter and the medieval masters.

The knowledge of the Chapter: speculative theoretical science

The medieval cathedral *ecclesia materialis* was viewed in terms of its construction, although this conceals the desire to create an *ecclesia spiritualis*, represented in the Chapter's Archives. Its beauty depended on the skill of the medieval masters, whose *practica* was *activa*, in contrast to the *teorica,* which is *speculative,* of those commissioning the cathedral, and which they passed on to the builders.[18] These concepts were coined by al-Fārābī (c.870-950) and disseminated by the philosopher Domingo Gundisalvo (Dominicus Gundissalinus) (c.1100-90) in his *De Scientiis.* These concepts were disseminated throughout Europe and the communities of cathedral builders by Vincent of Beauvais (c.1194-1264), in his *Speculum Doctrinale.*[19]

> The medieval Gothic order, which was idealized in the Chartres school, took shape through training in the liberal arts. The definition was recognized by Saint Augustine (354-420) in his *Disciplinae Liberales intellectum Efferunt ad Divina* in *De Ordine* (L. II.16),[20] which can be found in the Tortosa Chapter Library (ACTo 40). The ideal curriculum comprised:
>
> *Arithmetica: Omnia sub numero que possum discernere quero.*
> *Geometria: Corpora mensura claudo, data hec mihi cura.*
> *Musica: Dissona consio consors modulamine studio*
> *Astronomia: Astrorum iura monstro persigno futura*

Augustinian patristics refers to numerical theory in *Civitatis Dei* (ACTo no. 20). As well as the perfection of the number six, which is the first number that is the sum of its parts (Civ. Dei.XI-30), the number 7 represents the seventh day, recognizing the rest day of the Lord; (Civ. Dei. XI.31). Other significant numbers were twelve (= 3 x 4 Civ. Dei XX.5.3), and one thousand, which is the perfect number for the fullness of time - a flat square figure (10 x 10), given a similar height, it is made cubic and, multiplied by ten to give a thousand (Civ. Dei XX.7.2).[21] The influence of such metrics on the design of Tortosa cathedral is clear; six in the modules of the naves, seven in the heptagonal layout of the apse, and the large keystone of the presbytery, of 10 palms, is located at a height of 100 palms, which makes a thousand.

Neoplatonic cosmology based on Plato's dialogue *Timaeus* had produced the forms of the Gothic, in the sense of providing the geometrical constructions and the global proportions of the buildings: the right-angled triangle (Tim.53 cd), the square (Tim.53 d) and the equilateral triangle (Tim.53 of), and the numerical sequences 1, 2, 3, 4, 8, 9, 27 (Tim. 35-36) which constituted the proportional substratum of music and architecture.[22] A copy of the translation and commentary by the 4th-century philosopher Calcidius (fol. 350), *Timaeus translatus commentarioque instructus,* is to be found in ACTo No. 80 (146r-155v), *Socrates in exortationibus suis virtudes Laudan...*, with the graphic from fol.155v. [tab.9] of the *Descriptio tertia, quae est armónica* (XLIX).[23] The sesquialtera proportion, or the perfect fifth, is a ratio of three to two (3/2). These proportions would inspire the cross section of Tortosa cathedral (9/6), and the tonal ratio (9/8) is reflected in the radial chapel and the width of the naves. Other Platonic ratios found in the commentary of the 5th century Roman philosopher Macrobius Ambrosius Theodosius (fol. 400), containing the *Comentarii In Somnium Scipionis* in the ACTo. 236,[24] was applied directly in the proportions of the apse; 150 palms wide, 100 palms deep and 100 palms high (approx. 34.8 m x 23.2 m x 23.2 m). (Figs 2 and 3)

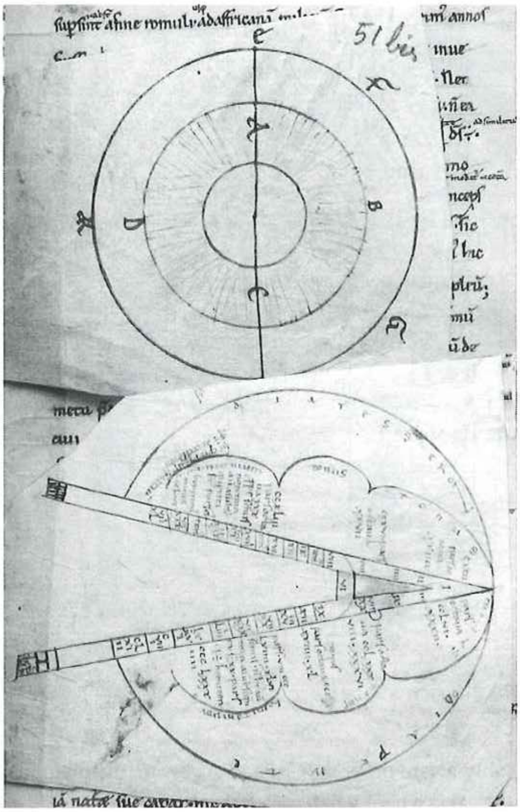

Figure 2. Neoplatonic sources. Macrobius ACTo 236

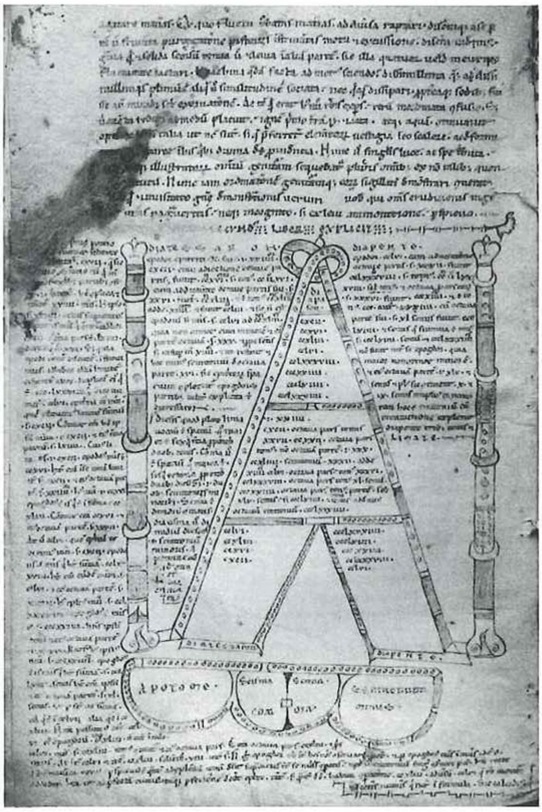

Figure 3. Neoplatonic sources. Calcidius ACTo 155

The link to the Chartres School was achieved by the work of several philosophers: Gerbert of Aurillac (c. 940-1003), ACTo No.80 (159r – 160v), with the *Geometría Incerti auctoris* (c.1000); William of Conques (1080-1145) in the *Dragmation Philosophiae*, (ACTo No.144 fol. 38r – 90v) in the complete work, and an *excerpt* in the (ACTo No.144, fol. 163r – 188v);[25] and Alain of Lille (c.1128-1202) in the *Anticlaudiamus* of the ACTo 175.[26] The geometry of the ACTo 80 traditionally attributed to Gerbert is today found in three separate texts - one by Gerbert (fol. 159r l.1 - 160v l.27), *Geometría inecrti auctoris*, the second part (fol. 160v l.28 – 161r l.6) is the Geometry of Book VII of *De Nvptiis Philologiæ te Mercvrii*, by Marciano Capella (fol. 430); *Planorum alia scemata dicuntur Ergastica, alia Apodictica...* (715,[254]) … *Sextum Reton Kai Meson Dinamene Alogos* (720, [257]); and the third part (fol. 161r l.7-13) appears to be an excerpt from Euclid in the version by Al-Hajjaj.[27]

Another key factor is the presence in the Chapter's library of the liturgical treatise *Prochiron, vulgo rationale divinorum officiorum,* (1291) by William Durand (1230-96), ACTo No.58, (fol. XIII), and pamphlets (incunables) bound in the same work, from Rome (1477) (ACTo No.258) and Venice (1482), (ACTo No.290), which define the philosophical relationship between the *ecclesia materialis* and the *ecclesia spiritualis.*[28] This new liturgy led to the change in design of the French cathedrals. The model was tested by Jean Deschamps in Clermont-Ferrand, and later influenced Catalan cathedrals, such as at Girona where the Chapter required the construction of nine chapels.[29] One consequence of this new arrangement was the Gothic layout of the plan by Antoni Guarc *fábrica* No. 49 for Tortosa Cathedral.[30] A study of the plan depicted on the parchment and the plan that was actually executed provides a comparison of the Gothic design and the masonry. (Fig. 4)

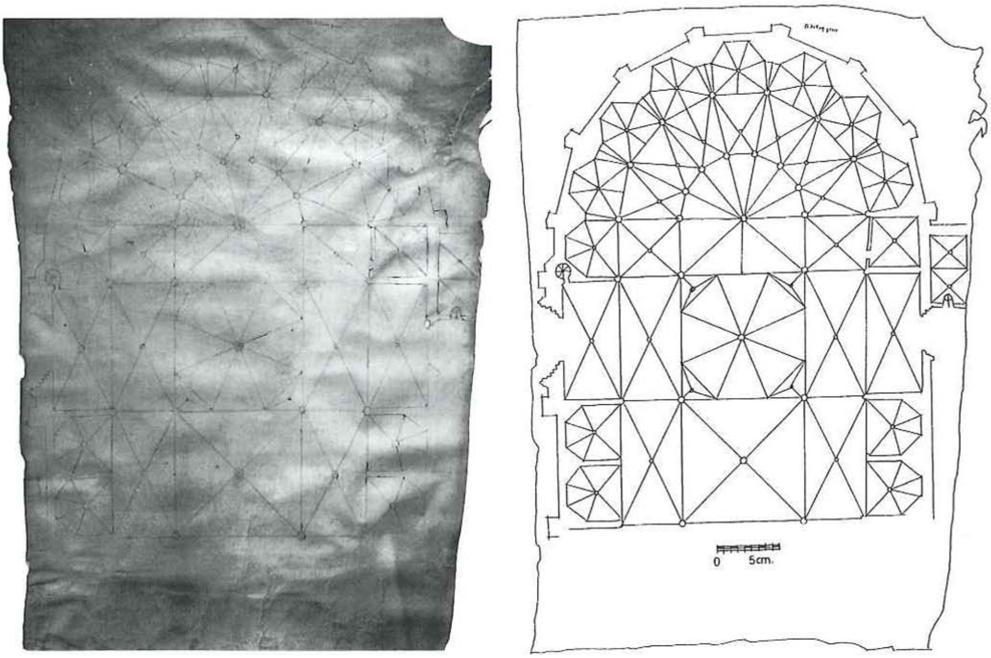

Figure 4. Antoni Guarc parchment (c.1345-1380). ACTo Fábrica 49

The Augustinian canons of Tortosa cathedral were probably aware of, or at least had access to, the major theoretical works of the *De scientia doctrinali* (mathematical science) when undertaking the new Gothic cathedral in around 1345 which replaced the *ecclesiam vetulam* and was consecrated in 1178.[31]

The knowledge of the *magister operis: the scientia practica activa*

The Chapter commissioned Bernat Dalguaire to build a new Gothic cathedral in 1347. The design of the apse is a special case, because it has a double ambulatory and radiating chapels. This achieves a structural liberation from the wall separating the chapels of the apse. Construction of the model had been tentatively tested at Santa Maria de la Aurora in Manresa in 1328. The work at Tortosa was halted in 1349 and resumed in 1377, when the wall separating the radiating chapels was completely removed. This structural problem was also considered a few years later at Milan Cathedral (1392).[32]

The nine radial chapels in Tortosa each have a square ground plan and ribbed vaulting, with a chancel with a heptagonal plan. The removal of the radial wall led to a new model and a change in the structural conception of the overall mechanics of the masonry. With the new system, it was necessary to include a restraining support for the vaults in the chapels, before they could be counteracted by the ambulatory. The chancel of Tortosa cathedral, like those of Gerona and Barcelona, had to have nine chapels, each with identical measurements. Geometrically, it is necessary to place seven on the semi-circle, with two of these lines perpendicular to the radius, and it was therefore necessary to work with the figure of the heptagon. (Fig.5)

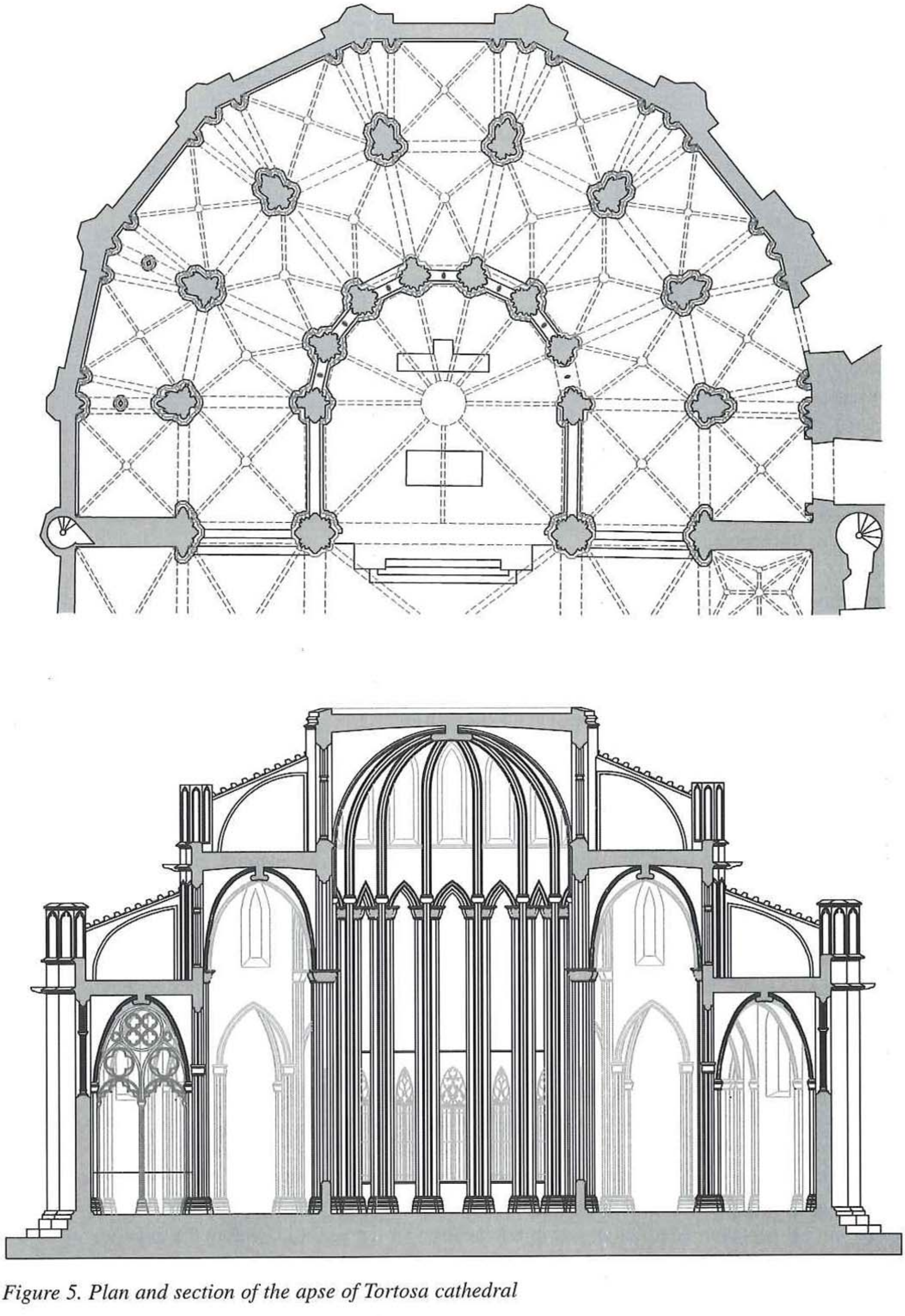

Figure 5. Plan and section of the apse of Tortosa cathedral

In the culture of Christianity and the Fathers of the Church, the number seven represented the Creation; six days devoted to work (Gen. 1,1) and the seventh, on which God rested (Gen. 1,2). The humanist Charles Bouvelles (1478-1567),[33] author of the *Geometrie practique* published in Paris in 1542, acknowledged that a heptagon, so important in Christian symbolism, did not appear in the *Elementa* (Chap.2.57) of Euclid (c.325- c.265 aC).[34] The *Elementa*, as translated in around 1142 by Adelard of Bath (1075-1166), discusses the layout of the regular polygons in Book IV, but does not refer to the heptagon, and neither does Book I of the *Almagesto* by Ptolemy (c.85-165), translated in around 1175 by Gerard of Cremona (1114-87).[35]

The method of constructing a heptagon that has come down to us in the present day is that of Dürer (1471-1528) in *Underweysung der Messung, mit dem Zirckel und Richtscheyt: in Linien Ebnen vo gantzen Corporen* (1525), through the corollary of the pentagonal layout (LII.15) rather than the heptagonal (LII.11), which determines that the side is equal to the height of an equilateral triangle on the side of the radius.[36] This method had, in fact, already been established by Abu'l-Wafa Al-Buzjani, (940-998) in *A Book on Those Geometric Constructions Which Are Necessary for a Craftsman* (c.990) (CII.6) and (CIII.13)[37] and in his Arithmetic (P2, C.IV-V).[38] The heptagon's construction using geometrical instruments was refuted by Kepler (1571-1630) *Harmonices Mundi, Libri V* (1619) in *Propositio. Heptagonus et figurae ab eo ommes* (LI.45).[39] Later, Gauss (1777-1855) in his *Disquisitiones Arithmeticae* (1801), (Section VII-Propositions 361-366), settled the issue of the commensurability of the side of the heptagon.[40]

The architect must have been aware of a method for setting out the heptagon, but the problem of laying out the chapels of the apse was more challenging, as the centre of the circumference was not accessible, since the *ecclesia vetula* was occupied by the presbytery. The *magister* had to resolve three problems when constructing the apse; first, to find a method of constructing the heptagon, as this does not appear in the texts of the time; second, to construct the figure without knowing where the centre was; and finally, commensurately solving the relationship between the radial chapels and the side chapels, which had to be equal.

The parchment drawing of the Gothic plan by Antoni Guarc includes points, compass traces, auxiliary construction lines and other final lines, which make it possible to establish an interpretation of the methodology for the layout of the cathedral's chancel. Among the points plotted with a compass are some that are used for the circumference and others for the transfer of certain dimensions. The straight lines were traced with a stylus and the curves with a two-pointed compass, which fit the drawing and define the proportions. Other auxiliary lines were traced with graphite, while the final strokes were made with ink. The layout of the figure of the heptagon began with preliminary operations to determine the length of the side. (Fig. 6)

Guarc's plan is structured on a baseline of length 9 units. The central nave is 9+9, the side is 9 and that of the collateral chapels to the outer wall is also 9. The side chapel measures 8 units. Guarc's development is both geometric and arithmetic, meaning that the plan on the parchment and its construction are inextricably linked. Guarc draws because he knows how to build and draws sequentially in the same way as building takes place in the Gothic period of *La Corona*. The 18/8 ratio used by Guarc to set out his heptagon does not appear in any treatises of the period. Dividing the circumference of a semi-circle with a radius of 18 units into seven equal parts gives a length of 8.011 units. In fact, Guarc recognised the practical advantages of dividing the semi-circle into six equal parts and one slightly larger part, an approach that had been discovered by others:

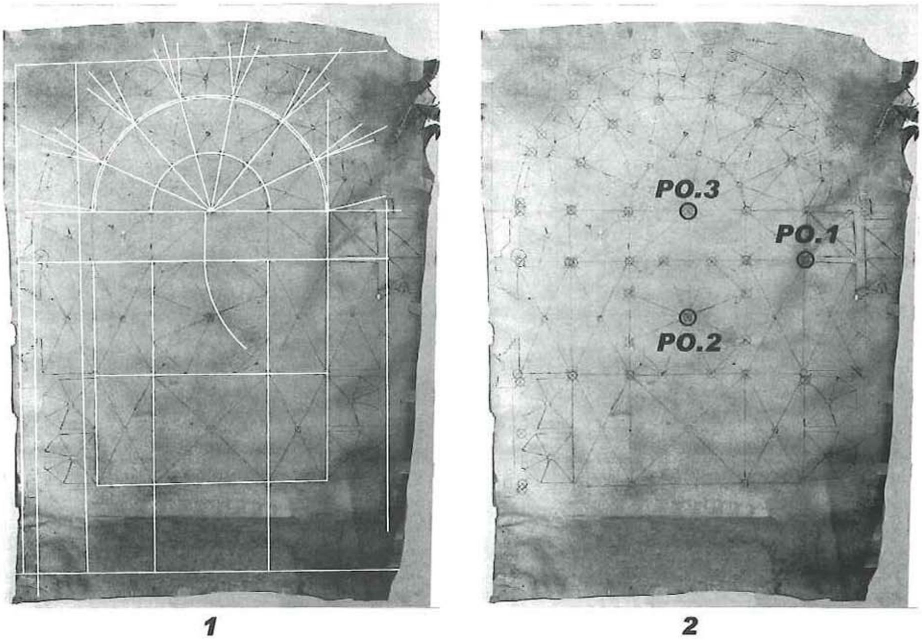

Figure 6. Auxiliary strokes on the Guarc parchment; (1) lines, (2) dots

- Heronis Alexandrinus (c.20-62) (16/7); six of 7.875 and one of 8.823[41]
- Abu'l-Wafa (c.990) and his derivatives; six sides of 7.994 and one of 8.113[42]
- Guarc (c.1345-1380) (18/8); six sides of 8.000 and one of 8.075,
- Fray Ignacio Muñoz (1683), (9/4) one side of 8.000, four of 8.009 and two of 8.019[43]

All the methods involve a good approximation for the Gothic layout, which were acceptable for the dimensions of normal masonry. Guarc's method is one of those with the least error from the mathematical point of view. Its importance lies in the fact that the ratio between the radius of 18 modules of the circumference and 8 on the side of the fourteen-sided polygon establishes a solution that is simultaneously geometric, arithmetic and metrological. According to the theory of proportions; if the presbytery has a width of 18, the radial chapels must be 8 units;, and in the masonry itself, it was necessary to build a chapel of 3 canas (24 palms), and a radius of 6 canas and 6 palms (54 palms). In his drawing, Guarc established a tonal relationship (9/8) between the width of the chapel and the width of the aisle. This method allowed him to work geometrically with the compass, and arithmetically to transfer the measure to the masonry at the same time. Guarc's method and the work executed are identical, and resolve the three problems that arise in the plan of a heptagonal apse. (Figs 7 and 8)

Order - the imposition of unity on the construction of the apse

When the work began on outline of the new cathedral in 1347, the master set the *cana,* in the form of an iron rod, as the standard unit of measurement: *Item fiu fer lo maestre de/la obra a-n Antoni ferrer una cana de ferre per pendre mesures de l'obra costa... .V. s"* (Ll.o.2 1345-47, fol. 36v).[44] The standard measures, from the *Llibres d'Obra* (ACTo), were the cana comprising 8 palms, each of which was 12 fingers. The Tortosa *cana* is defined in Book IX, Section 15.5 of the *Consuetudines Dertosae* (1272) (AHCTE cod. 53, fol. 256r), and in the copy from 1346, when work on the Gothic cathedral started, the *Llibre de les Costums Generals feutes de la insigne ciutat de Tortosa* (FBMPM, fol.100r). The Tortosa *cana* used in the cathedral is 1.858 m and the span is 23.23 m.[45]

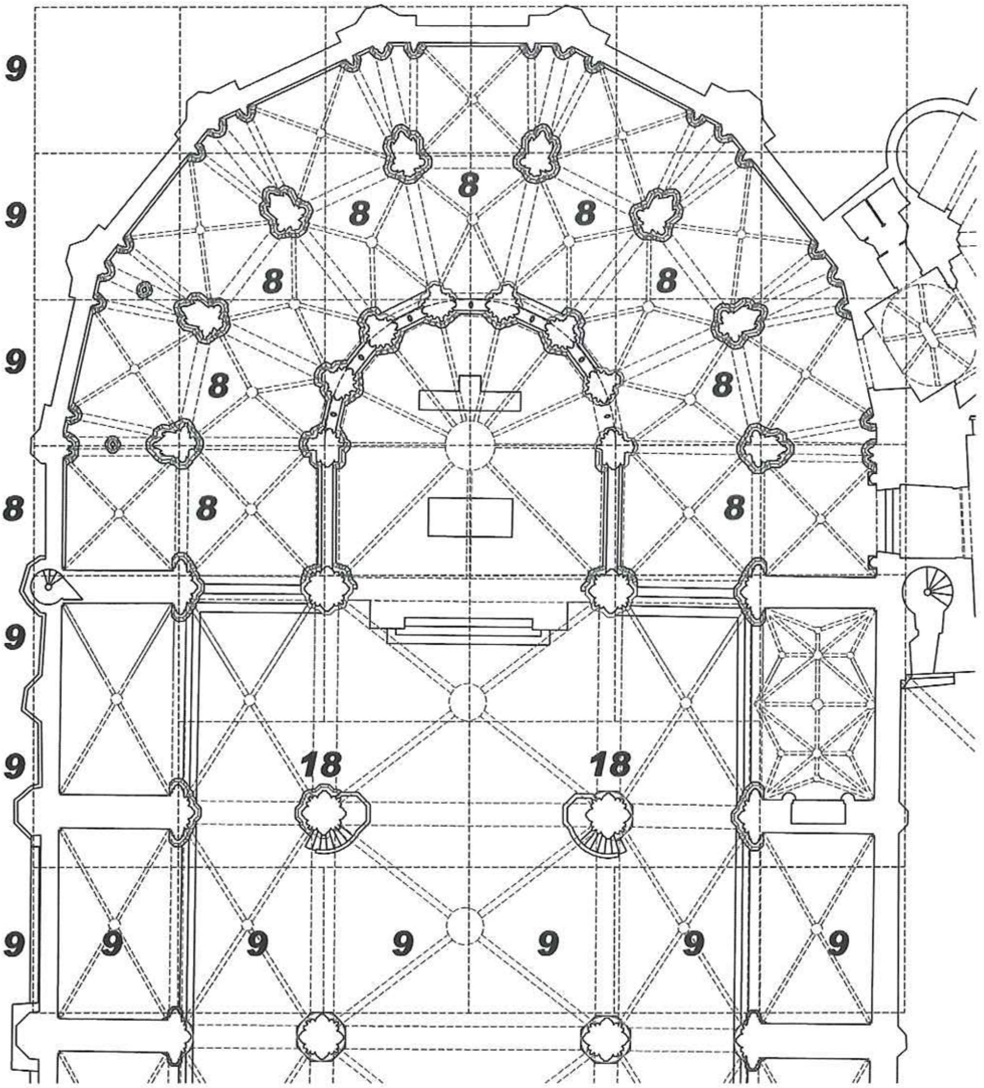

Figure 7. Tortosa cathedral geometrical structure

The radial chapels were constructed in the form of a belt around the old Romanesque cathedral, while it was still in use. The vaults were covered consecutively and sequentially, from the gospel area to the epistles, between 1377 and 1424. The conclusions from the current joint assessment of the primary sources and the as-built masonry have enabled the identification of three construction phases in the empirical trials of the new structural model. Phase one (F1) consisted of the initial tests during 1377-83, with the square ground plan, ribbed vaults and the release of the side wall, in the first chapel, St. Peter. There followed two subsequent phases during which the model was adjusted and consolidated: phase (F2), during 1387-97, with the construction of the next two chapels, and phase (F3), during 1412-24, with the systematization of the masonry of the four remaining chapels. (Fig. 9)

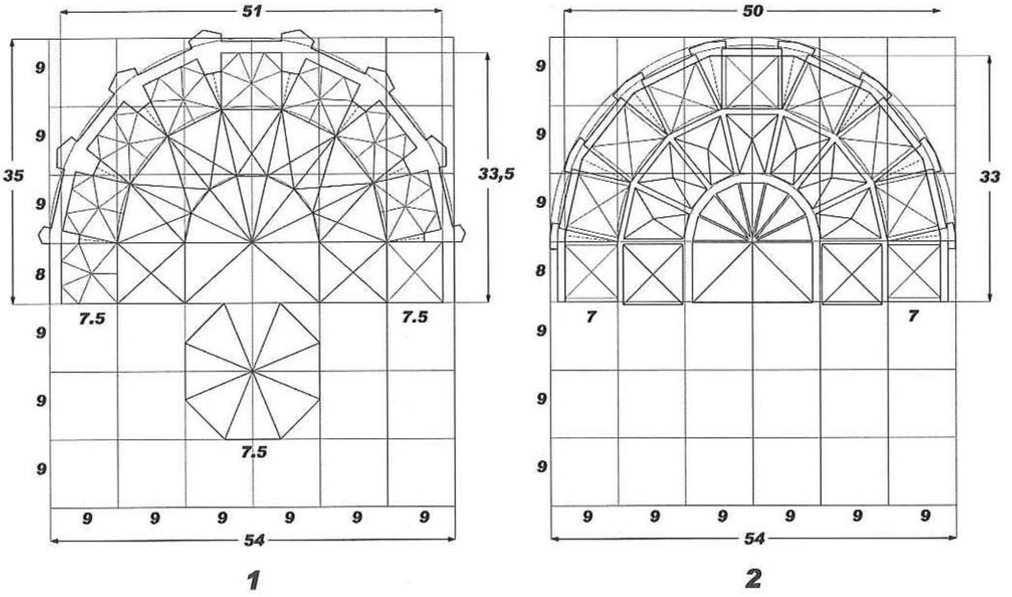

Figure 8. Guarc's geometrical structure and the work executed on the same metrological basis

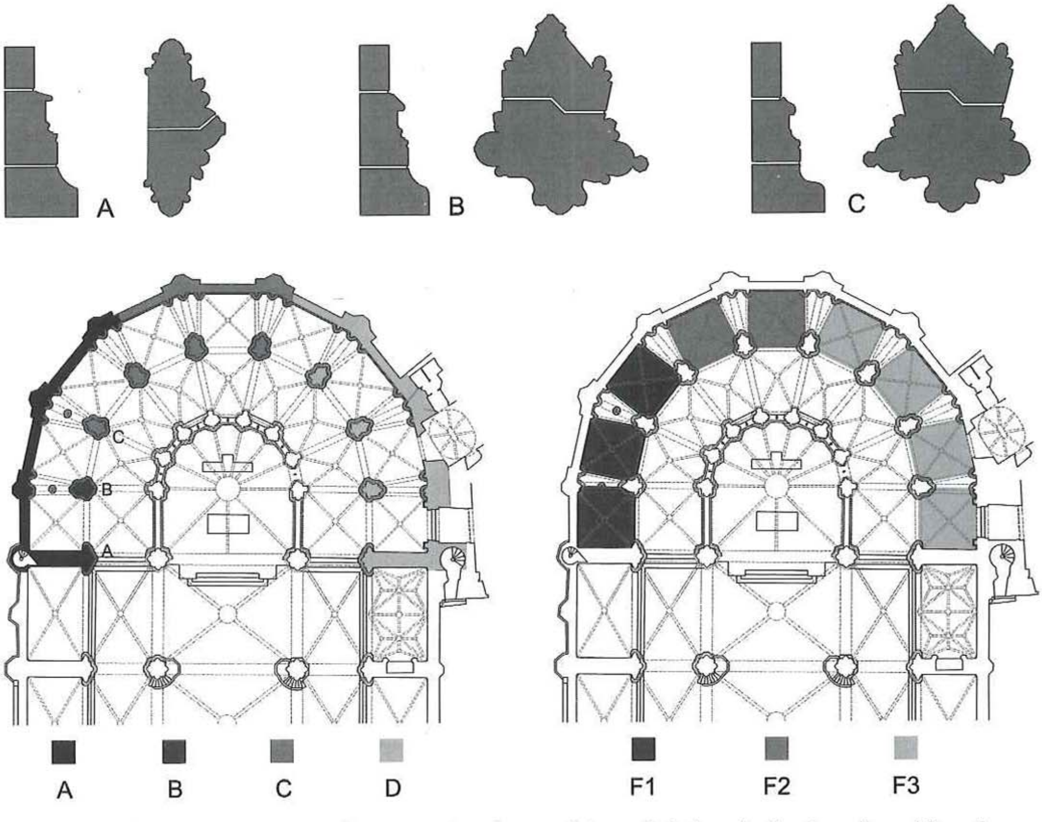

Figure 9. Changes in masters and construction phases of the radial chapels. Section of mouldings by masters A, B and C

In the records (*dubios)* for phase one of the construction work (1377-83) three different masters were identified with three different models. Master A, who was responsible for the base of the pilaster of the Chapel of San Pedro and the enclosure wall to the third radial chapel, defined the model by removing the wall separating the radiating chapels. Master B straightened the moulding at the base of the column of the Chapel of San Pedro, and covered that first chapel. Master C made a further change in the mouldings in the other chapels, which confirmed the initial model and introduced nuances in the carving of the column. A fourth Master D systematized the radial system and completed the apse.

The essential element for the erection and construction of the Tortosa structural model is the pillar or column, as it includes the series of arches in the vaults located in the lower nave, but also anticipated the future dovetailing of the ambulatory into a higher nave. This element initially had to contain the thrusts of the radial chapels, but in the future, after the the ambulatory had been built, it had to carry the loads from the ambulatory and then the presbytery. The eight columns of the chancel are not geometrically equal. The carving of the six columns arranged around the circular body is symmetrical around the toroidal arch and at an angle (180°/7), but this is not the case with those in the straight section of the apse, since the toroidal arch is not aligned with the bisector of the angle (90°+90°/7). In geometrical terms, the distance between the centres of the columns of the radial chapels is 24 palms, or in other words, three Tortosa canas, and the span from the square (in ground plan) ribbed vaults is 21 palms, creating a metrological base of 8 x 8 and 7 x 7 respectively, on a base of 9 modular units.

The first column has an asymmetrical cross-section (1.92 x 1.57 m) and the symmetrical columns (1.99 x 1.49 m) have gauges of between 0.31 and 0.36 m. The base of the symmetrical columns needs a minimum stone cut of 2.45 x 2.14 m, with a section of 3.69 m2 and a weight of 2,191 kg. The top of the column has two parts, the larger weighing between 681 and 802 kg, and the other where the transverse arches meet between 256 and 302 kg. The structural model of the radial chapel is complex as there are up to four imposts to contain the thrusts of the arches. As a result, the transverse arch on the column's axis supported the thrusts of the ambulatory, the diagonal arches of the chapel's vaulted ceiling, the formeret (the rib in the plane of the wall) on the gallery of the ambulatory and the transverse arch, with the location of the thrusts changing in each case. In the new model of the apse, the radial chapel had to have an inverted structural polarity, as the column acted as a buttress to change the line of thrust, which would not be the case if the traditional wall separating the radial chapels had been built. As a result, the largest piece, located on the upper surface of the chapel, acts as a buttress for the body of the radiating chapels, but later, when the ambulatory was built, the smaller pieces performed this function.

After covering the first chapel, Master C cut the second symmetrical column, modifying the inner moulding that was preserved in the rest of the apse. Every rib of the ribbed vaulting is different to those of the first chapel, with a much larger cut than the one performed by Master B. The third column is the start of phase (F2), and after verification of the model (1392-97), the working and carving of the columns was altered, and increased to four cuts for each row of the column. The new layout meant that the blocks used were considerably lighter, facilitating their transport and positioning. However, the number of pieces increased, and hence the need to arrange them, leading to the appearance of masons' marks with Roman numerals to ensure their correct positioning on site.

At the start of the model, the pieces in the columns were large, while the voussoirs in the vaulted ceiling were much smaller than the later ones. The carving process changed as the apse progressed, with the terms of the carving of the stone reversed. The large size of the ashlar stones meant that handling their weight was complex and positioning them was difficult. Large blocks were used to ensure the stability of a model that had not yet been tried and tested. In terms of medieval mastery, the fewer the joints and the greater the uniformity of the material, the greater the consistency and endurance. After these checks had been made, the masonry was able to progress with a systematization of the model in the third construction phase (F3).

The development of the model involved an experimental approach with several trials. In the first phase, where the section is much lower than the North of the Crown, the *ad triangulum* system was deployed. The initial cross-section at Tortosa has a span-to-rise proportion of 9/5, which is more similar to southern models such as the Cathedral of Valencia and the archpriestal church in Sagunto. The master that completed the first belt of the apse at Tortosa had built the nine radial chapels 3 canas wide, reaching the final radial chapel exactly 150 palms from where he started, thereby establishing the total interior width. The final column was placed exactly 108 palms from the first. This distance was initially not directly accessible because of interference from the Romanesque cathedral. The Gothic masters had laid out the radial chapels, dividing the semi-circle into seven parts without access to the centre of the circle.

A careful study of the parchment original of the *Traça de Guarc* has allowed the sequence of construction of the drawing to be determined. The master first drew the semi-circle with its centre at PO.3, which would be the centre of the circumferences of the apse. At P16 a compass mark is made, and a semi-circle is drawn with a centre at PO.3 and a radius (P16-PO.3). The operation is repeated along the curve. On the chord of the circumference of the semi-circle from point P16, the distance P2-P14 = P14-P15, obtaining point P17, reiterating the transport of the measurement P2-P14 or P16-P17, thereby determining P18, P19, P20, P21, P22 and P23, and then determining the internal layout of the chapels. (Fig. 10)

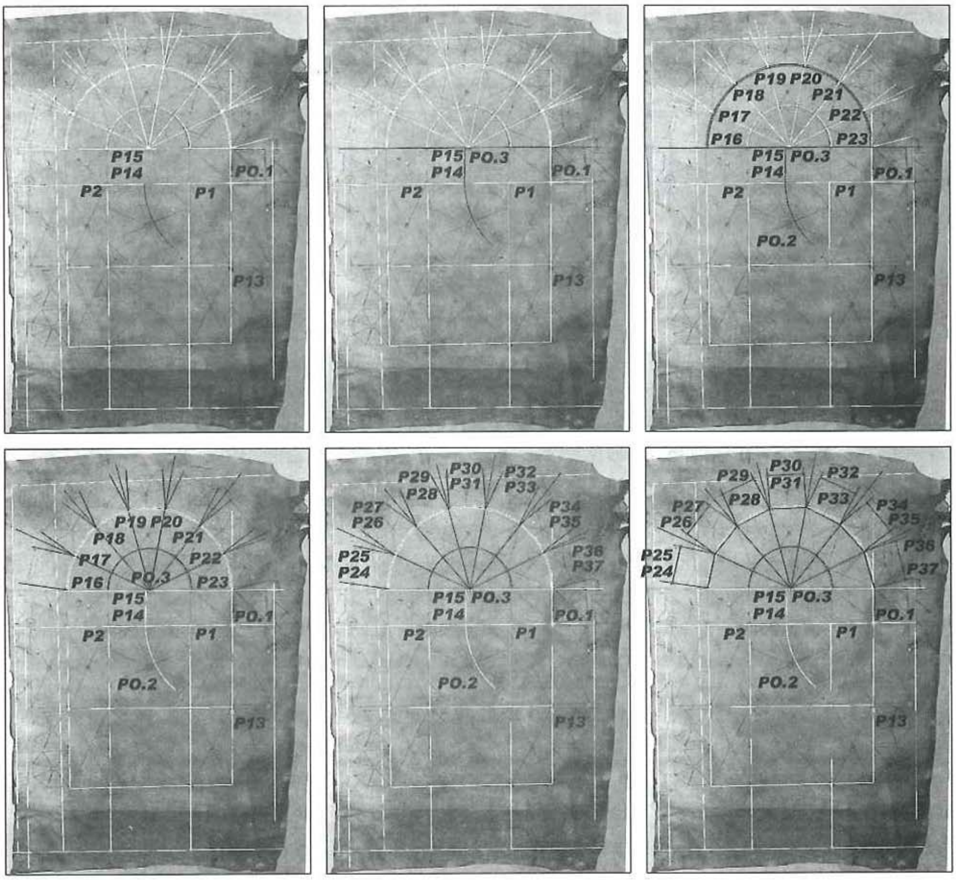

Figure 10. Layout of the Guarc heptagonal parchment

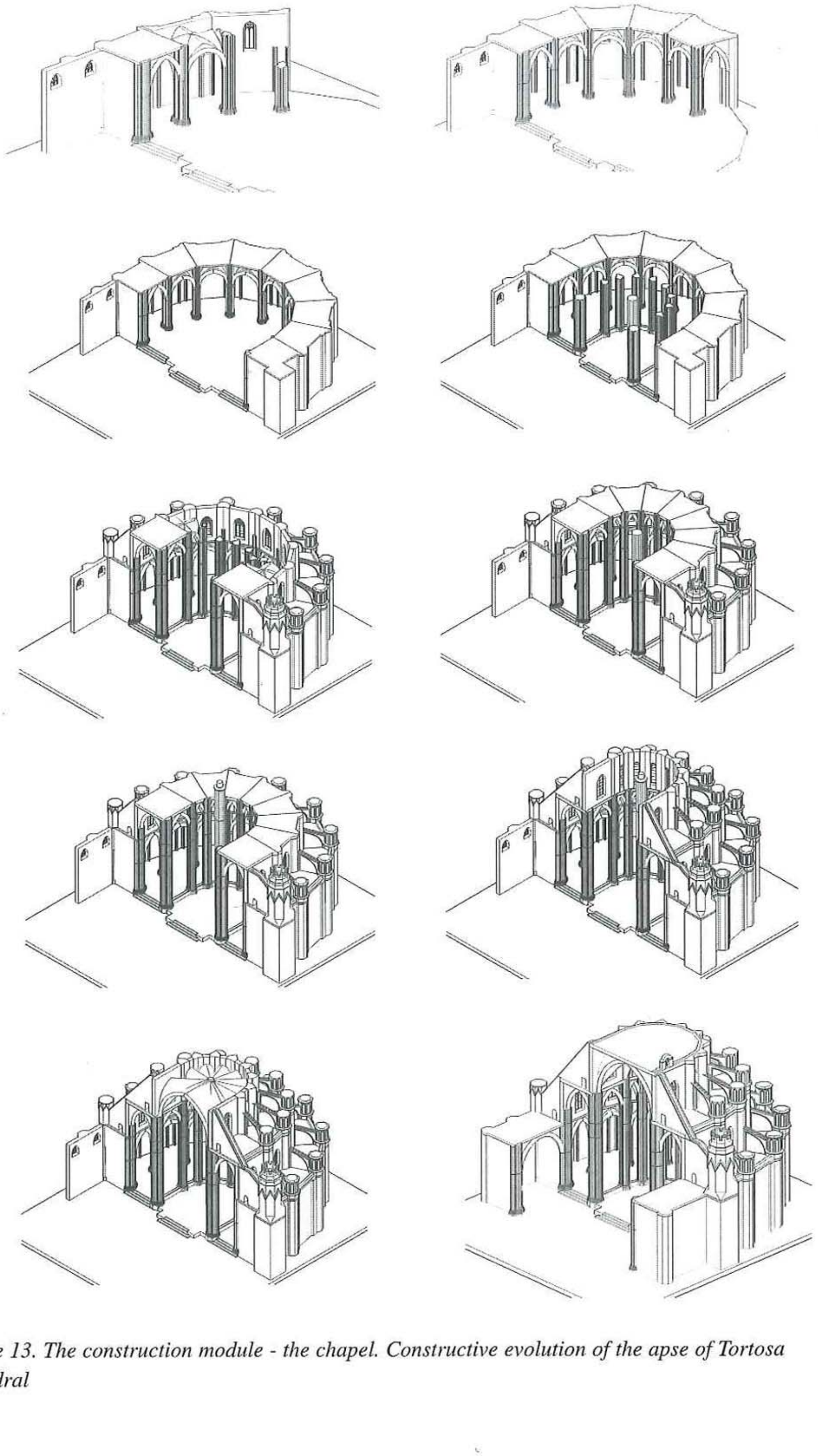

Figure 13. The construction module - the chapel. Constructive evolution of the apse of Tortosa cathedral

A new cathedral model: the construction of the ambulatory

The construction of the ambulatory vaults took place during 1432-34. They were executed symmetrically about the central axis, unlike the radials, which were executed sequentially. A development of the original cross-section (9/5) in the chapels took place, and in the ambulatory the ratio was increased to 9/6. Structural changes were made, as unlike the radial arches, the formerets, transverse arches and diagonal arches of the ambulatory were executed on the same impost. The building of the *pilar mayor* began after completion of the chapels surrounding the Romanesque cathedral in May 1428. This took place at the same time as the work to demolish the chancel of the Romanesque cathedral which starting in August of that year.[46] The temporary central column in the presbytery was raised behind the Romanesque altar, before the first vaults in the ambulatory were covered in July 1431. It was removed in March 1440, after the striking the centring supporting the vaults of the presbytery, and also before the consecration of the chancel of the new Gothic cathedral in April 1441. (Fig. 11)

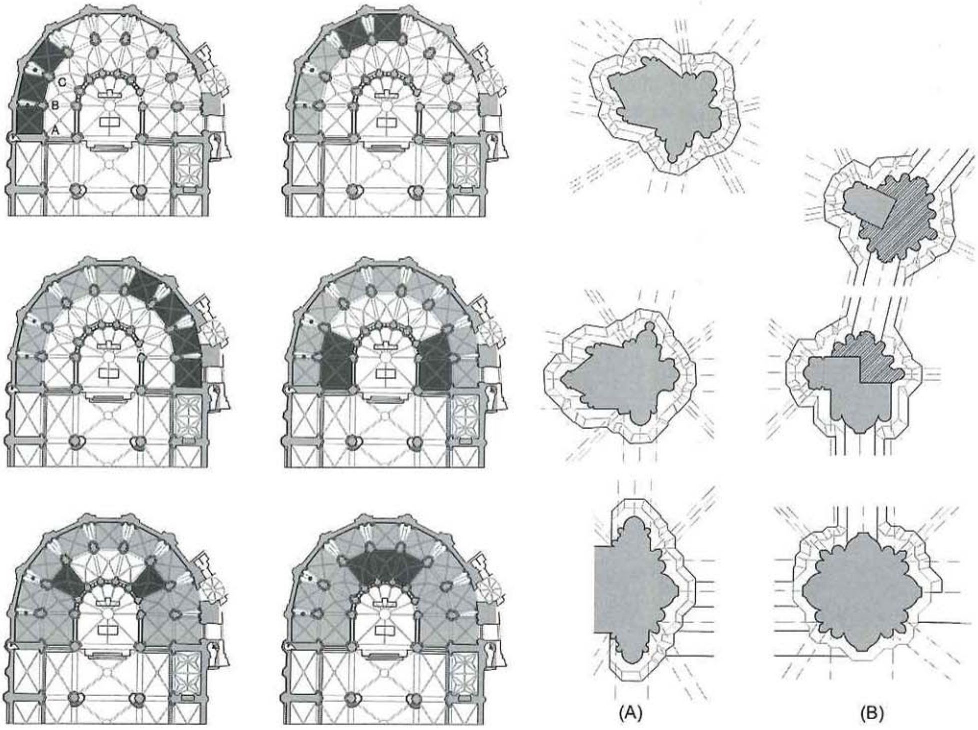

Figure 11. The construction evolution of the radial chapels and the ambulatory. Types of columns and mouldings in the ambulatory; (A) radial chapels, (B) ambulatory

The master who designed the ambulatory had to build the columns of the presbytery, and was forced to take into account the mouldings that converged from the radiating chapels, but he was able to design new ones in the arches of the vaults in the presbytery. The columns thereby have two moulding models depending on the convergence of the arches - the first above the chapels and the later ones converging in the presbytery. The columns at the mouth of the presbytery have a section similar to the rest of the central nave, and had to have a sufficient section to act as a buttress and counterbalance. The situation as regards the eight columns closing the presbytery was different, since they are not geometrically

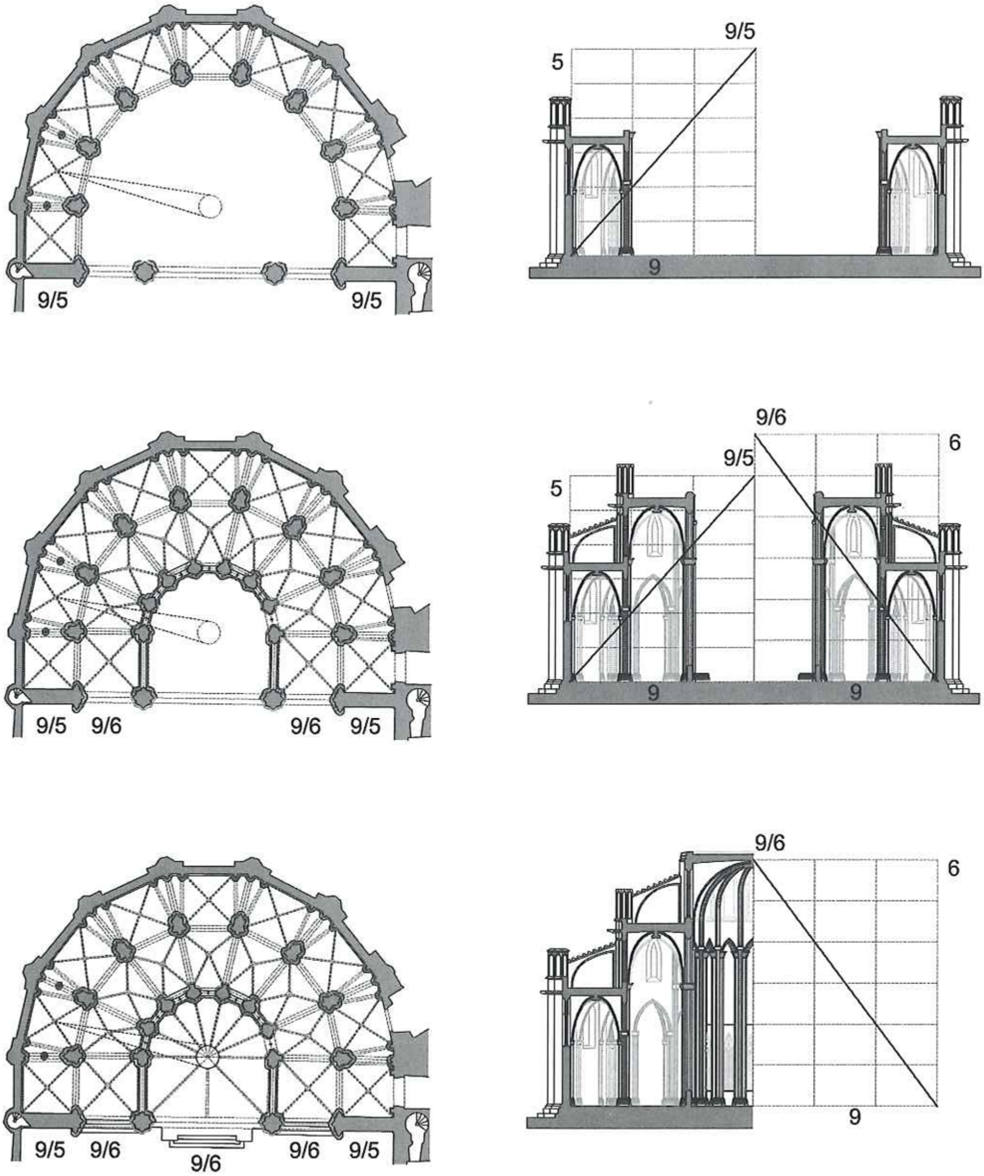

Figure 14. Change in the section of the ambulatory and location of the main keystone

top, so that the view of the large keystone was tangential to its lines observed from the centre of the radial chapels. The large keystone thus visually presides over the space, with not only the frontal view of the nave, but also from the ambulatory. (Fig. 14) identical and their design changes significantly. Those located along the diameter of the presbytery, executed after those in the nave, are larger towards the axis of the cathedral, and designed for balancing the thrust of the vaults towards the chancel of the apse. This action is so obvious that there is no formal overlap in the composition of the upper window centred on the vault of the presbytery, unlike the axis of the formeret in the vault of the ambulatory.

After this procedure, the vaults of the ambulatory began to be covered - first the two on the square ground plan, and then the seven trapezoidal vaults on the line of the presbytery. The structural elements - formerets, transverse arches and diagonal arches are concentrated in the same impost at 11.67 m (50 palms + 3 fingers) and the closing of the vault at 16.70 m (72 palms), placing the shoring plane at 56 palms. It is possible to establish the sequence of construction of the vaults with an area of 20.03 m^2; the scaffolding was assembled on 24th July 1433, the formwork was placed on 31st July, the vault was constructed between 1st and 5th August and the formwork was removed on 27th August. The filling of this vault, the inner wall and the *trespol* or surface pavement in two layers was built between 2nd and 13th September, and a vault in the ambulatory was built and covered in just eight weeks.[47]

The construction strategy of the ambulatory differed from that of the chapels, and the cover of the ambulatory began with the chapels of the Gospel and Epistle respectively. The thrust of these square ground plan vaults of 29.16 m^2 was easily resisted by the masonry of the flying buttresses of the radiating chapels that had already been built. However, the balancing stage towards the interior of the presbytery is more complicated, which raises the question of what happened with the thrust towards the centre of the presbytery before it was covered. The existence of thrusts towards the interior and the symmetrical construction of vaults suggest that they could have been balanced by the column built behind the Romanesque altar. The *pilar major* may appear as an auxiliary feature, neutralizing these horizontal actions as a simple bracing, acting as a support for the inner scaffold. The symmetrical execution of the ambulatory would involve an execution by means of two different supports and provisions - one from the roof of the Chapel of San Pedro and one from Santa Caterina opposite. After the ambulatory with its finish of flat rooftops, finished with *trespol*, it was necessary to complete the presbytery located in the centre of the cathedral.

The cross section of the masonry was determined by the inner width of the cathedral. The master set the height of the finish of the presbytery at 100 palms, and then designed the arches, domes and the shoring plane.[48] In Tortosa, the keystones of the arches and the keystone of the crown are of the same thickness and whole. The curvature is determined either by the perpendicular distance from the shoring plane to the keystone,[49] or to the support of the curved section.

The span of the structure of the presbytery is 6 canas (11.15 m), with a height of 9.5 canas (17.65 m), the height of the second terrace. The first operation to cover the presbytery was to place the large keystone with a diameter of 2.323 m (10 palms), and weighing approximately 8,746 kg, at a height of 100 palms above the floor. It was not easy to cut the piece because of the large size of the block, and the first attempt failed. The final cutting of the stone took place in June 1438. The keystone was lifted and placed at the top of the presbytery on 27th September 1438 - an event that was celebrated with great ceremony.[50] (Fig. 12)

The size of the keystone should have solved the problems of the carving of the iconography of the Coronation of the Virgin Mary,[51] and those of the geometry of the cutting of the Gothic stonework. The lower sculpture is arranged on a circle 10 palms in diameter, but the neck of the keystone had to accommodate the geometric concurrence of the nine diagonal arches that converge onto it. There must be therefore a relationship between the length of the circumference and the dimensions of the diagonal

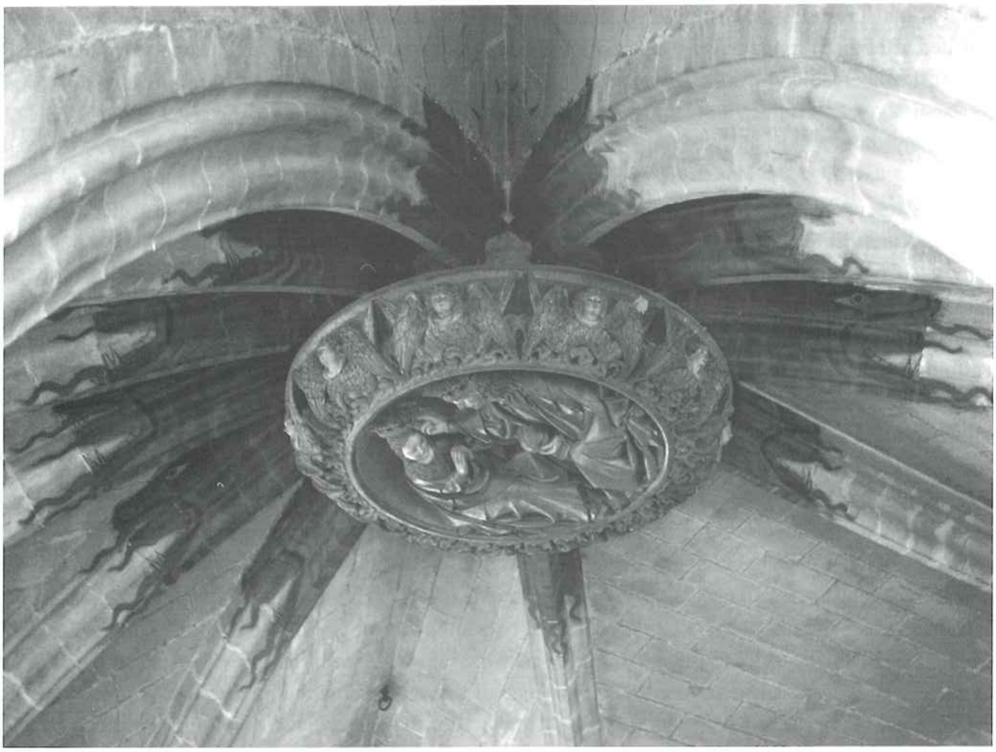

Figure 12. Keystone. The Coronation of the Virgin Mary

arch. The keystone was cut prior to the closing of the diagonal arch in the presbytery, and as such the size of this feature was determined by the niche at the start of the column in the ambulatory and the presbytery. The size of the keystone is implicit in the modulation of the base of the column, and was previously designed and sized when the ambulatory was laid out. By ascertaining the ratio (18/8) it is possible to determine the radius of the circle based on the rib, and vice versa. The diagonal arches of the presbytery are 18 cm wide, making the neck of the keystone 80 cm, which is three and a half palms, corresponding exactly to Guarc's ratio. This measure was an important part of the general order of the work, as it includes the geometric shape of the masonry from the construction of the base of the columns in the ambulatory. After the keystone was placed in December 1438, the formwork was laid and the arch connecting the toroidal arch at the mouth of the presbytery and the large keystone was constructed, with the vaults constructed inwards from the outside. The temporary column and the main scaffold were finally dismantled in March 1440. (Fig. 13)

The keystone in Tortosa cathedral, with the Coronation of the Virgin Mary which presides over the presbytery, was designed after the radial chapels had been completed. It was at this point that the cross-section span-to-rise ratio was changed from 9/5 to 9/6, and the large keystone was designed, which had to be seen from both the nave and from the double ambulatory. The change in the model involved a new spatial conception of the apse, in search of a slimmer model. At this point, it was necessary to dismantle the Romanesque cathedral fully and realise the expectations for the model of a new cathedral with its double ambulatory. From the perspective of proportions, the originally-plan to use the 9/5 section situated at 84 palms and 4 fingers was changed, and the final section of the cathedral was determined; it was 150 palms wide by 100 high, with a cross-section of 9/6. The change of section was a visual as well as a geometric issue. The design of the arches at the close of the presbytery was six palms wide at the

Conclusion: Neoplatonic order and medieval construction

The cathedral's chancel has metrological dimensions; it is 150 palms wide, 100 deep, 100 high with a sesquialtera proportion. The columns of the radial chapels are equidistant at 24 palms, 3 Tortosa canas apart. The square ground plan radial chapels measure 21 x 21 palms. The cross-section of the apse measures 45 palms in the radial chapels, 72 palms in the ambulatory and 100 palms in the presbytery, and the keystone is 10 palms in diameter. This is a feat of arithmetically- and geometrically-based metrics which is executed as if it was a sequence on a large abacus. The canons of Tortosa cathedral commissioned the *magister operis* to build a cathedral with a basic unit, the radial chapel, which was built with a measure of 3 canas (24 palms). Everything is proportionately arranged in a pre-established order based on this unit.

The builders of the cathedral were encouraged to build in large dimensions by the canons who were influenced by the Neoplatonic culture. The measurements of the Cathedral are proportionally the same as those given by the authors of the codices of the ACTo, such as the *Civitatis Dei* (ACTo no. 20) of St. Augustine, the *Timaeus Translatus commentarioque instructus* (ACTo no. 80, 146r-155V) by Calcidius, the *Comentarii In Somnium Scipionis* of (ACTo. 236) Macrobius, and the numerology of the propositions of *Geometría Incerti auctoris* in (ACTo No. 80, 159r-160v) by Gerberto of Aurillac (c. 940-1003), ACTo No.80 (159r-160v). The proportional basis of the masonry is metrological, with very elementary and notably Platonic integers and fractions in the sequence of creation - 1, 2, 3, 4, 8, 9 and 27 (Tim. 35-36).

However, the *magister operis* also had some geometric knowledge, the *geometria fabrorum*, which do not appear in the scientific texts. These were very helpful in solving seemingly complex problems from a modern perspective. The construction of the heptagon is an example of this. The relation between size of the radius and the side of the heptagon known to the masters of Tortosa Cathedral therefore has values of approximation that are much better than those that became widespread during the Renaissance. The proportion used in the construction of the heptagon by Master A and B and Guarc (18/8), also expressed as the ratio of (9/8) between the side nave and the side of the radial chapel, is extremely simple. It is possible to draw a heptagonal apse without knowing its centre using a set square or twine. This maintains the same distance between the radial and side chapels. The cosmological operational method was established by ascertaining the tonal relationships (9/8) between the width of the side nave and the deployment of the elevation. This enabled work to be done geometrically with the compass, with the opening of 8 units on 9 parts, as well as arithmetically, the same ratio of one cana to a cana and a palm. The proportion (9/8) represents the tone of medieval music, and the relationship between Jupiter and Mars, in complete harmony with the *ars* of the *quadrivium*.

This arithmetic and geometric knowledge form part of a *corpus* of the experimentation with new models. The apse in Tortosa cathedral can be seen as a large empirically-based laboratory. The removal of the wall between the radial chapels had been tentatively tried at *Santa María de la Aurora* in Manresa (1328), with a section *ad triangulum*, but the walls of the apse were completely removed in Tortosa in around 1377, albeit in exchange for establishing a lower initial cross-section of 9/5. Faced with the new challenge, the *magister operis* not only lowered the section, but also created columns with large pieces of stone, which in *practica* terms for the medieval master meant fewer joints and greater uniformity, consistency and resistance. After the model and its stability had been checked, the columns were carved with smaller and lighter cuts, which led to an increase in the number of pieces, complicating the work of positioning the stones and forcing an organizational systematization.

After meeting the first challenge in the radial chapels, the model was changed once again, and the ambulatory increased the cathedral's section, from a ratio of (9/5) to (9/6). By this time similar issues were being faced in other cathedrals. The cathedral in Mallorca had rectified its chancel, there was a debate regarding the single nave in Gerona cathedral, and the Castel Nuovo in Naples was being reconfigured. The master who traced the ambulatory at Tortosa witnessed the debate about Gerona Cathedral and therefore had other references for the execution of the main southern Gothic masonry, and took up a new challenge, involving increasing the ambulatory cross-section. The Chapter decided to complete the presbytery with a major symbolic feature - the coronation of the Virgin Mary after her ascension into heaven. The keystone was laid with great ceremony on Assumption day, 27th September 1438, in the presence of the entire city. The image presided over the presbytery from the naves, and from the double ambulatory that projected as a tracery over the ogives in the columns of the ambulatory.

The origin of this high medieval stonework lies in the synthesis between a theoretical knowledge derived from the association of the terms *spiritualis, teorica, speculativa* of the canons who promoted it, with other, purely practical terms of the medieval builders defined as *materialis, practica, activa.* The foundations of this knowledge culminate in the construction of cathedrals under the terms of *De Scientiis* disseminated by Domingo Gundisalvo, and disseminated in European cathedrals by Vincent of Beauvais in his *Speculum Doctrinale*, thereby enabling a City of God built by men.

Abbreviations

ACTo: Arxiu Capitular Catedral de Tortosa
AHCTE: Arxiu Hitòric Comarcal Terres de l'Ebre
FBMPM: Fundacion Bertomeu March Palma de Mallorca

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Notes and References

1. R. O'Callaghan *La Catedral de Tortosa. Descripción histórica de la misma, relacionada con la Historia de dicha ciudad.* Tortosa: Impr. Católica de Gabriel Llasat, 1890.
2. J. Matamoros, *La catedral de Tortosa. Trabajos monográficos acerca de su construcción y de su contenido artístico y religioso.* Tortosa: Editorial Católica. 1932.
3. P. Lavedan, *L'architecture Gothique Religieuse, en Catalogne, Valence et Baléares.* Paris: Henri Laureen. 1935.
4. V. Almuni, *La catedral de Tortosa als segles del gòtic (2 vols.),* Barcelona: Fundació Noguera. Col·lecció Estudis. 2007.
5. Lluis; Llorca, *Pla Director Sancta Maria Dertosae. Tortosa: Bisbat de Tortosa. Departament Cultura Generalitat de Catalunya, 2000.* Manual survey combined with an instrumental survey using a total station SOKKIA SET 3BII, with 10cc of angular precision in 2cc resolution mode, and a maximum range of 2500 metres using reflector (WILD GPR-1), with a precision of +/- (3mm + 3 ppm).
6. J. Lluís i Ginovart, "La Scientia vero de ingeniis". El concepto de homogeneidad del material de frente a la resistencia en los pilares de una catedral gótica", in S. Huerta, (Ed.) *Proc. of the Sixth International Congress on Construction History. Valencia 2009,* Madrid: Inst. Juan de Herrera, 2009.
7. V. Almuni Balada; J. Lluís i Ginovart: "La clave de la clau". El cierre constructivo del presbiterio gótico", in S. Huerta, (Ed.) *Proc. of the Sixth International Congress on Construction History. Santiago de Compostela 2011,* Madrid: Inst. Juan de Herrera 2011.
8. The 3D model is generated from surfaces obtained with stereoscopic pairso of oriented photographs. It is used the software Image Master (Topcon) to process the data, obtaining triangulated meshes TIN *(triangulated irregular network).*
9. Otto von Simson, The Gothic Cathedral: the origins of Gothic Architecture and the Medieval Concept of Order, New York: Pantheon, 1956.
10. N. Hiscock, *The Wise Master Builder. Platonic Geoemtryin Plans of Medieval Abbeys and Cathedrals.* Aldershot and Brookfield, Vermont: Ashgate, 2000.
11. R. Bork, R. *The Geometry of Creation: ArchitecturalDrawing and the Dynamics of othic Design.* Farnham: Ashgate Press, 2011.
12. E. Bayerri, E. *Los Códices Medievales de la Catedral de Tortosa. Novísimo inventario descriptivo.* Tortosa: Talleres Gráficos Algueró y Baiges, 1962.
13. The International Catalogue of Mediaeval Scientific Manuscripts of the Institute for the History of Science of the University of Munich and the Max Planck Institute for the History of Science of Berlin attribute to Occidental Europe the existence of over 30.000-35.000 codices, (500-1500) which 80 belongs ACTo.
14. Matamoros, *Tortosa* (Note 2), pp. 8-9
15. A. Querol, . During Lent of the Olympic year. Official schedule for Easter week. 1992
16. V. Almuni, *La catedral románica de Tortosa. Aproximació documental a la seva historia.* Recerca, 8. 2004, pp. 211-250.
17. Osterreichische Nationalbibliothek, Vienna, Cod.min 41 (fol. 7r, fol. 8r, fol. 8v.).
18. W. Addis, Structural Engineering - the Nature of Theory and Design, Chichester: Ellis Horwood, 1990, pp. 123-33. Bill Addis, Building: 3000 years of Design, Engineering and Construction. London & New York: Phaidon, 2007. pp.73-110.
19. Editions of Al-Fārābī of; González Palencia, Á. *Alfarabi. Catálogo de las ciencias.* (Madrid: Facultad de Filosofia y Letras, 1932): 39-53. The work *De Scientiis en Gundisalvo, D. De Scientiis. Compilación a base principalmente de la de Al-Farabi* (Madrid: Consejo Superior de Investigaciones Científicas, 1955): 85-112. The reconstruction of *Speculum Doctrinale* by V. Beauvais, 1591, appendix I, pp.143-167.

20. Agustín de Hipona, *Obras Completas San Agustín I. Escritos filosóficos (1º).6 ed.* Madrid: Biblioteca Autores Cristianos, 1994. Del Oren pp. 594-707.
21. Agustín de Hipona, *Obras Completas San Agustín XVI. La Ciudad de Dios (1º).5 ed.* Madrid: Biblioteca Autores Cristianos, 2000; and *Obras Completas San Agustín XVI. La Ciudad de Dios (2º).5 ed.* Madrid: Biblioteca Autores Cristianos, 2001.
22. Platon, *Dialogos VI. Filebo, Timeo, Critas.* Madrid: Gredos, 1997, pp. 155-261.
23. In the cataloge by Bayerri appears as the *Republica de Platón; Socraets in exortationibus suis virtutem laudans...* it is the *Isocartes in exhortationibus suis virtitem laudans edición de Mulliachus, Fr. Fragmenta Philosophorum Graecorum. Volumen II. Pythagoreos, Sophistas, Cynicos et Chalcidii in priorem Timaei Platonici partem comentarios continens.* (Paris: Editore Ambrosio Firmin Didot, 1867).
24. The codex (fol.1r-61v) is part of the corpus of the 123 copies of the XIIth century.
25. There are 61 full copies of the work, and 20 *excerpta.* The codice 144 of Tortosa from XII-XIIIth century is one of the oldest.
26. Despite a XVth century copy, *Incipit prolugus Anticlaudiani Alani de antiruffino,* belongs to the family BNF. Lat. 8300 de 1463.
27. The study of the geometry of Gerbertus together with the Dr. Ignasi Baiges from the University of Barcelona, and the Mn. Josep Alanyà from the ACTo. It have been also a basic resource the comments by Menso Folkers about the *Geometria de Capella* and also Charles Brunett about *Euclides.*
28. S. Sebastián, *Mensaje Simbólico del Arte Medieval. Arquitectura, Liturgia e Iconografía.* Madrid: Ediciones Encuentro, 1994, pp. 352-355.
29. G.E. Street, *Some account of gothic architecture in Spain.* London: John Murray, Albemarle Street, 1926, pp. 318, 339.
30. The plane was made available in the work by José Matamoros. *La catedral de Tortosa. Trabajos monográficos acerca de su construcción y de su contenido artístico y religioso.* Tortosa: Editorial Católica 1932. p. 53. Appearing in: P. Lavedan, *L'architecture Gothique Religieuse, en Catalogne, Valence et Baléares.* Paris: Henri Laureen. 1935, p. 185. Modificarán los errores hasta 1984, Lluis i Ginovart."*Una breu reflexió de l'Àbsis de la Catedral de Tortosa*". La Veu del Baix Ebre No.1.405, 1984-31-8: 25-26.
31. V. Almuni; J. Lluis i Ginovart, *Sancta Maria Dertosae. Catedral de Tortosa. Guia Històrica i Descriptiva.* Tortosa: Capítol Catedral de Santa Maria, 2000. p. 30.
32. G. Valentini, *Il Duomo di Milano. Una disputa medievale sul modello del tempio.* Milano: Nuovo Edizioni Duomo, 1990, p 30.
33. Bouvelles appears in the ACTo No.300, *Tractatus varii de rebus philosophicis.* It is the work known as: *Liber de intellectu, Liber de sensibus, Libellus de Nihilo, Ars oppositorum, Liber de generatione, Liber de Sapiente, Liber de duodecim numeris, Philosophicæ epistolæ, Liber de perfectis numeris, Libellus de Mathematicis rosis, Liber de mathematicis corporibus, Libellus de mathematicis supplementis.* Paris : Henri Estienne, 1510.
34. Ch. Bouvelles, *Livre singulier et utile, touchant l'art praticque de geometrie,composé nouvellement en françoys, par maistre Charles de Bouvelles.* Paris: G. Cavellat, 1551, p. 25 Bouvelles [1542].
35. Euclides L.IV; Triangle (IV.5), square (IV.6 a 9), pentagon (IV.11 a 14), hexagon (IV.15), pentadecagon (IV.16). In the first Spanish edition doesn't appear the pentadecagon; Euclides. *Los seis libros primeros de geometría de Evclides: traduzidos en lengua española por Rodrigo Çamorano Astrólogo y Mathemático y Cathedrático de Cosmographía por su Magestad en la casa de la Contratacion de Sevilla.* Sevilla: Casa de Alfonso de la Barrera, 1567, pp. 71-79. T. L. Heath, *The Thirteen Books of Euclid's Elements.* Cambrige: At the University Press 1908, vol.2: pp. 88-111.

36. Durero, *Underweysung der Messung, mit dem Zirckel und Richtscheyt: in Linien Ebnen vo gantzen Corporen.* Nürenberg: Hieronymum Formschneyder, 1525, pp. 27v-28v.
37. M. F. Woepcke, *Recherches sur l'historie des Sciences mathématiques chez les orientaux, dápres des traités inedits Arabes et Persans. Deuxième siecle. Analyse et extrait d'un recueil de constructions géométriques par Abûl Wafa.* Journal asiatique, 1855, Fevier-Avril. Vol. V: pp. 218-256:309-359. H. Suter, "Das buch der geometrischen Konstruktionen. Suter H. Das Buch der geometrischen Konstruktionen des Abu'l Wefa", *Abhandlungen zur Geschichte der Naturwissenschaften und Medizin*, 4/1922, pp. 94-109.
38. A. S. Saidan, "The Arithmetic of Abu'l-Wafa", *Isis*, Vol. 65, No. 3 (Sep. 1974): pp. 367-375.
39. J. Kepler, *Joannis Kepleri Astronomi Opera Omnia. Volumen Quintum. Edidit Dr. Ch. Frisch.* Francofurti A.M. et Erlangae: Heyder & Zimmer, 1864, vol. 5: pp. 101-108.
40. C. F. Gauss, *Disquisitiones Arithmeticae. Auctore D. Carolo Federico Gauss.* Lipsiae: In Commissis apud Gerh. Fleischer, Jun 1801: 454-463.
41. The *Metrica* by Heronis Alexandrinus (c.20-62) (I, 29 theorema 54), also known as *Dimetiendi rationes* (I, XX). From the regular hexagon figure deduces that the equilateral triangle formed with 8 U radius has a height of 7 (I.IXX). From here it is possible to deduce in the proposition (I.XX), that an heptagon with side 7 has a radius of 8, raising the relation 16:7 between the diameter of the circumference. H. Schoene *Heronis Alexandrini opera quae supersunt omnia. Vol III: Rationes dimetiendi et commentatio dioptrica.* Leipzig: Teubner. Schoene, 1903, pp. 55-59
42. The firs geometry widespread outside the logias was *Geometrie Deutsch* (1488) by M. Roriczer (+c. 1495). The construction of the heptagon by a combined operation of compass from the height of the equilateral triangle which side is the radius of the circumference. The main Renaissance treatises operated similarly using the equilateral triangle. Dürer (1471-1528) *Underweysung der Messung* (1525) (L II. 12) and the corollary of the penthagon (L II. 15), Juan of Arfe (1535-1603) *De varia commensvracion para la escvltvra y architecura* (1585), LI. Chap.II, Heptágono (Arfe, 1585, 7v). All these methods operate with the same adapted matrix appearing in *Libro de construcciones geométricas* (c.990) by Abu'l-Wafa (940-998).
43. Fray Ignacio Muñoz (1612-1685), *Manifiesto Geométrico del Muy Reverendo Padre Fray Ignacio Muñoz, Maestro en Teología, de la Orden de Predicadores, Catedrático propietario de Matemáticas de la Real Universidad del Imperio Mexicano, y Reformador de la Hidrografía Universal y particular de todo cuanto se navega en el Mar Océano y en el Mediterráneo*, 1683. The heptagon has a relation 4 to 9, with the main diagonal of the figure tracing the other 5 vertex with a different method tan Guarc's.
44. V. Almuni, *L'Obra de la Seu de Tortosa (1345-1441).* Tortosa: Cooperativa Gràfica Dertosense, 1991, p. 214.
45. Comparing the unification documents of the *cana* of Tortosa and the Barcelona one (24-VII-1593), ordered by Felipe II (1527-1598) after the *Cortes de Monzón* (1585). Chapter 89, unifies metric criteria. The procurators refer the reduction of the *cana* of Tortosa to Barcelona. AHCTE, 387 (Comú II-63) Registre.
46. V. Almuni, "La catedral romànica de Tortosa. Aproximació documental a la seva història". *Recerca* 8. 2004: pp. 211-250.
47. Placed in front of chapel of Saint *Vicente*. V. Almuni, *La catedral de Tortosa als segles del gòtic. 2 Vols.* Barcelona: Fundació Noguera. Col·lecció Estudis. 2007, 2: pp. 584-587.
48. G. Ungewitter, *Lehrbuch der Gotischen Konstruktionen.* Leipzig: T.O. Weigel Nachfolger 1890, 1, p. 118.
49. R. Willis, *On the construction of the vaults of the middle ages.* London: Royal Institute of British Architects, 1910, p. 11.
50. O'Callaghan. *Anales de Tortosa I.* Tortosa: Imprenta Católica de Gabriel Llasat Ramon 1887, pp. 17-20.

51. Viollet-le-Duc mentions a keystone with an iconography like the one of the Collégiale Notre-Dame of Semur-en-Auxois (1235). E. E. Viollet-le-Duc, *Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle. 10 vol.* Paris: Bance et Morel. 1854-1868, 3: pp. 268-269.

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