Studies in the History of Construction

Proceedings of the Second Construction History Society Conference

Queens’ College, University of Cambridge, 20-21 March 2015

Edited by

James W.P. Campbell
Wendy Andrews
Amy Boyington
Gabriel Byng
Amy DeDonato
Karey Draper
THE SECOND CONSTRUCTION HISTORY SOCIETY CONFERENCE

Organised by:
The Construction History Society

Hosted by:
Queens' College, University of Cambridge
&
The Department of Architecture, University of Cambridge

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Published by: the Construction History Society
1 Scropo Terrace
Cambridge
CB2 1PX

www.constructionhistory.co.uk

© 2015, First edition
ISBN 978-0-9928751-1-4

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Formatting and layout by Amy Boyington

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James W P Campbell
2015

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Introduction

Studies in the History of Construction forms the second volume in the series of conference proceedings on construction history published by the Construction History Society. It records those papers presented at the Second Annual Conference held at Queens’ College, Cambridge on 20–21 March 2015. This year we have chosen to give the volume a proper title. Like the previous volume there is no particular theme per se. The original plan was to have a smaller conference in 2015 devoted entirely to British Construction, but the call for papers yielded only six abstracts, so the scientific committee were forced to rethink. A revised call for abstracts was issued in late July 2014 that called for submissions on any aspect of construction history and sixty were received in response.

The twenty-seven papers in this volume are those selected for inclusion from that sixty and, following our usual rules, all those submitting papers have undertaken to appear in person to present them, some of them travelling from as far away as Australia to do so. This volume reveals the extraordinary breadth of studies that come under the broad umbrella of Construction History and it is precisely this breadth that is exciting about the subject. Every reader will hopefully be able to find something in this volume to interest them and everything presented here is new research. As last year, our presenters are not confined to academics and many have a background in the building industry.

Last year, the conference proceedings were simply arranged alphabetically by author. This year I have tried to arrange the papers into more logical groupings, organising them into general themes and broadly chronologically. The order is entirely one of my own devising and it is inevitably somewhat arbitrary because of the range of subjects, which were not submitted or accepted with any general plan in mind. In future years, if the conference expands, it might be possible to actively solicit papers to give balance, but for this year at least, the arrangement is based on what was accepted from those submitted. In the previous conference, the scientific committee played a very active role. This time, due to the lesser number of submissions, it has been largely passive, with the Chairman of the Committee, David Yoomans and myself doing the selection and the editors doing the revising of the texts, and other members only occasionally being called upon to arbitrate. I am extremely grateful to all of those involved at every level for their hard work. Any omissions or mistakes are entirely my fault, not theirs.

Epistemology of Design

I have chosen to start this volume with Bill Addin’s paper The epistemology of engineering design as a contribution to construction history (pp.3–16) because it covers a very broad theme: what we mean by design and how engineers have explored it through the ages. Design is a subject that is discussed at length in architecture schools, but I think less so in engineering departments. In architecture schools, it is rarely approached from a historical point of view and usually in only very vague artistic terms. Bill’s paper calls for a more rigorous approach to looking at how buildings were thought about in the past and suggests useful directions for further research in this regard.

History is partly about the transmission and development of ideas and it is paper that deal with these issues that I have chosen to include next. Javier Galian’s paper Understanding Roman construction before A Chosy:
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There were, of course, many ways both ideas and books could be transmitted. The next paper by Josep Lluís i Gibert, Agustí Costa, Sergio Coll and Mónica López (pp.23-32) presents the fascinating and surprising story of how the idea of the catenary arch may have been traveled from seventeenth-century Britain to eighteenth-century Spain. No less surprising is the story told in Ying-Ting Pao's paper (pp.33-42), about how two of the most important early 20th century Chinese building textbooks were largely copied (in places word-for-word) from English ones. Lastly on the subject of books, Richard Hayes's paper (pp.43-54) explores how and why A.S.G. Butler chose to include redrawn construction details in the Lutyns Memorial Follies which might so easily have been simply a photographic record of Lutyns work accompanied by conventional plans and sections.

The Seventeenth Century Building World

A surprising number of the papers included in this volume cover twentieth century subjects. There are no sadly no papers on Ancient, Roman or Medieval construction or even on Renaissance buildings. Hopefully future conferences will have more on these topics, but this volume is noticeably lacking in these areas. Chronologically the earliest studies included in the present work are on the seventeenth and eighteenth centuries with passing references to earlier periods. The paper on the transmission of Hook's ideas from the seventeenth century being transferred to eighteenth-century Spain (pp.22-33) presents the fascinating and surprising story of how the idea of the catenary arch may have been traveled from seventeenth-century Britain to eighteenth-century Spain. Stephenson closely examines building accounts to show the degree to which building traditions in this period were acting as building firms. It is the only piece in the current volume that looks at economic history, an area that surely deserves much more attention in the future of construction history than it currently receives. Indeed it is strange to think that one of the best previous pieces of research on this very topic, Knop and Jones's 'The London Mason in the Seventeenth Century' was published as long ago as 1935 and is thus 80 years old this year. The fact that it is still widely referred to is both an indication of the longevity of good research and indicative of how little has been done since.

The other paper covering the seventeenth and eighteenth centuries, Rosa Ana Guerra-Pestonit and Paula Fuentes, 'The grand staircase of the Colegio del Cardenal in Montfórd de Lemos (Spain): revisiting a daring structure' (pp.67-78), provides a structural analysis of an extraordinary vaulted staircase in Spain. The exact date of the construction of this staircase remains a mystery and will hopefully provide for an interesting paper at a future conference. It may date from the very late sixteenth century, but it is probably seventeenth century or possibly early eighteenth. What is certain, however, is that it is a fine example of a vaulted stair of a type found in Spain, but not widely discussed in treatises at the time. The current paper details restoration work which has given a useful opportunity to examine its construction in detail. The authors show not just how it was constructed why it has survived largely intact.

The Manufacturing of Materials

The eighteenth century is generally cited as marking the start of industrialization production and provides a good point to introduce two papers looking at manufacturing techniques. Chris How's 'Early Steps in Nail Industrialization' (pp.81-90) shows that various techniques that were widely used in later nail production can actually trace their origins back into the Middle Ages. In 'Wallpaper's role in Construction History: innovations in wallpaper manufacture in the 16th and 17th centuries' (pp.91-100) Wendy Andrews uses the Cowan papers, an extraordinary collection of wallpaper at the Victoria and Albert Museum in London, to show how this building material has changed and how it too can trace its origins far earlier than is often supposed.

Nineteenth-century Industrialisation and the Arrival of the Railways

The railways were revolutionary in transforming nineteenth-century Europe in so many ways. In this volume we have three very different papers on aspects of railway building. Robert Thorne provides a fine introduction in his paper 'Railway Engineering and the Picturesque' (pp.103-118). It is naturally presumed that in the nineteenth-century, as now, civil engineering works were laid out principally to minimise cost and minimise profit, but Thorne's paper shows how the situation was much more nuanced and there is plenty of evidence that aesthetic considerations played an important part. Dermot O'Dwyer and Ronald Cox's paper on 'Early Irish Railway Construction' (pp.119-130) provides an introduction to the similarities and differences between railway construction in Ireland and the rest of Britain between 1830 and 1860. They show how wet ground led to new construction techniques and dramatic bridges and that some of these survived today. Lastly, Antonio Borregas Núñez, Rosalía Crespo Jiménez and María Paz Sáez Pérez, 'The Civil Engineering in Southeast Spain 1890-1894' (pp.131-140) tell the wholly unexpected story of how British engineers and local know-how constructed railways in late nineteenth-century Spain, providing a fascinating example of how technology can be transferred and translated by importing foreign expertise. Gracia López Patiño and Pedro Verdejo Gimeno, 'The transfer of a British Victorian architecture of smoke to the industrial brickwork chimneys of Eastern Spain' (pp.141-152) tells a similar story but this time for brick factory chimneys. All these papers cover topics that illustrate that construction history covers not just buildings but also works of civil engineering.

Building the Houses of Parliament

The Palace of Westminster, which had housed the British Parliament since the Middle Ages, famously burnt down in a dramatic fire in 1834, leaving only a few fragments still standing, including Westminster Hall with its famous medieval hammer beam roof so beloved by construction historians. The competition that followed the fire, and the discussions that surrounded it, are a worthwhile story in their own right. Construction of the current building started in 1840, but it was not completed until 1870, a period of thirty years. As a major public
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project the building works were meticulously recorded and all the relevant documents have been retained. It thus provides a wonderful source for the study of the history of nineteenth-century building construction and the operation of the building industry at the time. The building boasted a number of innovations including very a complex system of ventilation. The two papers here are concerned with this particular aspect. The first, The architecture of the not-quite-well-tempered environment: on the making of the new houses of Parliament (pp.155-164) by Jing Zhao discusses how the management structure and separation of architecture and technical design hampered the design of the Houses of Parliament and led to failures in its technical performance. In a parallel paper, Henrik Schoenefeldt’s, Reid’s short-lived ventilation system for the Permanent House of Commons, 1847-54 (pp.165-178) shows how the ventilation was designed to work and the problems that arose in practice. It is interesting how two independently-produced papers could be submitted on the same subject in the same year to the same conference and yet how different they are in approach, providing an interesting demonstration of the fact that two people working on the same subject in history are unlikely to produce similar results, each bringing with them very different interests and perspectives.

Steel and Concrete in the Early Twentieth Century

The early twentieth century is represented by five papers each explaining separate structures and widely differing approaches. The first presented here is Nicholas Bill’s meticulously researched account of the construction of the concrete dome of the Melbourne Public Library, which was completed in 1913 (pp.181-196). This is followed by Christiane Weber’s moving account (pp.197-206) of the Starnberg Municipal Baths with its dramatic concrete vaults, constructed at a similar time (1895-1908). Concrete again features in Ljubljana Slovenia, in the context of constructing a 13 storey building containing flats, offices and shops in the middle of Ljubljana in 1933. It tells how the building had to be especially designed to withstand earthquakes because in 1985 the city had been devastated by one and there was considerable concern about high rise construction as a result. Roland Machmann paper (pp.223-238) looks at the Glasgow School of Art (built between 1896 and 1909). The building suffered a dramatic fire on 23 May 2014 and the iconic library was gutted. The paper is thus timely. It examines the selection of materials in the building, including the use of much structural steel. Steel is also the subject of David Yeoman’s paper (pp.239-244) on the construction of the De La Warr Pavilion at Bexhill (1935). In particular it highlights the role played by Felix Samuely (1902-1959), an émigré engineer who had been born in Vienna and moved to England in 1933 and his innovative use of welded frames. It is perhaps no surprise that steel, concrete and early 20th century design continue to attract so much attention. This is the period when structural engineering (as opposed to civil engineering) emerges as a separate discipline in building construction. But it is also a time of huge advances in our understanding of concrete and steel, two materials that dominate construction to this day.

Prefabrication

Prefabrication is an area that continues to provoke considerable discussion and one of those in which there is extraordinarily little interest in learning from the successes and failures of the past. World War I was an appalling waste of human life. The desperate struggle for survival on both sides led huge technical advances at a time of great material shortages. The war and its aftermath demanded innovation and ingenuity in equal measure. This is amply demonstrated by Carey Draper’s study of Second World War prefabricated buildings in Britain (pp.247-256) in which she discusses the number of systems developed in the period to provide temporary accommodation for war. Surprisingly many have survived remarkably well, but as they were never designed to last, they are beginning to disappear, and Draper’s study provides an important starting point for those recording or seeking to retain those last few that remain as well as providing valuable insights into an important episode in history.

The temporary huts of the British war time era were developed into prefabricated housing systems after the War, all of which failed for one reason or another. The failures were carefully documented at the time and widely reported afterwards but they seem to have been entirely forgotten today, now that most of those involved are dead. The next two papers look at the post-war housing effort in the rest of Europe where various systems were developed with greater or lesser success. The first by Pepa Cassinelli, Eduardo Torriaga’s 1949 International Housing Competition on Industrial Design (pp.257-266), tells the story of how the government sought to introduce prefabrication to housing in Spain while Mario Mandel’s paper, Stagnation and innovation in prefabricated large-panel technologies in the USSR: A case study of production in the Tallinn house-building plant (pp.267-276) provides a fascinating insight into the production of panelled blocks of flats in the 1960s Soviet Union. A huge number of these Soviet flats, of course, remain. The more we understand about their construction the better they can be maintained and informed decisions can be made about their future.

Post 1945 construction

The last four papers dealing with construction after 1945. Stefania Morsati and Laura Greco’s paper, The Gothic Tower by Melchiorre Bega (1956-1959): the removal of building technologies in the face of Italian tradition (pp.279-290), details the building of a key modernist high-rise concrete building in Milan, with its innovative structure and use of curtain walling. This sits well beside Marcello Zorlani and Franco Frangipoli’s paper, The curtain wall experimentation in Italian building office: the sixties (pp.291-300), which provides an overview of the spread of curtain wall technology in Italy over the ensuing decade.

Louis Kahn was renowned for his love of materials. Anna Rosellini’s paper, Joint, growth and ornament of Kahn’s cast-in-place concrete (pp.301-312) which grows out of her book on the same subject, explores in detail his use of reinforced concrete and how Kahn’s use of joints and other construction features for visual effect often created problems in construction and challenges for the building team. Often what appears to be a construction feature is not what it seems.

Finally in Re-envisioning Historic Cottolieni Vaulting Techniques: A case study in Medellin, Colombia (pp.313-323) Mallory Taul and Katherine Prazer revisit the catalan vault. This type of vaulting is constructed using thin tiles laid on each other using fast-drying gypsum mortar and thereby not requiring any expensive and wasteful formwork. It was in use in Mediterranean in the 1300s and is similar to vaulting techniques found in Peru and the Middle East in the Middle Ages. It was popularised again by Rafael Guastavino (1842-1908) whose company used a similar technique to produce thousands of thin shell vaults in the USA in the late nineteenth and early twentieth century. This paper shows how this historical technique has been further understood by experiments in constructing them full size and using them to make modern buildings. It
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provides a fitting ending to the proceedings by showing how historical understanding can inform contemporary practice.

**Future Directions**

The papers in this volume highlight how the twentieth century remains a focus of much research construction history and how much work remains to be done. There are large areas of the subject that are not even touched on here: there are no papers on individual engineers or architects, large periods of history go unmentioned, materials are touched upon, but only in two isolated cases. This volume was never intended to be very extensive. What was originally envisaged as a one-day event with 10-15 papers grew in the planning to two days and twenty-six papers. The resulting proceedings are over 325 pages. We hope that the conference in Cambridge will become a regular event and next year it will again be two days with more papers. The aim must be to get a more general coverage and get papers in a broader range of subjects. However, what this volume does show is there is a genuine and growing interest in construction history that bodes well for the future.

James W P Campbell
2015

**Epistemology of Design**
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Hooke's chain in the Spanish Enlightenment of the XVIIIth century

Josep Lluís i Ginovart, Agustí Costa, Sergio Coll and Mónica López
Department of Architecture, Universitat Rovira i Virgili, Spain

Introduction

In Spain it has been believed that the crenary arches are one of the main characteristics of modernist architecture, developed as a consequence of the theory of the masonry arches, applied to the graphic estate of the XIX century, whose main exponent was the work of Antoni Gaudí (1852-1926) [1]. But, as we will prove below, it was the teaching in the Mathematics Academy of Barcelona (1720), and the emigration of the Catholic families coming from Scotland and Ireland, who were the first to build this kind of arch fifty years before Antoni Gaudí would build them.

The theory of the chain, in the shape of a hanging collar, was proposed by Robert Hooke (1635-1703) at the end of his treatise A description of helioscopes, and some other instruments (1676); Hooke presented a solution that would be revealed as "Ut pendet continuo flessile, sic stabit contiguum rigido inversum" [2]. The awareness about the shape of the crenary was applied by Christopher Wren (1632-1723) in the dome of San Pablo (1675), with the collaboration of Robert Hooke in the design[3]. The mathematician Tschirnhaus (1656-1708) formulated the solution of the crenary theory in the shape of a hanging collar, to simulate the behavior of a constructive element [4]. This solution inspired the analysis by Giovanni Poleni (1680-1761) in the Memorie storiche della Gran Cupola del Tempio Vaticano (1749)[5], who developed a methodology similar to Stirling's, to understand the breaking of the vault of the San Pedro Basilica [6], and its posterior application will be determinant for the essays of Gaudí.

The development and application of this theory takes place in the context of the Mathematics Academy of Barcelona (1720). It is a main reference for the work of Bernard Forest of Béllérou (1698-1763), La science des ingénieurs (1729), partially translated by John Miller (1689-1784), A treatise containing the elementary part of fortification, regular and irregular. For the use of the Royal academy of artillery at Woolwich (1755), which was translated again for use in the Academy en Traite de fortification, ó Arte de construir los edificios militares, y civiles (1769)? As a consequence of these teachings, 74 projects of gunpowder warehouses of the General Archive of Simancas, which date from 1715 to 1798 have been studied. Between them, three projects with a crenary vault have been found which are: Miguel Marin for Tortosa (1731) and Barcelona (1731), and Jean de la Ferrière in A Canulla (1756). (Fig. 1).
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The libraries of the military engineers of the XVIII century

One of the functions of the Mathematics Academy of Barcelona (1720) was the formation of a fund of scientific works for its library. The bibliographic interest of the engineers, who had their own libraries, would lead Vicente García de la Hoyos (1734-1787) to the publication of the Bibliotheca Militar Española (1760) with the cataloging of the main treatises of the XVI-XVIIIth century [9].

Among the works that the military engineers accessed in the libraries we highlight: L’architecture des voûtes (1643) of François Du Raud (1588 -1644), in the library of Jorge Prosper Verboom (1665-1744), and the treatise on stereometry of Abraham Bosse (1604-1676), La pratique du trait à preuve de M. des Arque Lyonnois pour la coupe des pierres en Architecture (1643), in the Library of Barcelona Academy.

El Compendio Matemático (1767-1715) of Fray Vicente Tomás Toscan (1651-1723), dedicates the XVI Treatise of the V Tome, divided in six books, to military architecture (1712). In masonry mechanics, the XV Treatise, De las Montes y Cortes de Cantaría is dedicated to the dimensioning of arches and vaults and its collapse mechanisms. It determines that the perfect shape of an arch is a mixed arch, the interior formed by a rounded arch and the exterior by a pointed arch. The stringcourse, or corbel arch will be improved, as in the II Book III Prop. For the first time the geometric construction of the ovals is determined fixing them by the measures of its two main axes. This is extraordinarily useful for the drawing of the vaults in the de ame de poner shape [10].

Another author of note is Hubert Gautier (1669-1737) with the Traité des Ponts (1716) [11]. In the second edition of 1723 appears: Ut pondera libra, sic aestimatio architecturae, referring to the difference of thrust of a rounded arch, which unbalances, compared with a pointed arch. The text is based on the theory of the mechanics by Philippe de La Hire (1649-1719), to which he alludes continuously [12].

But the main references for the Spanish military engineers are without doubt the works of Bernard Forest of Belidor (1698-1761), et Nouveau cours de Mathématique (1725), La science des ingénieurs (1729), and the Architecture hydraulique (1737) and the second Tome of his hydraulic (1739) [13]. In le Nouveau cours de Mathématique (1725), Bernard Forest of Belidor, considers a practical application of the masonry mechanics for the construction of gunpowder warehouses [14]. He determines the abutment for a caisson vault and for a tiered pointed arch. He synthesizes, in a table, the dimension of the pieds droits, in ratio with its curve and localization. In the La science des ingénieurs dans la conduite des travaux de fortification and architecture civile (1729) [15], II Book, III Chapt, 5 Prop, Belidor sets out the curve that must be given to a vault so all its parts weigh the same and stand in equilibrium [16], and as a result its curve will have the shape of a catenary. And as he determines, for military constructions, up to five types of different vaults: round, tiered pointed, elliptic drawn as a segmental arch, the flat ones, and the derived forms of the catenary [17].

At the same time, De la pompe des voûtes, (1729) de Pierre Couplet (1743), refers also to the chaineauette, the hanging chain, as the best of all shapes for the construction of vaults. He also says that if it was desired to build on any part of the vault, there would have to be added to the corresponding part of this hanging rope a proportional weight of the construction with which it needs to be loaded, so the resultant curve will be the one to be used [18].
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After the access to the throne by the dynasty of the Bourbons in Spain (1700), Catholic diplomatic and military families of Irish and Scottish origin enlisted under royal protection, keeping their status. The O'Connor family was installed in Baniarles in the XVIIIth century, and associated with the McDonnell in the wine export business. In the construction of the O'Connor wine cellars of Carlist de Baniarles (1757), catenary vaults were used.
Hooke's chain in the Spanish Enlightenment of the XVIIIth century

Furthermore, Philippe de La Hire (1695) in *Traité de mécanique* (1695), formulated the equilibrium of the arches and vaults under the theory of the quoin. He establishes, for the first time, that what has to be the weight of the vousoirs or its stability, the process will be advanced with the mastic polygone. De La Hire, in *Sur la construction des voûtes dans les édifices* (1722), noted that when the abutments of a vault are insufficient, they break in at 45-degree angle. Therefore, he theorizes that the upper part of an arch works as a quoin, without friction, generating a force that tends to push over the buttress. Belidor (1725) will simplify De La Hire's method on a data table, reducing it to the required abutment for construction. The Masonry theory of De La Hire appears in the bridge treatise of Guiter (1716). After that, the engineer Charles-Augustin Coulomb (1737-1806) in the *Essai sur une application de maxima et minima à quelques problèmes de statique, relatif à l'architecture* (1773) will determine the existence of maximum and minimum strength in the arch. This will enable authors of the XVIIIth century, as Claude-Louis-Marie-Henri Navier (1785-1836) in *Résumé des Leçons données à l’École des Ponts et Chaussées sur l’Application de la Mécanique à l’Édification des Constructions et des Machines* (1826), R. Misy (f. 1840) in *Le Mémoire sur l’équilibre des voûtes en ferrocram* (1840) and Henry Moseley (1802-1872) in *The Mechanical Principles of Engineering and Architecture* (1843), to complete the elastic theory of masonry arches and vaults.

The gunpowder warehouses in the military architecture treaties

The military architecture treaties of the end of the XVIIth and XVIIIth century, make reference to the construction of the warehouses, especially if it has a high resistance element, made brickwork, or disposed in caves or underground [19]. The work of reference will be *Mansones de fortificar según la méthode de Monsieur de Vauban, et Sébastien Le Prestre, Vauban* (1633-1707), edited by the abbot De Fay in 1681. The morphology of the gunpowder warehouses with double enclosure is determined in the treaty, and also the dimensions of its roofing [20]. It is done with the construction of a masonry vault with a thickness of five to six feet of torea, which is recovered as bombproof, with a layer of earth of six feet thick. In the second edition of the work in 1693, the double enclosure with a central body, with cannon vault, on walls with trampills will be drawn.

In the Spanish treaty *El Ingeniero Primero Parte, de la Moderna Arquitectura Militar* (1687), by Sebastián Fernández de Medrano (1644-1703), it is solved with a masonry vault with four feet of torea "vuru". This first thread of the vault is completed, with another six layers, some of earth, some of wood and others with dung; forming a thickness of eleven feet edgewise [21]. Further on, in the *El Arquitecto Perfecto en el Arte Militar* (1700), the thickness will be increased up to twelve and fourteen feet [22]. In the *Escuela de Palas ó sus Curso Matematico* (1693), attributed to José Chablot (1653-1698), in the *Libro de Artes Militars, XI Tratado* [23], similar constructions to the Vauban ones exist. He solves, the dimensions of the main constructive elements. He builds a wall of six feet of "vuru" and also the wall with an reinforcement of two buttresses. This vault is solid and built with lime masonry, which differs to Sebastián Fernández’s.

The importance of these strategic elements will oblige Belidor to dedicate the whole Chapter no.9 of the IV Book of *La science des ingénieurs* (1729), to the construction of the gunpowder warehouses. He builds the vaults with four layers of ceramic masonry with a thickness of three feet of torea, until it forms a total section of eight feet of thickness. The work of Belidor was translated into English by John Müller (1699-1784), under the title *A treatise containing the elementary part of fortification, regular and irregular. For the use of the Royal Academy of artilleria at Woolwich* (1755). This text was also translated into Spanish by the professor of the
Hooke's chain in the Spanish Enlightenment of the XVIIIth century

Furthermore, Philippe de la Hire (1695) in _Traité de mécanique_ (1695), formulated the equilibrium of the arches and vaults under the theory of the quoin. He establishes, for the first time, what has to be the weight of the voussoirs for its stability, the process will be advanced with the same result. De la Hire, in _Sur la construction des voûtes dans les édifices_ (1745), noted that when the abutments of a vault are insufficient, they break in a 45-degree angle. Therefore, he theorized that the upper part of an arch works as a quoin, without friction, generating the force that tends to push over the buttress. Bélidor (1725) will simplify De la Hire's method on a data table, reducing it to the required abutment for construction. The theory of De la Hire appears in the bridge treatise of Guiter (1716). After that, the engineer Charles-Augustin Coulomb (1736-1806) in the _Élémens de physique théorique et de mathematique appliquée_ (1786) and _Traité de l'équilibre et du mouvement des corps_ (1787), developed the theory of the equilibrium of the arches and buttresses, completing the static analysis through a mathematical approach. The equilibrium of the arches and buttresses will be established in the second half of the 18th century, with the work of Restout (1791) and the _Traité de la construction des édifices_ (1796) of Bélidor. The equilibrium of the arches and buttresses will be completed in the 19th century with the work of Marc Seguin (1840) and Joseph Dupuis (1842), establishing the modern theory of the equilibrium of the arches and buttresses.

The gunpowder warehouses in the military architecture treaties

The military architecture treaties of the end of the XVIIth and XVIIIth century, make reference to the construction of the warehouses, especially if it has a high resistance element, made of reinforced masonry, or disposed in caves or underground. The work of reference will be _Monumental improvements_ (1640) by David Lacroix, edited by the abbé Du Fay in 1681. The morphology of the gunpowder warehouses with double enclosure is determined in the treaty, and the thickness of its doors. It is done with the construction of a masonry vault with a thickness of five to six feet of stone, which is recovered as bombproof, with a layer of earth of six feet thick. In the second edition of the work in 1693, the double enclosure with a central body, with cannon vault, an cellars with turrets will be drawn.

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Mathematics Academy Miguel Sánchez Taramas, in Barcelona (1769) [24]. The translation of the _Tratado de fortificación, de Arre de construir los edificios militares, y civiles_ was done for the use of the pupils of the Mathematics School. Determinations for the construction of the gunpowder warehouses their references are the texts of Vauban (1661) and Bélidor (1729) [25].

John Müller explains that, according to tradition, constructions with cannon vaults support better bomb impact than those that have a gothic shape. He specifies that the materials used for the construction of the vaults have to be of masonry, or ceramic bricks. In the case ceramic bricks, it has to be set out in three threads, and with a thickness, on the ribs of the vaults, of three feet. The vaults specify a total thickness of nine feet. The constructive dimensions of the elements of the gunpowder magazine are in ratio with the tradition of Vauban. So the buttresses will be of ten or eleven feet, while the foreheads walls have a thickness of five feet. The buttresses are of five feet long and seven feet thick, with a separation between them of thirteen feet. In the construction of vaults he also specifies that the formwork must to stay in place for at least six months.

The equilibrium curve in military Spanish engineers

In the construction of gunpowder warehouses, cannon and pointed vaults are generally used, although there are some examples with elliptic vaults, like the one built in 1664 by Hércules Torellí in Pampolona. This was remodelled by Francisco Lombardo de Mauclus (1718). The Robinson School of Barcelona and Zaragoza, and the Institute of the Escuelas de la Guerra y Arte Militar also published in Barcelona (1699). The Vicente had ordered the repair of the fortifications and the gunpowder warehouses, to make them bombproof. The elliptic vault was replaced, the concept introduced in the military treaties by the General Anriquez (d. 1587) in _Le Timon du Capitaine_ (1587) [27], for a cannon one, reinforced and reduced in height, to be less visible and vulnerable to the enemy artillery.

The simple vault of the warehouse project of Miguel Martín, done for the building in Tortosa (1731) [MPD, 3.035], does not have either an arch circumference generatrix. The geometric study reveals that the vault has a length of 21 feet of stone, a thickness of 3.5 feet and a buttress of 7 feet. It is observed that if a chain was disposed that would pass through the impost and the keynote of the vault the geometric element could be traced, in a castaneous shape, with the stone length and stone of the vault, and very similar to the one drawn on the project.

The projects for gunpowder warehouses in the mountain of Montsia, in Barcelona (1731) [MPD, 0.07], whose design is attributed to Miguel Martín, are similar to the layout of the warehouse of Tortosa. Another similar project is the simple warehouse layout by Juan de la Ferlité y Valentin in A Coruña (1736) [MPD, 1.037].

Previous layouts have been assessed in detail through CAD applications. The study concluded that the geometrical figures are neither rounded arches, nor curves drawn through pointed arches, nor ellipses or oval shapes. The spring-line of the vault. The layout of the pointed vault is compared with the calotte obtained with a chain over a reproduction of the plans on a larger scale. Thus, the arch described by the chain is very similar but not coincident to the profile of the vault, since there are slight deviations near the spring-line of the vault.
Hooke's chain in the Spanish Enlightenment of the XVIIIth century

This deviation is due to the fact that it is not possible to layout the catenary with traditional drawing tools like the ruler and compass. To draw the projects of the warehouses, both Miguel Marín and Juan de Terrión y Valensín used a method of approximation to the curve through the construction of an oval (Fig.2). The assessment of the original drawing of the section of the warehouse reveals three marks of compass. One point is over the vertical axis of symmetry of the figure, and the other two over the perpendicular axis, slightly below the spring-line of the vault. It proves the intention of drawing the curve of the vault using the arch apimoleado, a cayomel of Tosca (1712), or arce de panier of Bélidor (1729).

Fig. 2. Assessment of catenary vaults: 1: Tortosa; 2: Barcelona; 3: A Coruña.

The geometric layout of these arches and vaults based on ovals were well known by the XVIIIth century military engineers. They began from the essential feature that oval vaults are tangent to the springline of these building elements. When ovals are sectioned parallel to its main axis, a non-tangent curve to the springline is obtained, according to the definitions given later on by Pérez (1738) about the catenary. At the same time, Bélidor (1729) specifies the method to layout the true shape of the catenary vault. By knowing the rise and the span of the vault the architectural shape is determined with a hanging chain. Thus, a scaled model can be built which can easily be taken to the construction site. By contrast, the layout of the catenary in the project of military engineers is more complex, which forces the use of an approximation of the catenary through the geometrical shape of a lowered oval.

The catenary arch of O’Connor cellars (1757)

It is not known if the projects by Miguel Marín for Tortosa and Barcelona (1733), and by Juan de la Terrión y Valensín in A Coruña (1736) were built, but we have evidence of the use of catenary arches in the construction of the Carlin cellars of the O’Connors in Benicarló (Fig. 3), where on its façade appears the year 1757 inscribed. The construction is built with eight diaphragm arches of 35cm in depth, which defines nine bays. The ceramic masonry arches are supported over a limestone basement carved according to the curve of the arches.

Fig. 3. Real indoor view of O’Connor cellars.
Hooke's chain in the Spanish Enlightenment of the XVIIith century

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![Diagram](image1)

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![Image](image2)

Fig. 3. Real indoor view of O’Conner cellars.
Hooke’s chain in the Spanish Enlightenment of the XVIII century

Bélidor determined up to five types of arches and vaults: rounded arches, tier-on-point pointed arches, elliptical, planar and the ones derived from the chain. In order to determine the geometrical layout of the arches (Tab. 1), a topographical capture of the points of the intrados has been done [30].

### Tab. 1. Measured size of different arches of O’Connors Cells.

<table>
<thead>
<tr>
<th>Height (cm)</th>
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<th>1886</th>
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<td>9.83</td>
<td>9.69</td>
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The geometrical assessment of the arches involved the use of statistical methods, determining two coefficients: the coefficient of variation and the coefficient of correlation, related to the equations of the curves of reference: the ellipse and the catenary. The coefficient of correlation indicates the proximity between two distributions; values near to (1) or (-1) means a high correlation, while values near to (0) means low correlation (Tab. 2). The coefficient of variation enables us to compare and to quantify the geometrical dispersions between two different groups of points, as long as their arithmetic mean is positive. This assessment concludes that, according to the coefficient of variation, the most coincident curve is the catenary (0.3515) in front of the (0.3789) of the ellipse. It also coincides with the results of the coefficient of correlation, with a (0.98) for the catenary and (0.89) for the ellipse. Moreover, from the assessment of the angle of incidence of the arch over the horizontal plane it can be deduced that there is a variation between 2 and 9 degrees in all arches, so these do not have a vertical tangent perpendicular to the horizontal plane (Tab.3).

### Tab. 2. Statistical study to compare the ellipse and catenary.

#### Correlation coefficient

<table>
<thead>
<tr>
<th>Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
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#### Variation coefficient

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</table>

### Conclusions

The assessments of the gunpowder warehouses by Miguel Marín fur Tortosa and Barcelona (1733) and by Juan de la Ferriére y Valortis in A Coruña (1736) are only a 4.65% of the projects analyzed. It proves the intention to layout the vault as a catenary. They knew that in a catenary, any force pushing inside means the same thrust outside. These engineers had a wide knowledge about the mechanical principles of the modern theory for masonry. From a scientific point of view, catenary vaults are the most interesting, as they introduce the principles established by Hooke (1676) which were taken to Spain through military engineers and the text La science des ingénieurs (1729) by Bélidor. This work was partially translated to English by John Müller (1755), which was also translated to Spanish as Tratado de fortificación, o Arte de construir los edificios militares, y civiles (1729). Despite there being no evidence of the construction of the gunpowder warehouses, it is possible to confirm the use of catenary arches in the construction of the Carlij cells of the O’Connor in Benicarló (1737). The theory line of thrust followed by most of English engineers of the XVIIIth century was used in Spain one century and a half before the modernist architecture lead by Antonio Gaudí.

### References

Hooke's chain in the Spanish Enlightenment of the XVIIIth century

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Yiting Pan and James W.P. Campbell

British Influence on Chinese Building Construction Books in the early 20th Century

Yiting Pan and James W.P. Campbell
Department of Architecture, University of Cambridge, UK

Introduction

Building construction books were very rare in Imperial China. The best preserved books on building were written by government officials, to provide guidelines for officials supervising construction. The 12th-century Yingzao fashi 营造法式, Gongzhu gao 龚自珍 (published in 1734, and Qingshi jingzao zhi 田代 营造法式, a compilation of various official construction manuals compiled between 1644-1911, are all of this type. These manuals were selective in recording building techniques and were not written for or by craftsmen. Indeed, techniques were passed down through apprenticeship and commonly treated as trade secrets. Except in rare cases such as the 15th-century Luhun jing 落闻经 and the early-20th-century Yingzao fa yuan 营造法原, craftsmen’s manuals were not openly available.

The increases in literacy, Western influences in building practice, and the importation of many Western techniques gradually created a new market for books for building workers. But even so, Chinese building construction books were still very rare in the early 20th century with very few appearing before 1930. The flourishing technical schools over the first decade probably commonly used teachers’ lecture notes based on foreign books. By the 1930s using English textbooks directly in the teaching had become the norm. Modern studies on architectural writing in China, including those by Lai (2007) and Xu (2010), have cited Jiuanuo xinfu (Building construction) 建筑新法 (1910) [2], or “new building methods”, as the earliest Chinese book on architecture in modern China. The waive writers have stated that the source of information in the book was largely Japanese, based on the author’s educational background. Actually, as this paper will show, this is far from being the case. Another Chinese work worthy of attention is Yingzao su (营造字) published in serial form in Shanghai Architectural Association’s monthly magazine Jiuanuo yu jie (建筑界), or The builder, between February 1935 and April 1937. Yingzao su was written in parts with the intention of publishing it subsequently as a single volume, but this ambition was never realised as the Sino-Japanese War intervened. These two works, Jiuanuo xinfu and Yingzao su are among the most influential Chinese construction books in the early 20th century. They attempt to present new construction methods, mixing traditional Chinese constructions and imported Western ideas.

As already stated, it has been generally assumed that the source for Jiuanuo xinfu was Japanese, and the sources for Yingzao su were a number of different English books, but an exhaustive search of separate editions of English building construction books published between 1840 and 1940 carried out for this paper, reveals for the first time that these two Chinese books were largely based on two English ones. In fact in each case they drew heavily on just one book: Jiuanuo xinfu relies heavily on Gwill’s An encyclopedia of...
Hooke’s chain in the Spanish Enlightenment of the XVIII century

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