

The *Ciborium* or Lantern Tower of Valencia Cathedral: Geometry, Construction and Stability

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Early 18th century treatise writer Tomás Vicente Tosca¹ includes in his *Tratado de la montea y cortes de Cantería* [On Masonry Design and Stone Cutting], what is an important documentary source about the lantern of Valencia Cathedral. Tosca writes about this lantern as an example of vaulting over cross arches without the need of buttresses. A geometrical description is followed by an explanation of the structural behavior which manifests his deep understanding of the mechanics of masonry structures. He tries to demonstrate the absence of buttresses supporting his thesis on the appropriate distribution of loads which will reduce the “empujos” [horizontal thrusts] to the point of not requiring more than the thickness of the walls to stand (Tosca [1727] 1992, 227-230).

The present article² assesses Tosca’s appreciation studying how loads and the thrusts they generate are transmitted through the different masonry elements that constitute this *ciborium*.³ In order to do so, we first present a geometrical analysis and make considerations regarding its materials and construction methods to, subsequently, analyze its stability adopting an equilibrium approach within the theoretical framework of the lower bound limit analysis.

The construction of the cathedral

Works began on the apse end in 1262, during the bishopship of Andrés Albalat (Bérchez Gómez and Zaragoza Catalán 1995). This Dominican monk commissioned the design and direction of the works to *magister operis* Amaldo Vidal

(Navarro Fajardo 2004, 1: 193). Construction moved towards the west alongside the demolition of the early Islamic mosque, and before the end of the thirteenth century the head was completed. By the mid 14th century the crossing was finalized and work progressed on the nave and aisles (Navascués Palacio 2000, 151). The bays of the nave are square in plan which is unusual in the Spanish gothic architecture. *Maestro Vidal* was succeeded by Italian Nicolás de Antona or Ancona [1303] and Andrea Juliano who built the chapter house around 1358 (Torres Balbás 1934, 94). At mid-14th century, the construction of two singular pieces originally detached from the fabric

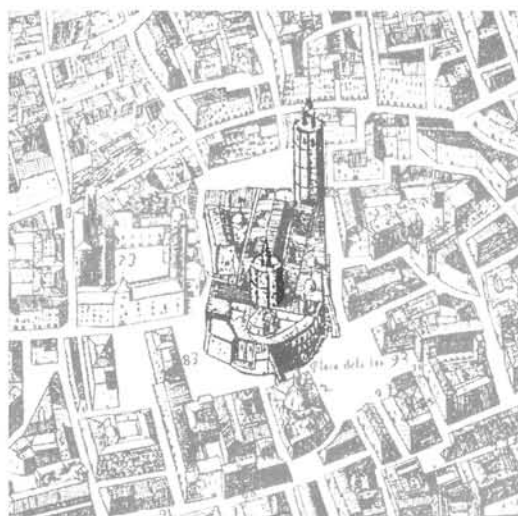


Fig. 1: Valencia Cathedral, showing the lantern, as depicted in the city map drawn by Tosca (1704).

of the cathedral – the chapel of the Holy Grail and the *Micalet* – had been undertaken. The *Micalet* bell tower was erected at the west end freestanding from the body of the cathedral in the manner of the Italian campaniles and following the tradition of the octagonal bell towers in Aragón and Cataluña (Lampérez 1909, 130). Later, towards 1459, master masons Baldomar and Pedro Compte built the last stretch and these two elements were incorporated into the volume of the cathedral (Torres Balbás 1934, 94). (Navascués Palacio 2000, 155).

The austerity, amplitude and somehow archaic and robust character, together with the nave's square rhythm and its spatial connection with the aisles, denote a lack of correspondence with the French Gothic tradition but proximity to Italian *trecento* models (Street 1863, 261-262) and to local and vernacular features (Torres Balbás 1934, 97).

After its completion, the cathedral continued to expand and be reformed. The most substantial alteration took place at the end of the 18th century when the Gothic interior was overlaid with a neoclassical skin. Architect Antonio Gilabert commenced in 1774 the works at the lantern and transept continuing to complete the interior of the cathedral (Navascués Palacio 2000, 155) which lost its severe Gothic character. Torres Balbás attributes to the "heavy proportions of the building" the easy manner in which it could be "disguised in a perfect neoclassical fashion" (Torres Balbás 1934, 97). The year 1967 saw the start of the efforts to return the cathedral to its original state by removing the neoclassical and baroque additions. These works were supervised by architects Alejandro Ferrant and Juan Segura de Lago and in 1972 by Fernando Chueca. The last intervention was accomplished by architects Ramiro Moya and Francisco Pons-Sorolla in 1976-1979. In this restoration, the lantern was cleaned of its classical cladding and reverted to its gothic appearance.

The lantern: Historical elements

Eminent Victorian architect George Edmund Street considered that the "lofty lantern or Cimborrio" of Valencia Cathedral was "one of

the finest examples of its class in Spain" (Street 1863, 263) implicitly referring to other octagonal lanterns in the Mediterranean region⁴ (Fig. 2).

The shaft of the lantern rises on conical pendentives comprising two parts built in distinct stages. Its construction may have begun in the 14th century, being completed in the 15th.⁵ Oñate (1981, 14) notes that "from 1380 until 1397 there is evidence of works performed in the "cembori": on the terraces, gargoyles, stairways, roofs, etc. It is possible that Martin Llobet – "mestre de obra del campanar nou" – was the master mason who, later on, closed the lantern in the first half of 15th century (Sanchís Sivera 1909, 193-196).

The formal description of the structure as offered by Street is as follows: "It is an octagon of two rather similar stages in height above the roof. Crocketed pinnacles are arranged at each angle, and large six-light windows with very rich

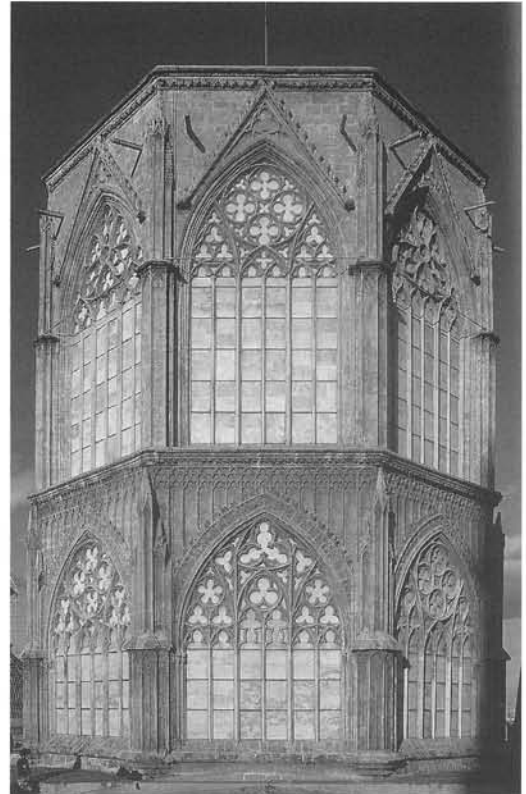


Fig. 2: West view from the nave roof level.



Fig. 3: View of the crossing from floor level.

and varied geometrical tracery fill the whole of each of the sides. The lower windows have crocketed labels, and the upper crocketed canopies and the string-courses are enriched with foliage. From the very transparent character of this lantern, it is clear that it was never intended to be carried higher. It is a lantern and nothing more, and really very noble, in spite of its somewhat too ornate and frittered character" (Street 1863, 263-264). The upper body is surmounted with an octopartite brick vault on stone ribs in the form of pointed arches converging on a decorated ring boss (Navarro Fajardo 2004, 1: 198) (Fig. 3).

Both the lantern and crossing have suffered several structural interventions (Oñate 1981; Bérchez and Zaragoza 1995; Zaragoza 1998; Soler and Soler). The crossing pier next to the choir on the Gospel side had to be repaired in the 17th century and the one adjacent to the nave on the Epistle side was renovated in the 18th century. The lantern itself was reinforced with ring tie beams: by Timoteo Calvo in 1863 (Zaragoza Catalán 1998, 151) and an external ring bracing the upper wall

arches at the springs level by Francisco Mora in the first third of the 20th century. The last major structural intervention, between 1976 and 1981, was directed by the architects Francisco Pons Sorolla and Ramiro Moya Blanco [from MOPU, Ministry of Public Works and Urbanism] and the cathedral architect Luis Gay. It included underpinning the foundations of the four piers of the crossing and consolidating the two on the nave side. Two more tie beams were introduced at the base of both bodies of the lantern. Mora's bracing was renovated, and reinforced concrete elements were introduced over the vault. Inside, the walls were restored to their original state "stripping from them that witless neoclassical cladding that disfigured the interior" (Oñate, 1981, 16).

Geometry and stability

Amongst Vicente Tosca's most important works, we find the *Compendio Mathematico* (1709-1715), with two posthumous editions of 1727 and 1757. Its Treatise XV, written in 1712, *Trazado de la montea y cortes de cantería* [On Masonry Design and Stone Cutting], is devoted to "the most subtle and exquisite part of Architecture [...] the formation of every sort of Arches and vaults, cutting their stones, and adjusting them with such artifice, that the same gravity and weight which would make them fall, maintains them constantly in the air, supporting one another in virtue of the mutual intricacy which links them, and in such way surmount masonry buildings with all strength and safety" (Tosca [1727] 1992, 81). In this work, Tosca shows his admiration and appreciation of Gothic construction.

Trazado de la montea... comprises problems dealing with different types of masonry designs.

Problem XIII refers to the construction of "cross-vaults on any polygon of more than four sides [...] to stand without buttresses" (Tosca [1727] 1992, 227-230). He illustrates this with the lantern of Valencia Cathedral. His contribution is meaningful as, besides providing a geometric description, it makes structural considerations regarding thrust and the distribution of loads. His explanation of the

structural behaviour manifests a profound understanding of the mechanics of masonry structures. He first explains how, as the vaulting of the different webs is quite pointed, their thrusts are not large and are balanced with the thrusts of the adjacent portions. He continues by analyzing the stability of the rib arches which “need for their strength to be loaded at the crown and at the third OP” (see Fig. 4) to prevent both “the crown bursting upwards” or collapsing as the abutments give way. It is evident, as Huerta (2004, 289) notes, Tosca knew the typical collapse mechanism of pointed arches. He finishes stating that is this correct distribution of the loads at the crown and close to the springers what allows the vault to stand without the need of buttresses. He relies on the “experience and skill” of the master mason to achieve it.

Tosca's and the actual geometrical configuration

The geometrical configuration given by Tosca has been represented in Figure 4 left. According to him the diagonal ribs are in the form of equilateral arches with a span equal to the diagonal of the octagon. The formerets are also equilateral, now with a span equal to the side of the octagon and impost lines raised the same distance. Apart from Tosca's description and the diagram he provides, the other only representation of the geometry of the vault was a drawing from Moya

and Pons Sorolla's intervention project (Zaragoza 1998, 147; Soler and Soler). It depicts a cross section through the ridge of the webs including the internal elevation of the lantern walls.

With the aim of better understanding the geometry we carried out in situ measurements and observations which, together with close range photogrammetric techniques, assisted us in the study of the actual structure. Based on these investigations our proposal for the actual geometry is shown on Figure 4 right comparing with Tosca's. The diagonal ribs are not equilateral but stilted *quinto acuto* – pointed fifth – arches and the geometry of the formerets could be considered close to a pointed eighth profile. We understand that the aim of Tosca's idealized construction is not to provide an accurate description of the vault but to present a simple and clear construction which serves the didactical character of his treatise. On the other hand, while our results matched quite well the internal elevations as shown on the Moya and Pons drawing, we found discrepancies in the geometry of the ribs and vaulting. Their drawing seems to ignore the stiling of the cross ribs, and the top of the formerets is shown lower, resulting in a more oblique ridge line.

On the materials and the construction

The two bodied octagonal prism that forms the shaft of the lantern is built in limestone. Of the same material are the four pointed arches that form the ribs being approximately one foot wide.⁶ They meet at the top in an open ring boss with a radius of about two feet. As can be seen in Figure 6 from the level of the springs to approximately half the length of the haunches on the extrados there is a low spandrel wall built with horizontal courses of ashlar. The surface of the brick webs is limited then by the extrados of the pointed arches, the horizontal upper edge of the spandrel walls and the formerets. The brickwork that forms the vaulting is laid in straight courses from the formerets to the diagonal arches, raising from the spandrel walls to the ridge line that is as well straight. Therefore, the different portions of the vault are configured as ruled surfaces. The bond pattern that can be observed on the intrados suggests that the bricks are placed longitudinally. This, together with the absence of headers, would indicate that it is a single

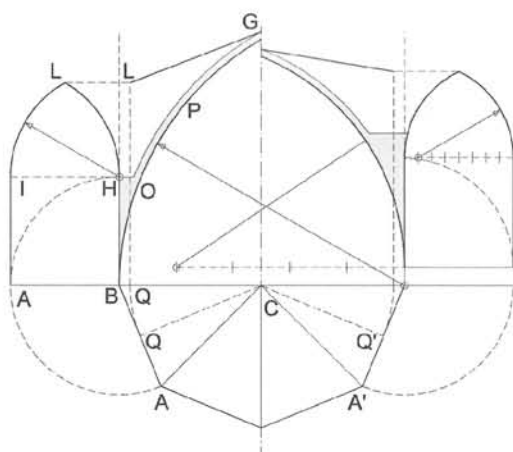


Fig. 4: Tosca's (left) and proposed actual geometry (right) compared.

ring .5 ft thick. Measurements made by the authors showed that the dimensions of the bricks could be around 30-31 cm by 14-15 cm by three to four cm which was standard in this age (Altarriba et al. 2001, 1: 235-254; Cristini 2008, 245). Mortar joints with an average thickness of almost equal that of the bricks can as well be observed. As the webs meet the rib arches quite vertically we have considered the valleys filled with solid masonry. The curve above the arch as shown on Figure 7 is the projection of the rib width onto the surface of the extrados.

It is possible that on the extrados, backing the haunches of the vault, there was a lightweight

filling. It could have been the typical *engarrado* with vessels or ceramic pots, as is commonly found in gothic vaults of the Mediterranean area (Zaragoza Catalán 2003, 1: 130-134). Coexisting with it, a net of thin brick walls could have been present, as frequent found on the extrados of vaults in this area. Both elements, alongside the practical role of providing support for a ceramic roof covering, help to improve the structural performance of the vault. They increase the overall stiffness of the construction and add to its stability allowing a pathway for the transmission of thrust. In any case little or none of the above has survived as the works carried out during the mentioned intervention by Moya and Pons-Sorolla dramatically transformed the extrados of the vault. A thin reinforced concrete layer was laid on the webs, an octagonal reinforced concrete ring beam cast above the crown of the formerets and from it concrete beams over the diagonal arches meeting in a hoop encircling the boss. After these, the configuration of the roof had to be modified and the gargoyles were duplicated to avoid the new concrete elements over the diagonal stone ribs (Soler and Soler). Compare Figure 2 with photographs in Lampérez (1909) and Torres Balbás (1934).

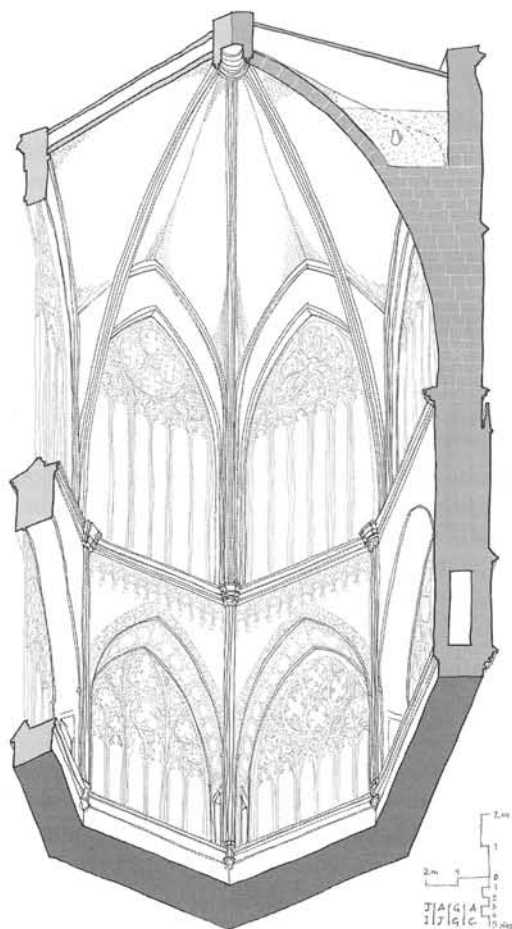


Fig. 5: Axonometric section of the lantern.

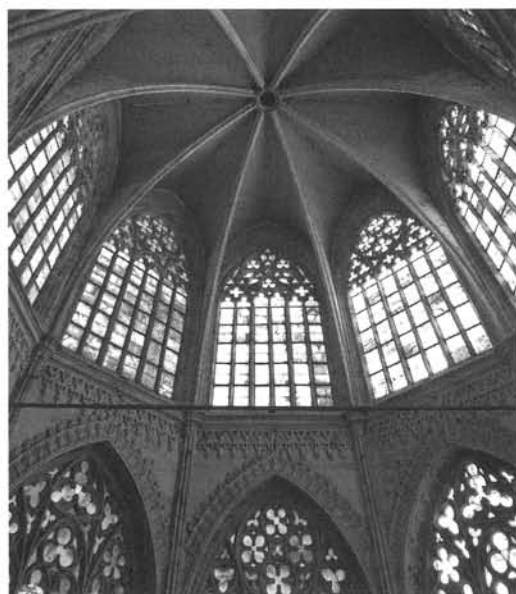


Fig. 6: Internal view of the vault.

Theoretical framework: Lower bound limit analysis of masonry structures

Heyman (1995), in order to be able to apply the basic theorems of limit analysis to the masonry structures characterizes the material with three basic assumptions: Masonry has unlimited compressive strength, no tensile strength, and sliding failure does not occur. Consequently, the lower bound [safe] theorem states that for a specific structure and load distribution, as long as it is possible to find an equilibrium state in compression, however unlikely that state seems to be, the structure is stable and the collapse cannot occur for the given loading (Heyman 1995). Graphically this equals to the possibility of drawing a line of thrust within the masonry. All the above implies that the analysis of masonry structures is not mainly a question of strength but of stability.

Stability analysis of the lantern

The analysis that follows tries to assess a hypothetical original state prior to the bracing of the upper arches and the introduction of reinforced concrete elements. As we have seen, to confirm the stability of the lantern, we will have to find a line of thrust within the masonry. A tridimensional CAD model has been developed in order to determine the weights and their distribution. It is based on the geometrical study already exposed, graphical documents from the intervention project by Moya and Pons (Zaragoza 1998, 147; Soler and Soler) and data by Navarro Fajardo (2004, 1: 208) for the stone ribs. A specific weight of 23kN/m^3 has been considered for the stone masonry and 15kN/m^3 for the brickwork (Huerta 2004, 14-17). The roof coverings have been modelled as a uniformly distributed load of 0.75kN/m^2 . Overall the weight of the octagonal shaft is 8992kN while the vault and roofing weights 762kN .

Figure 7[a] summarizes the analysis. Each of the webs has been imagined divided in ten arches whose respective minimum thrusts were used to determine the loads on the diagonal arches and subsequently draw the line of minimum thrust as shown in the figure. The thrusts from the arches in the walls of the octagon were as well obtained. As can be seen in the figure the line of thrust stays within the limits of the masonry and therefore, as stated by the lower bound [safe] theorem, we can

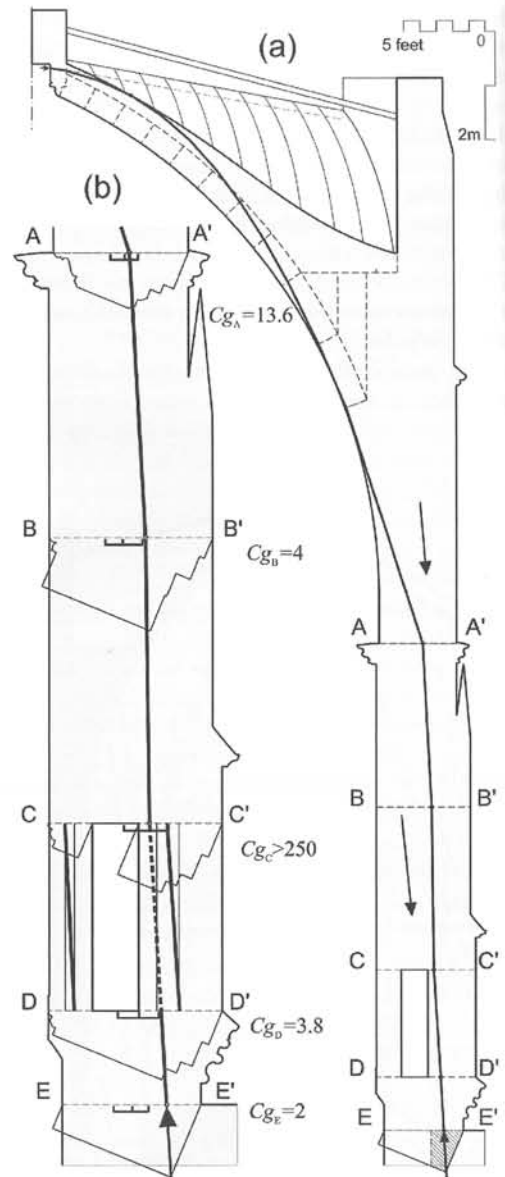


Fig. 7: Stability analysis. In (b) the bottom of the buttress is shown enlarged with the c_{g7} for every one of the sections AA' to EE'.

assert that the structure is stable. Assuming uniform distributions we obtain tensions of 0.94N/mm^2 at DD' and 1.93N/mm^2 at EE'.

At the base EE' the geometrical factor of safety, c_g obtained is 2. At first glance this value may

seem too low comparing with the typical of 3 for rectangular buttresses or 4 or higher as observed in many Gothic buildings but, as Huerta (2010) also exposes, to assess actual values of c_g it is necessary to study the impact that both fracture and leaning have on the stability of the system.⁸ In Figure 7[b] the centroid and the boundaries of the central core at the overturning direction are shown for each of the sections AA' to EE'. While at AA' the line of thrust is well centred, at BB' it has started to leave the core and there could be risk of fracture (Oschendorf et al. 2003). However, the stabilizing effect of the load from the lower wall arches alongside with the increase in the thickness of the buttress, and the passage void make that at CC' the thrust has perfectly centred passing very close to the centroid of the section. From CC' to DD' the thrust is divided in two lines that can be contained within the cores of the two respective pieces. It is evident that the problem is then limited just to the portion between EE' and DD' where, due to the abrupt reduction in the section of the buttress,⁹ the line of thrust leaves the core. The fracture would detach, yet, just a very small portion of masonry between sections E and D have little, if any impact on the stability of the system. The other reason to consider higher values of c_g in the case of buttresses is to limit the risk of inclination that an eccentric thrust, and the subsequent differential settlement of soil, would cause. This inclination would induce the distortion of the vault and even its collapse. We should not forget, however, that the base of the lantern is not resting on soil but on masonry elements, the latter being much stiffer. Besides, the pointed character of the vault makes it less susceptible to suffer great distortions in the event of the abutments slightly giving way. After all this we conclude that the value of 2 obtained for c_g can be actually considered reasonably secure.

The present article has limited its scope to the lantern but further research is required to study the full path of the thrust furtherwork, the base of the crossing piers. Tower additional assumptions

can be made for the original configuration of the vault's extrados and evaluate its contribution to the structural performance.

The slenderness and apparent lack of buttresses of the lantern tower of Valencia Cathedral has equally attracted admiration – for its boldness – and anxiety – of those which have considered it standing in a fragile equilibrium the present study, for the hypotheses considered, has shown that the structure in its original state was reasonably secure as cannot be otherwise in a fabric which has stood for five centuries. As is frequent in masonry buildings, the problems in the area of the crossing could be attributed to soil settlements at the foundations. But when the behaviour of these structures or the causes of their problems are not properly comprehended, fear usually leads to over of these construction intervention. As a result, many of these construction have been prevented from exercising their ability of maintaining themselves “constantly in the air, supporting one another in virtue of the mutual intricacy which links them,” as Tosca brilliantly expressed. The *ciborium* of Valencia, now subjugated by an alien corset of steel and concrete, could well exemplify it. Much needs to be learnt from Tosca's attitude, both reasoning the way the lantern stood without apparent buttresses and praising the skill of its builders.

Acknowledgments

We are grateful to Prof. Rafael Marín Sánchez for his support and the facilities he provided. Prof. Rafael Soler, who was Architecture Coordinator for the Valencia Cathedral Development Plan and has an in-depth knowledge of the fabric, kindly provided access to his unpublished manuscript (Soler Verdú and Soler Estrela) with facts and graphical documentation regarding the intervention by architects Ramiro Moya and Francisco Pons-Sorolla. Professor Santiago Huerta has supported us over the years, especially during the process of documentation and research.

NOTES

Unless stated otherwise, the photographs and drawings are by the authors.

1. Tomás Vicente Tosca i Mascó was born and lived in Valencia between 1651 and 1723. There, he developed a very productive intellectual activity. Between 1717 and 1720 he served as vice-rector of the University of Valencia. A priest from the Congregation of the Oratory of St. Philip Nerí, he studied mathematics, geometry, theology, natural philosophy, cosmography and architecture (Rosselló 2004, 160).
2. The present article is the latest state of an ongoing research by the authors that originated as an academic paper presented within the Construction History course lead by Prof. Santiago Huerta at Madrid School of Architecture (García Ares and Gil Crespo 2000) and further development for the Ph. D. course "Structural and constructive types of stone skeletons in Gothic cathedrals", supervised by Prof. Pepa Cassinello (Gil Crespo 2009).
3. The Spanish word "cimborrio" or "ciborio" derives from the greek "kibourion" and from latin "ciborium" (Oñate 1981, 13).
4. According to Chueca Goitia "the lantern of Valencia is the most monumental, but not the best fashioned of those which follow the tradition of the cathedrals of Tarragona, Lérida and San Cugat del Vallés" (Chueca Goitia 1981, 7).

5. There is no evidence on the first master builder who built the first part of the lantern at the beginning of the 15th century. We only know that at the middle of that century it was under construction (Oñate 1981, 14).

6. Tosca (1707-1715, 5: trat. 16, prop. 7, p. 286) indicates that the Valencian foot is equivalent to the Roman foot which is usually considered as 29.6 cm. long. This is the dimension we have considered.

7. This c_{ξ} has been calculated as in Huerta (2004,107) but considering eccentricity from the centroid of the buttress' sections.

8. An upper bound analysis to evaluate the ultimate value for the thrust could be carried out studying the collapse mechanisms exposed by Mohrmann (Ungewitter 1890, 358-359) and considering the fracture of the buttress as described by Oschendorf et al. (2003).

9. We do not know why the master mason reduced the width at the bottom of the buttresses. It is plausible to think he was constrained by the arrangement of the base walls and the widths of the arches of the crossing as configured by previous master masons he succeeded. He knew certain width was required and increases the thickness almost immediately, at the first cornice.

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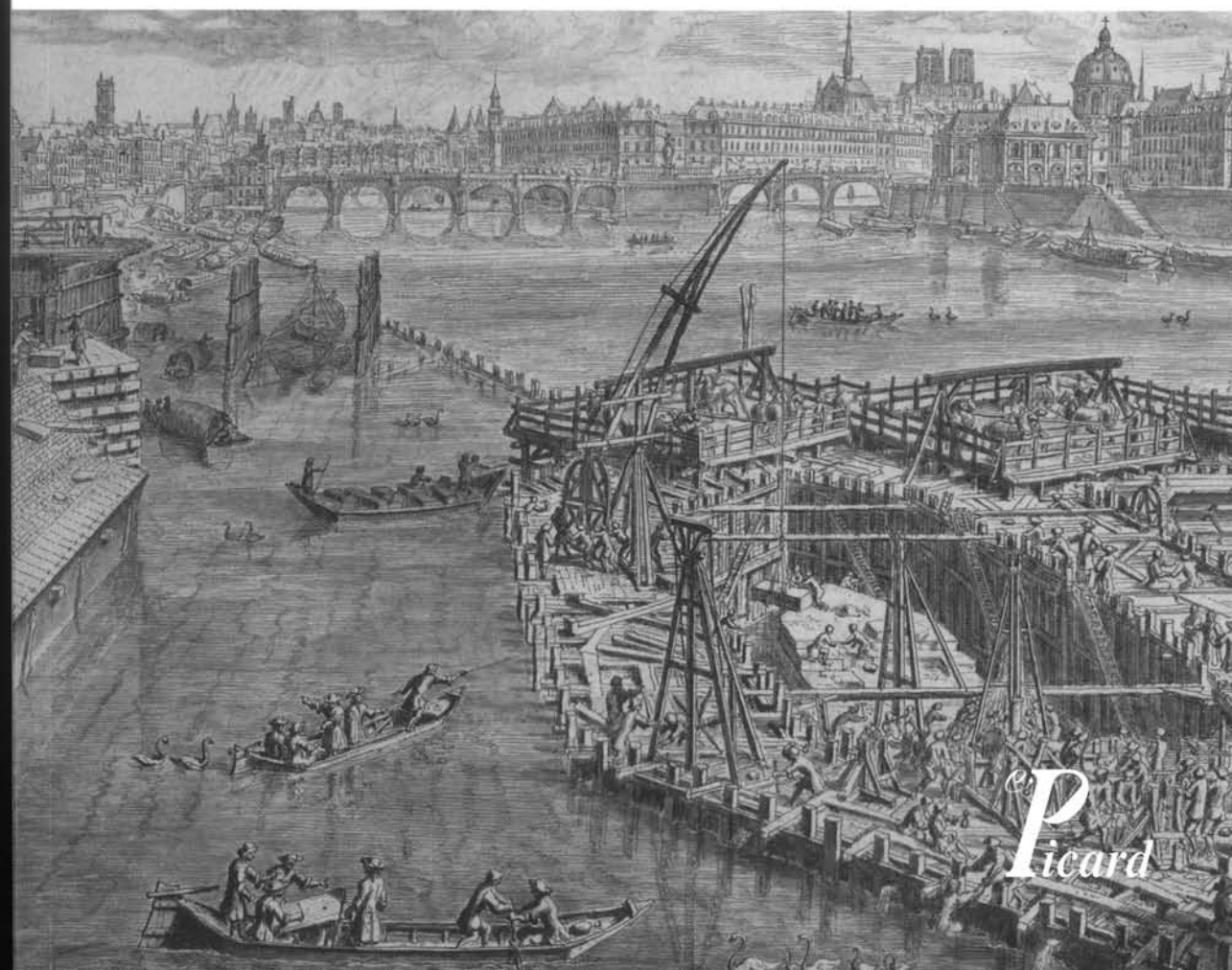
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