The Dome of the Colegio del Cardenal in Monforte de Lemos (Spain): Geometry, Construction and Stability

Rosa Ana Guerra
University of Santiago de Compostela, Lugo, Spain

ABSTRACT: The aim of this paper is to study three aspects of the extradosed ashlar dome of the Colegio del Cardenal: its *geometry*, *construction* and *stability*. The Colegio was built between 1593 and 1616, and it is considered an "offspring" of the Monastery of El Escorial. The original drawings have been lost, but a historic document with a thorough description of the work has survived. The geometrical part covers an accurate geometrical survey, a metrological study, hypotheses of geometrical patterns, and a comparison with the proportions of other domes. The construction part deals with the quartering and the building procedures described in the historic document. Finally, the third part of the study focuses on the stability, over which there is some safety concern, as the building was damaged by the Lisbon earthquake in 1755.

INTRODUCTION

In the introduction of his work *The Construction of the Vaults of the Middle Ages,* Robert Willis encouraged professionals dealing with the restoration of vaults to record and share their observations, in order "...to bring together a body of examples from which general rules might be deduced...for general rules deduced from single instances are commonly worthless." (Willis 1842, p. 3)

With the purpose of providing one of these examples, this paper shares the conclusions of the study of an extradosed ashlar dome built in Galicia —Northwest Spain— in the first years of the seventieth century. We wanted to know how the dome was built and why; if the constructive procedures were in line, or differed, from the building knowledge of the time; and to record the similarities and particularities that were found. For clarity, the study is divided in three parts focused in the *geometry*, the *construction*, and the *stability*, not always an easy classification as these three aspects are closely intertwined in masonry structures.

Extradosed domes —domes in which the quartering is visible in both intrados and extrados— are characteristic of Spanish Renaissance architecture. The main example is the dome of the basilica of the Monastery of El Escorial, which was built under the reign of King Philip II, between 1564 and 1584. The Monastery had a great influence on Spanish architecture, and also spread to the rest of Europe.

The Colegio del Cardenal was built a few years after the monastery was finished and it is considered one of its "offspring" buildings. It was sponsored by the cardinal of Seville, Rodrigo de Castro —an influential adviser to King Philip— who planned to set up a philanthropic school in his hometown, the small city of Monforte de Lemos, in Northwest Spain, and to entrust its government to the Society of Jesus.

The architects were Andrés Ruiz, a Jesuit from the school of Valladolid, influenced by the style of El Escorial; and Vermondo Resta, an Italian architect who worked for the Cardinal in Seville. They drew the plans, and wrote the thorough specifications for the works that were included in a legal document that has survived. Unfortunately, the building —the dome in particular— differs from the original intended description.

For the final design, neither documents nor drawings survived. Its authorship is uncertain, as several architects and master masons succeeded each other in the direction of the works. Two names that stand out are Juan de Tolosa, brother of Pedro de Tolosa, clerk in El Escorial, who took charge of the direction of the work soon after it began, and who probably made the main changes (Bonet Correa 1984, p.180); and Simón de Monasterio, the master mason who finished the presbytery and built the dome (Pérez Rodríguez 1995, p.520).

GEOMETRY

Description

The church is situated in an axial position in the layout of the building. The dome rises up in its centre, spanning approximately 10 m over the crossing. The shape of the dome is hemispherical —the inner surface slightly stilted— with projections in both its intrados and extrados. The centre of the outer surface is lower than the inner centre, and thus the thickness varies, decreasing with the height. The projections form eight double ribs. The dome is supported on a cylindrical drum over pendentives, and it is topped with a lantern, with cupola and pyramidal finial. Part of its singularity derives from the fact that it is the only dome built in Northwest Spain that comprises all these parts (Bonet Correa 1984, p.174). Light filters in through two circles of windows, one in the lantern, with six windows, and the other in the drum, with eight. The lower part of the extrados of the cylindrical drum is octagonal. The entire dome is built in granite masonry.

Figure 1: External view of the dome

Survey

There exist several surveys of the church, all of them markedly inaccurate in the definition of the dome. A geometrical survey was initially carried out. Data were recorded using a reflectorless total station, with coaxial laser pointer. Five different station base points were needed for recording the interior of the dome. Four referenced points were permanently marked on the four central pillars and at least two of them registered from every station base point. The five clouds of points were then merged overlapping the common references.
The outer part of the dome was recorded from three station base points. To merge inner and outer points the reference was taken along a window transom bar in the drum, as no common points were visible from internal and external positions. The perimeter of the drum was measured with tape measure to verify the position of the external profile from the axis. Vertical alignment was also confirmed with the horizontal joints in the drum. Two of the clouds of points —one inner and one outer— swept vertically the profile of the whole dome, providing a tight line of points. The outer vertical sweep was taken from the top of the northern tower. Manual measurements were taken to complete data from hidden areas.
The cross section of the dome was drawn on the same single 3D file of the merged clouds of points and exported to the 3D modelling program Rhinoceros, were the dome was modelled. Elevations, plans and cross sections were drawn from the model using an algorithm of the program, and finally exported to a common CAD program to be refined.

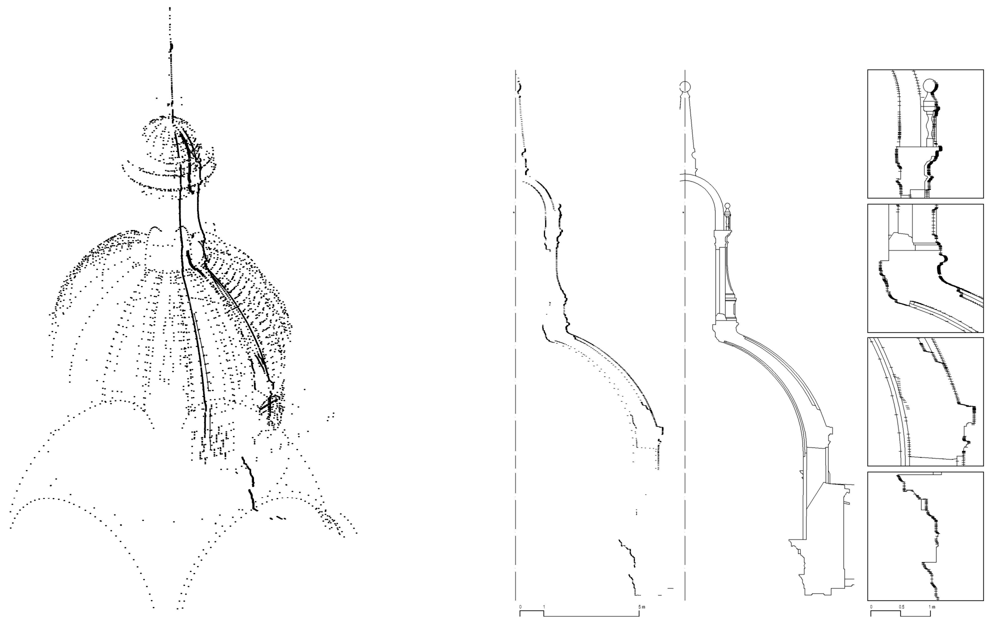

Figure 2: Left- Isometric view of the cloud of points. Right- Detail of the vertical sweeps of points and the profile derived from it

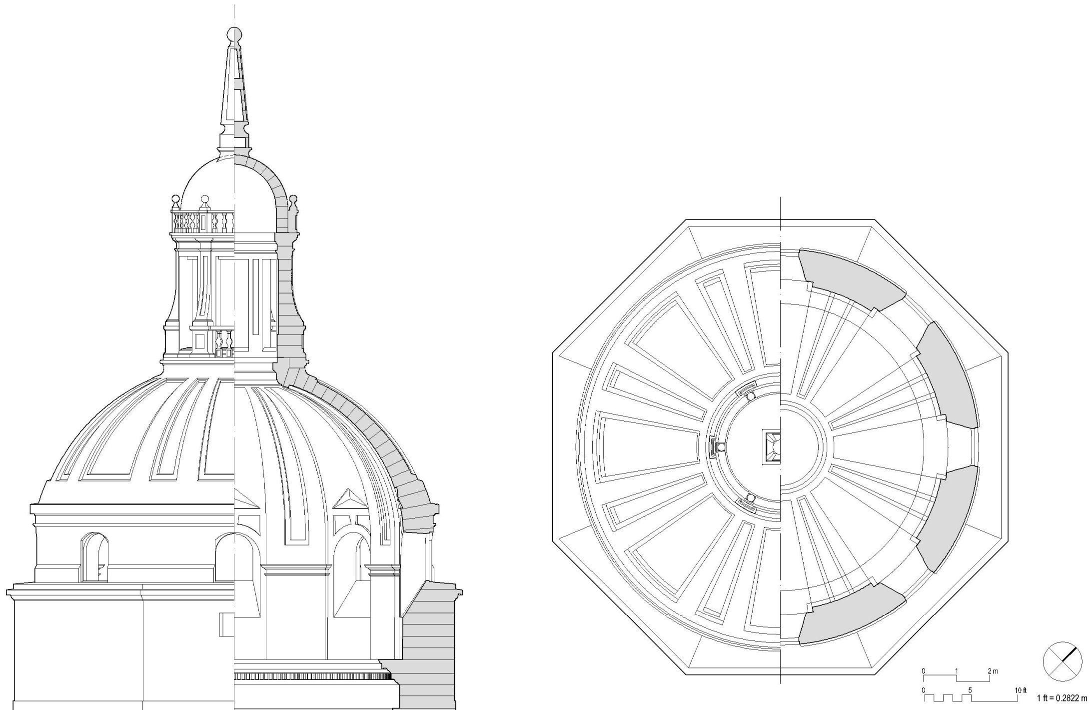

Figure 3: Plan, elevation and cross section

Metrological study

To reveal the length of the unit of measurement used in the definition of the dome we measured one of the pillars in the crossing. Results were inconclusive, mainly because construction tolerances distort such small dimensions. The possible lengths that resulted for the unit —the foot— ranged from 28.05 to 28.50 cm.

Freire Tellado (1998, pp. 178-179) had previously investigated the unit of measurement in the Colegio. He compared the measures described in the historic document with those taken in the building, founding out three probable foot lengths: 281.27, 296.06 and 282.222 mm.

To end with the uncertainty about the length of the foot we reached the base of the drum and measured the diameter manually with laser measure. The results were conclusive: 10.16 m, which equals 36 feet of 28.22 cm, or 12 *varas* (each *vara* equals three feet). This length —28.22 cm— was one of the three possible measures previously obtained by Freire Tellado. The diameter for the projections was 9.88 m, equal to 35 feet, so inner projections protrude 1/2 foot from the drum wall.

The unit of length is, therefore, a foot of 28.22 cm. The length of the divisions and multiples are shown in Tab.1. We keep the Spanish name vara to avoid confusion with the current imperial yard.

Table 1: System of measurements used in the construction of the Colegio

	Unit	Multiple	Submultiples				
Colegio units	foot	*vara*	1/2*	1/3	1/4	1/8	1/16**
Centimetres	28.22	84.66	14.11	9.41	7.06	3.52	1.76

*1/2 foot = 1/6 vara = 1 sexma
**1/16 foot = 1 finger

This metrological study must be taken with caution as the different stone masons that succeeded in the work may have used different yardsticks. Still, the unit has proved to be consistent in later studies.

Geometrical patterns

The main dimensions of the dome expressed in both feet and metres are shown in Tab. 2.

Table 2: Main dimensions of the dome

	Dome ø int.	Projec. ø int.	Dome ø ext.	Projec. ø ext.	Drum* thickness	Octagon thickness	Oculus ø int.	Lantern ø int.	Lantern ø ext.	Cupola ø int.
m	10.16	9.88	11.85	12.42	1.06	1.57	2.30	2.58	3.38	2.54
ft**	36	35	42	44	3 3/4	5 9/16	8 1/8	9 1/8	12	9

* Maximum thickness of the cylindrical part of the drum
**1 ft = 0.2822 m

These dimensions were compared with well known historic rules for single domes. No acceptable matching was found, but some coincidences occurred with the rules given by Palladio, Simón García and Fontana.
Andrea Palladio's book *I Quattro Libri dell'Architettura* (1570) includes descriptions and drawings of several ancient domes. It was Fontana who deduced from Palladio's drawings a rule of 1/9 of the span for the thickness at the springers (Lopez Manzanares 1998, p. 34). Palladio also discusses the profile of the domes in an expertise on the Duomo Novo of Brescia in 1567. Huerta (2004, p.201) provides an explanatory drawing showing the geometric pattern (Fig. 4). Inner and outer surfaces are hemispherical. The centre of the outer surface is aligned with the impost and the centre of the inner one displaced upwards, the result being a decreasing thickness towards the crown. Finally, an equilateral triangle with its base vertices on the impost defines the width of the lantern and the height of its cornice.
The dome of the Colegio coincides with two of Palladio's rules. The first coincidence is about the thickness of the springers. In the Colegio the maximum span is 36 ft and the outer radius 44 ft. The difference between the corresponding radii is 4 ft, which means 1/9 of the span. However, if we consider the thickest section —along the ribs— the difference between the inner and outer radii increases to 4 1/2 ft that equals 1/8. The second coincidence is related with the disposition of the centres of the spheres. As in Huerta's drawing, the centre of the outer sphere is in line with the imposts, and the inner sphere is moved some distance upwards. Finally, there is some similarity derived from the fact that the line that joins the impost with the intersection point of the cornice of the lantern and the axis of the dome, defines the width of the lantern, although the resulting angle, 64º, is slightly greater than the 60º of the equilateral triangle of Palladio's rule (Fig. 4).
The Spanish architect Simón García (ca. 1650-1697) provides several rules for domes in his unpublished manuscript *Compendio de Arquitectura y Simetría de los Templos* (*Lessons on Architecture and Symmetry of Temples*). For the oculus he establishes 1/4 of the span (Huerta 2004, p. 259) and this same proportion is found in the Colegio's dome. For the rest of his rules no good matching has been found, although the thickest section of the drum in the octagonal part, 8 ft thick, is close to the 1/5 of the span (7 1/5 ft) that Simón García prescribes.
Carlo Fontana discusses the rules for single domes in the XXIV chapter of his book *Il Tempio Vaticano e Sua Origine*, published in 1694. He delivered an "invented" geometric rule for tracing the profile of pointed domes (Huerta 2004, pp. 270-276), of no use in the hemispherical dome of Monforte. Nonetheless, his arithmetical rule of 1/10 for the drum coincides with the thickness of the upper—cylindrical— part of the drum. In addition, he mentions a common rule for the thickness of the upper part of domes of 1/18 of the span in his expertise on the dome of Santa María in Vallicella (López Manzanares 1998, p. 79). This proportion is also found in the Colegio's dome.

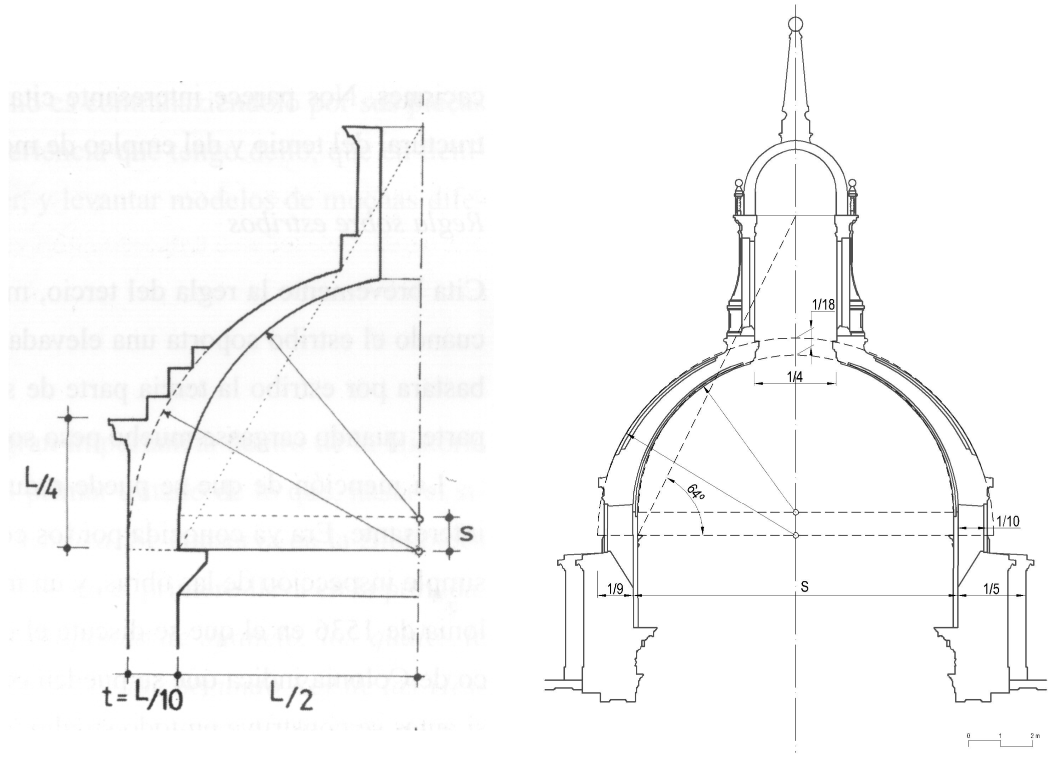

Figure 4: Left: Graphic explanations of Palladio's rules for domes; (Huerta 2004, fig. 6.8b). Right: Geometric rules from Palladio, Simón García and Fontana found in the dome

As the dome ribs are arranged in layers, the dome profile if defined by six circles. Centres are located along the axis so that the outer the circle is, the lower its centre is found. In the search for a pattern to explain the position of the centres, we tried the definition of the dome profile as a pencil of coaxal circles. Coaxal circles share a common radical axis, which is the locus of points that have the same power with respect to the circles (Coxeter; Greitzer 1967, p. 35). The radical axis is a line perpendicular to the line through the centres. Once the radical axis is defined the centres of the circles can be easily found. The pattern is drawn in Fig. 5.
The process is as follows: (1) The external circle is drawn with its centre A aligned with the impost ; (2) Two circles of 9 1/8 ft —inner diameter of the lantern— are drawn, the lower with centre in M; (3) The radical axis is drawn through point N; (4) T defines the tangent point of a line through N; (5) A perpendicular line is drawn through E being NE = NT; (6) The radius of the circle whose centre is sought is translated on the perpendicular line, obtaining point F; (7) An arch of radius NF leads to centre B. The same process is done for the rest of the circles.
As Fig. 5 illustrates, this hypothetical pattern shows a good correspondence with the dome profile. Whether this pattern reflects a general rule for this kind of dome remains an open question.

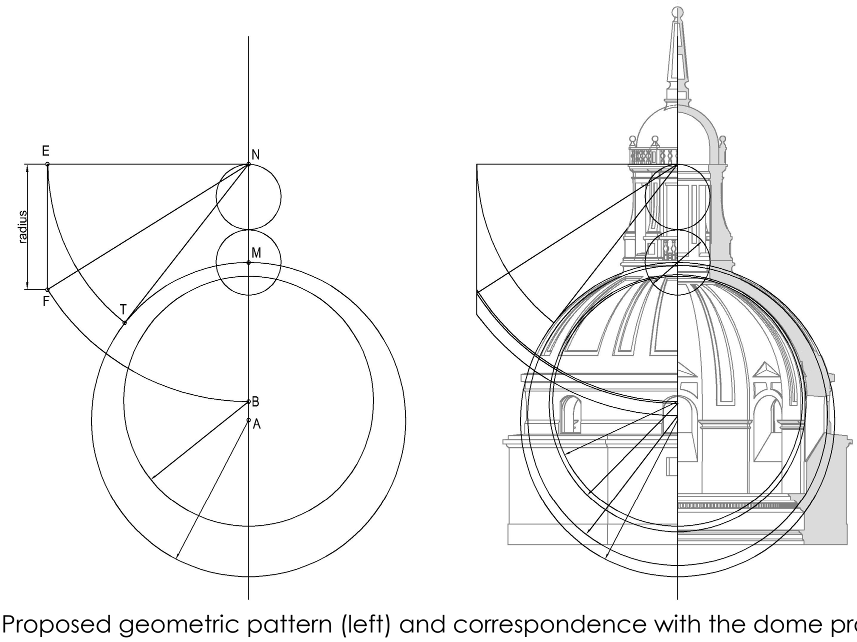

Figure 5: Proposed geometric pattern (left) and correspondence with the dome profile (right).

CONSTRUCTION

Historic documents

For the construction study we were able to count on a historic document that describes in great detail the prescriptions for the work (Cotarelo Valledor 1945, pp. 264-293). Although important modifications were introduced, these prescriptions provide interesting insights into the building process.

For the dome, the document defines the dimensions for the different parts —sadly, it does not mention the span. In general, the dimensions provided differ from the real ones. The described drum is octagonal, with no cylindrical part, thus shorter than the one built. The cupola, built plain, is described with projections.

It is worth emphasizing the definition of iron chains in the base of the half-orange and the lantern cupola. Also iron cramps are prescribed in the first courses of the dome, the base of the lantern, and the base of the lantern cupola. However, apart from this document, there is no evidence of the existence of iron ties in the dome.

Quartering

The inner quartering was recorded with the station in the visible parts of four sectors of the dome. For the outer quartering it was not possible to record the same area, as the station could only be positioned in the towers. Accuracy was conditioned by the fact that the joints had been repointed with wide bands of mortar, concealing the limits of the courses. To achieve more reliable data we climbed the extrados of the dome and sketched manually the quartering in a sector. This duplication of data —manual and from the station—allowed us to minimize inaccuracies.

Horizontal courses were clearly defined in the upper —visible— part of the drum. For the half-orange the possible centres of convergence of the bed lines showed some dispersion, as could be expected, for simple construction tolerances would suffice to multiply the possible intersections. Probable centres turned out to be situated along the axis, scattered in a length of 21 cm. The centre of the most internal of the profile circles was located in this segment, so this point was chosen as centre of convergence in a simplification of the drawing of the bed lines.

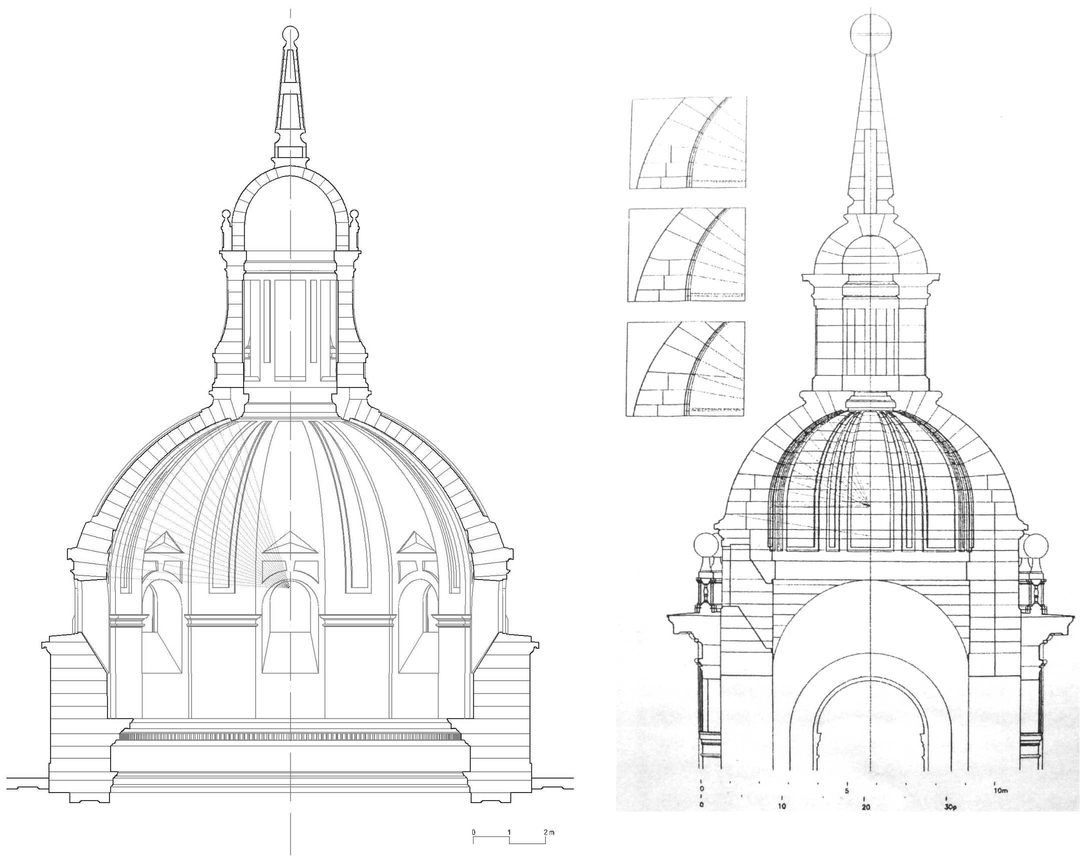

Figure 6: Left: Quartering of the Colegio's dome. Right: Quartering of the southern tower of the Monastery of El Escorial; (López Mozo 2003, Fig. 6)

For hidden quartering a hypothetical configuration was proposed as follows. For the lower part of the drum —hidden for the station, but photographable through a hole—, the current height of the courses was kept, and the result checked with the photographs. For the oculus and lantern base, a proposal is made inspired in historic drawings and congruent with the visible joints. The inner hollow configuration of the pyramidal finial was proposed after a detailed study that counterbalanced its stability against wind forces with the maximum load that the thin cupola was able to support.

For the top of the drum and springing of the half-orange, we found that courses began to lean towards the centre from the very beginning of the springing line. This fact runs counter to commonly assumed procedures, which tend to keep horizontal courses as high as possible. In particular, it differs notably from the quartering recently studied in the domes of the Monasterio of El Escorial (López Mozo 2003, pp. 1324-1325; Alonso Rodríguez; López Mozo 2002, p. 329), where horizontal courses reach almost half of the height of the half-orange. Horizontal courses are also recorded in the dome of the small church of San Sebastian of Cobos, contemporary with the Colegio (Alonso Rodríguez 2007, pp. 24-27). Further verification should be done to dismiss any reservation about this rarity.

From the recorded vertical quartering it can be deduced that the half-orange was built in two layers. The records have proved to be insufficient to establish if this is the rule for all the courses. There seem to be single layered courses amidst double ones, although this question requires further evidence.

STABILITY

In 1755 the effects of the Lisbon earthquake reached Northwest Spain and the dome of the Colegio was deeply damaged. Although the dome was repaired twice —1786 and 1841(Martínez González 2000, p. 27)— clearly visible structural movements can be observed: meridional cracks in the thinnest parts of the half-orange; and vertical cracks with vertical displacements in the cornice, near the key of the altar main arch. Safety concerns have been expressed in several occasions (Martínez González 2000, pp. 64-68).

To dismiss uncertainty, the equilibrium of the dome was assessed using the method of the arch analysis under limit state conditions. The dome was considered to be divided into lunes and its stability was assured —according to the lower bound theorem—by founding lines of thrust that lay in the thickness of the dome section (Heyman 1995, 1996).

For the half-orange two hypotheses were checked. For the first, the dome was divided into eight lunes of 45° each, similar to the actual division caused by the meridional cracks. No iron ties were considered in the whole dome —except the indispensable cramps of the pyramidal finial. The line of thrust could be comfortably adapted to the section along the ribs, resulting in a geometrical factor of safety c = 3.4 in the base of the cylindrical drum, and c = 7.4 in the base of the octagon. The second hypothesis considered a lune of 5.625° (360°/64) along the thinnest section. The line of thrust could also be drawn inside the section of the masonry. Resulting factors of safety were 2 and 2.5 as shown in Fig. 7.

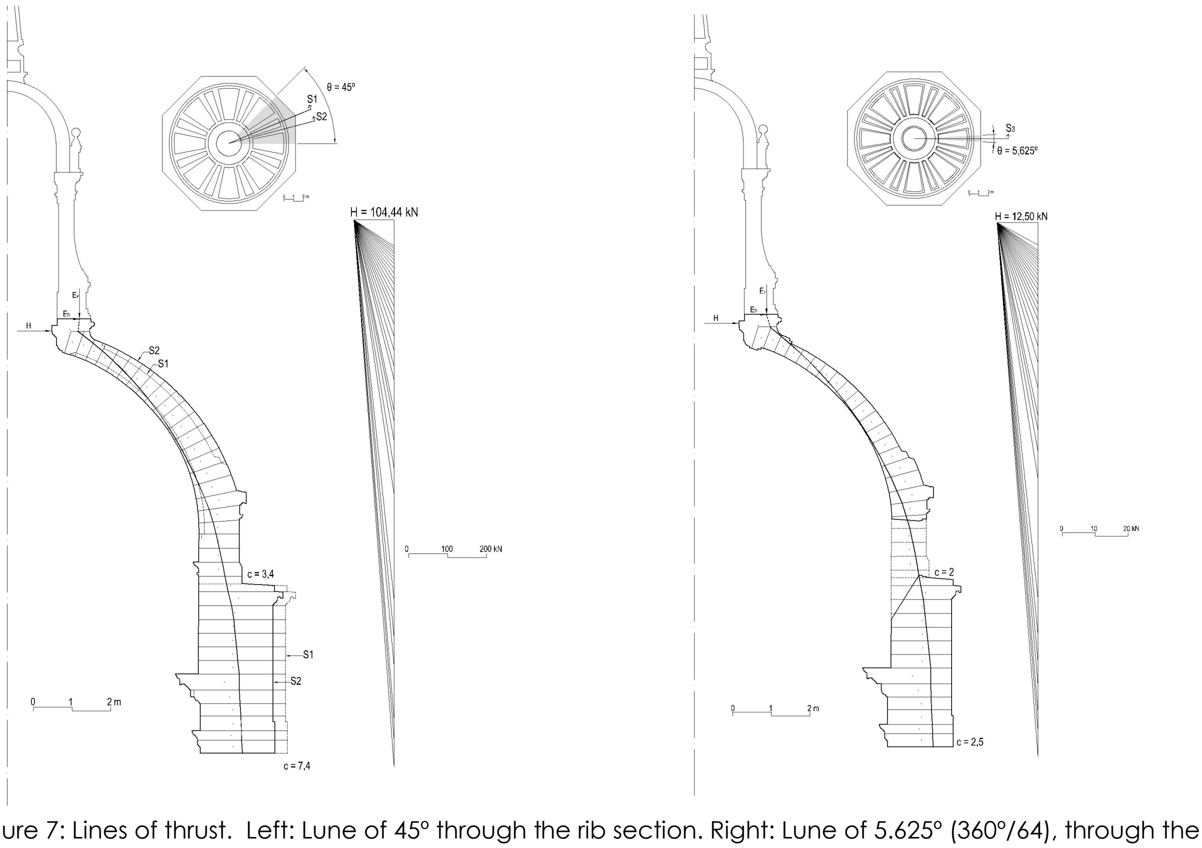

Figure 7: Lines of thrust. Left: Lune of 45° through the rib section. Right: Lune of 5.625° (360°/64), through the thinnest section of the dome.

CONCLUSIONS

1. The survey of the extradosed dome of the Colegio del Cardenal has confirmed its inner and outer hemispherical shape.
2. A metrological study has found the unit of measure used in the construction to be a foot of 28.22 cm. The span of the dome is 36 feet, equal to 12 varas.
3. Few well-known geometric rules can be tracked in the dome: 1/9 of the span as theoretical thickness of the springers; 1/4 span for the diameter of the oculus; 1/10 and approximately 1/5 for the thinnest and thickest parts of the drum; and 1/18 for the theoretical thickness in the crown.
4. The profile of the dome, composed of six circles displaced along the vertical axis, shows a good correspondence with a geometrical pattern of a pencil of coaxal circles.
5. There is a historic document with detailed descriptions of the work that, sadly, differ for the real building. For the dome, the document specify two iron chains in the springers of both the half-orange and the lantern cupola; as well as three zones tied with cramps —the first courses of the dome, the base of the lantern, and the cornice under the cupola. There is no evidence of the existence of these iron ties.
6. The quartering presents a puzzling rare feature: course beds begin to lean from the very springing of the inner surface. More evidence is needed to asses the way that single and double layers are arranged in de dome. The records show double layers for most of the courses.
7. Although the conspicuous cracks, the dome is safe even without counting on any iron tie.

This study is part of the author's doctoral thesis in progress, under the direction of professor Santiago Huerta.

REFERENCES

Alonso Rodríguez, M. A., 2007: Sobre la cúpula trasdosada de la Iglesia de Cobos en Segovia. In Huerta, S. (ed.): *Actas del Quinto Congreso Nacional de Historia de la Construcción*. Burgos, pp. 23-28.

Alonso Rodríguez, M. A.; López Mozo, A., 2002: Levantamiento de la cúpula de la iglesia del Monasterio de San Lorenzo de El Escorial. In *Actas del IX Congreso Internacional de Expresión Gráfica Arquitectónica*. A Coruña, pp. 327-332.

Bonet Correa, A., 1984: *La arquitectura en Galicia durante el siglo XVII.* Madrid: Consejo Superior de Investigaciones Científicas.

Cotarelo Valledor, A., 1946: *El Cardenal don Rodrigo de Castro y su Fundación en Monforte de Lemos*. Madrid: Magisterio Español.

Coxeter, H. S. M.; Greitzer, S. L., 1967: *Geometry Revisited*. Washington, DC: Math. Assoc. Amer.

Freire Tellado, M. J., 1998: Los trazados de montea de factura renacentista del edificio de los escolapios de Monforte de Lemos (Lugo). In Fernandez Salas, J.; et al. (eds.) *Actas del Segundo Congreso Nacional de Historia de la Construcción*, A Coruña, pp. 173-180.

Heyman, J., 1995: *The Stone Skeleton: structural engineering of masonry architecture*. Cambridge: Cambridge University Press.

Heyman, J., 1996: *Arches, Vaults and Buttresses*. Aldershot, Great Britain: Variorum.

Huerta, S., 2004: *Arcos, bóvedas y cúpulas: geometría y equilibrio en el cálculo tradicional de estructuras de fábrica*. Madrid: Instituto Juan de Herrera.

López Manzanares, G., 1998: *Estabilidad y construcción de cúpulas de fábrica: el nacimiento de la teoría y su relación con la práctica*. Ph. D. dissertation. Polytechnic University of Madrid.

López Mozo, A., 2003: Extradosed vaults in the Monastery of El Escorial: The domes of the church towers. In: Huerta, S. (ed.) *Proceedings if the First International Congress on Construction History*, Madrid, pp. 1321-1326.

Martínez González, E., 2000: *Colegio de Ntra. Sra. de la Antigua (Monforte de Lemos)*. León, Spain: Everest.

Pérez Rodríguez, F., 1995: Algunas consideraciones sobre la construcción del Colegio de Nuestra Señora de la Antigua de Monforte de Lemos (Lugo), 1592-1616. In *Monjes y monasterios españoles...* Madrid: Ediciones Escurialenses, pp. 497-521.

Willis, R., 1842: On the Construction of the Vaults of the Middle Ages. *Transations of the Royal Institute of British Architects* vol. I part II, pp. 1-69.