How to Build a Dome

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Introduction

Although domes have been a recurrent theme in European architecture through the centuries from antiquity to the 20th century, the big rise of the dome as the key feature of the monumental church started only with Brunelleschi's dome of the cathedral of Florence (1420–36). While Brunelleschi's dome is strictly speaking an octagonal cloister vault like many other medieval and early modern domes, it already presented several aspects which distinguished it from most of the preceding domes: It is located very high above ground, and rests on a drum supported by large arches/squinches. By contrast, the domes of antiquity (of course excluding St. Sophia's in Constantinople) are typically 'directly' supported from the ground by a contiguous cylindrical or polygonal masonry structure. Medieval European domes – notably the domes or cloister vaults of Italian baptisteries – mostly followed this Roman model, with the exception of a few rather small domes on crossings of basilicas. Like the domes of some medieval baptisteries such as the one in Cremona, Brunelleschi's dome is essentially a thin-shell brick structure with a few ashlar reinforcements, while the Roman domes are typically built in massive 'opus caementicium', i.e. in thick rubble masonry employing a lot of mortar and inevitably necessitating fully lagged formwork.

Brunelleschi's dome is of course most noted for its free-hand erection without formwork. While this method continues to fascinate researchers until today, the prevailing focus on this single aspect tends to obfuscate the remaining and perhaps even more important challenges of dome construction: The high position of the early modern domes above ground (some 50 m to the cornice in Florence) made lifting and temporary storage of building materials a key issue. Furthermore, in Florence, the sheer mass of the building material and the size of some of the ashlar elements ruled out the classical medieval transport method by carriers via galleries and spiral staircases, and clearly called for more efficient worksite technology, including Brunelleschi's famous ox-driven elevator. However, historic lifting devices employed before the advent of the modern crane in the 20th century permitted only very limited rotation and horizontal movement of the load. Brunelleschi's construction therefore definitely required a spacious working platform at the base of the dome which allowed the accommodation of lots of workers and which was stable enough to move heavy pieces around on it horizontally.

The immense putlog holes for a cantilevering platform at the base of the dome are still visible on site (Fig. 1)[1]. They traverse the entire thickness of the masonry and were designed to receive timber scantlings of almost 60 by 60 cm (i.e. probably composite beams made up from four pieces), testifying to a very robust platform indeed. Probably, most modern reconstructions of this platform have grossly underestimated its actual size. Reinforced by raking struts from the gallery at the base of the drum, 13 m below, such a sturdy platform could easily have cantilevered 10 to 12 m towards the centre of the dome, as can be easily determined by a rough statical calculation. Such a spacious working platform, designed to last more than a decennium, also made the installation of the templates for form control easy, and it permitted setting up trestles for works at the lower sections of the dome. In the case of conventional dome construction with formwork, the formwork and its supporting truss could be erected with relative ease if such a platform was present at the base of the dome. On the other hand, the very fact that a dome of the size of Brunelleschi's could be erected without formwork indicates that one tends to over-estimate the role of the centring in dome construction. No matter whether the dome is erected in a free-hand approach or on formwork, it is typically built in successive self-supporting rings. Ironically, this makes a dome much easier to build than a barrel vault, and permits the application of much lighter centring.

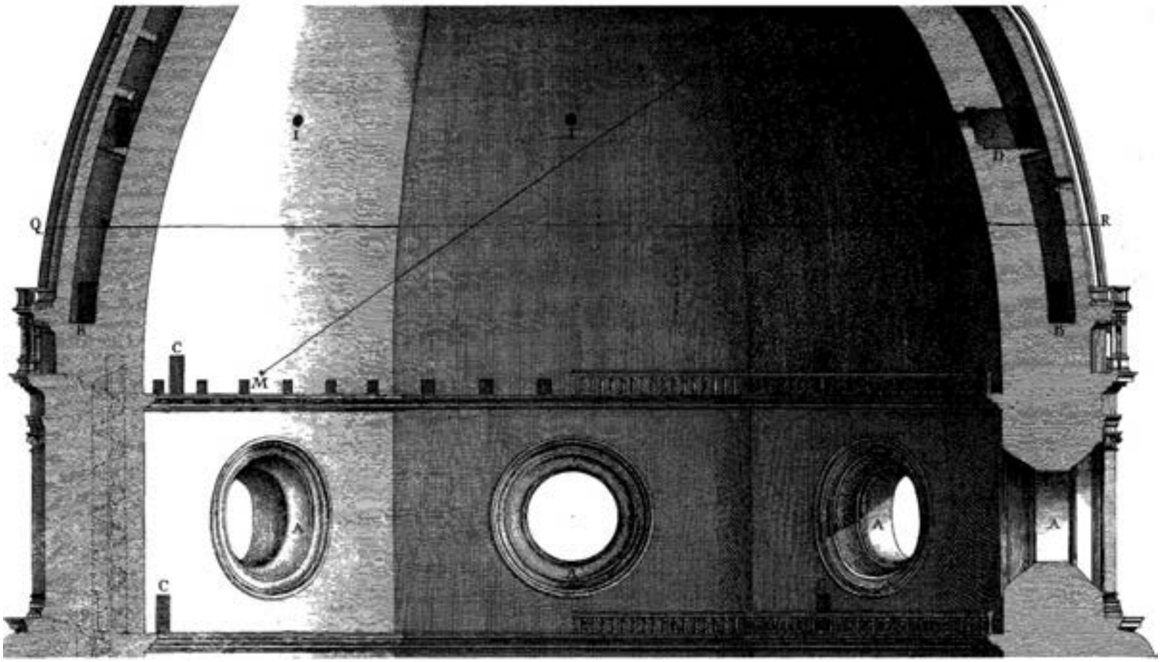

Figure 1. Putlog holes at the base of Brunelleschi's dome of Florence cathedral. Engraving by Bernardo Sgrilli 1733, plate IX, detail.

The remainder of the present paper will focus on a few well-documented examples of early modern dome construction where archival details about the scaffolding and centring are available. The attention is more on the "standard" baroque dome than on exceptional constructions like the cathedral of Florence or St. Peter's, Rome, where it is known that formwork was employed, but the available sources on the construction of the centring are in fact very fragmentary.

The question of dome construction has troubled architects and engineers for centuries. When Leonhard Christoph Sturm (1669–1719) wrote a special treatise on church architecture in 1718, he gave special emphasis to dome construction. In the preface to this work, he wrote: "As to building large domes, only very few people – particularly in Germany – know the key issues, let alone how to organize the worksite. In books, one also finds only very sparse instructions on this topic. The great Italian architects keep this knowledge among their arcana [2]." The present paper attempts to shed some light on this enticing enigma of construction history.

The Baroque

The dome was the most prominent 'leitmotif' of baroque architecture, particularly in 17th century Italy. None of the famous Italian architects of that century failed to design at least one significant dome. However, sources on how these domes were actually built are indeed difficult to find. It is therefore highly significant that one early case is documented in detail, namely, the church of Santa Maria della Salute in Venice. Recently, prof. Mario Piana has edited a letter written by the architect of that church, Baldassare Longhena, which was sent in 1649 to the principals, asking them to take care of the tender for the erection of the main dome [3]. Unfortunately, the drawings, which had originally accompanied this letter, are lost, but the letter contains detailed descriptions of all the members required to build the scaffolding and centring, so that the intended procedure of dome erection can nevertheless be reconstructed in detail.

The octagonal central space of the church (21.55 m diameter) had already arrived at the level of the principal cornice above the drum windows. What remained was to close the space by a (circular) brick dome. Longhena specified that the shell should be built on a continuous formwork made from spruce boards. The boards should be nailed to no less than 96 (i.e. twelve per side of the octagonal substructure) radial wooden arched ribs (each one 17.40 m in length), which Longhena suggested be constructed by three to four overlapping layers of sturdy boards nailed together. These radial ribs were to be fixed to laminated timber hoops both at the bottom and at the oculus of the dome. This primary formwork was to be supported by a truss that would rise another 12.50 m above the level of the cornice of the drum, in other words, up to the very top. The truss was to rest on an already established platform at the cornice level, carried by sturdy composite beams. The substructures of this platform were to be reinforced by additional struts. Longhena specified: "For safety, and to prevent this work from collapse, all struts shall reach from the floor of the church up to the already established platform [4]." In other words, the whole church was eventually filled with an impressive timber trestle, reaching from the ground up to the very top of the dome, quite unlike the fancy 'free-spanning' centring which was allegedly used for St. Peter's in Rome, according to Carlo Fontana [5]. When lagging of the 96 ribs was complete, Longhena himself would draw the outline of the dome's square coffers on it, the carpenters would build the templates for the coffers accordingly, and then the bricklayers would start to build the dome. Indeed, the huge shell with its thickness tapering from 80 to 50 cm was actually completed within just a few weeks.

Compared to Brunelleschi's 'minimalist' cantilevering temporary works, one may be surprised that the loads of the centring were carried to the very ground in the Venice church with its comparatively light dome. However, it appears that both the presence of a platform at cornice level and the direct support from below were current practice in the 17th century. Anyway, it is likely that a rough sketch showing the temporary works employed for the construction of Gian Lorenzo Bernini's domed church San Tommaso di Villanova in Castel Gandolfo can be interpreted in that sense [6](Fig. 2). At upper left, the wooden templates defining the shape of the dome and carrying the lagging are shown. However, in our context, the little drawing at the lower right is much more interesting: Obviously, it shows a simplified ground plan of the dome. A circle in the centre marks the lantern. Next to that circle, four small squares represent supports, which carry two orthogonal pairs of major beams spanning the entire interior of the dome. With a view to the other pieces of evidence shown in the present study, it becomes clear that the four supports are meant to rise from the very floor of the church to the base of the dome, where they support a large working platform carried by the four long beams. The circular templates for the dome itself are then erected on that platform, as shown on the bigger sketch in the upper left. That sketch includes a further interesting detail: It demonstrates that the lowest part of the shell is constructed in horizontal rather than conical courses of masonry, up to a certain level where the cantilevering rings were replaced by actual vaulting with radial joints.

For Filippo Juvarra's church of Superga near Turin, a preserved inventory of the timber employed in 1724 to erect the scaffolding of the cupola appears to indicate the use of a similar platform as Bernini's at Castel Gandolfo [7]. The inventory explicitly mentions four beams, each of almost 22 m length (7 Piedmontese trabucchi of 3.08 m). They are difficult to accommodate inside the dome with its diameter of slightly more than 22 m unless they spanned its entire interior and supported the principal platform, in a similar manner to Bernini's construction in Castel Gandolfo. In fact, it is stated in the archival record that the four beams were employed to carry a platform made from 110 boards, each 3.70 m long. This could not be anything else but the principal platform. In case the long beams were not used as the horizontal girders carrying that platform, they could at best have supported the platform vertically from below, again like in Bernini's design.

Further insight into the use of the platform at the base of the dome is provided by an interesting text written in the years between 1712 and 1725 by Giovanni Battista Nelli, then operaio of the cupola of the cathedral of Florence. The essay entitled Ragionamento sopra la maniera di voltar le cupole senza adoperarvi le centine was published posthumously in a collection of architectural texts in 1753 [8]. Even though Nelli's main topic is vaulting without formwork, he stresses explicitly the importance of solid scaffolding: "Therefore, instead of formwork, spacious, strong and commodious platforms are required in order to expedite the transport of all the materials required [9]." Nelli continues with a detailed description of the principal platform, which, in his case, is supported from the ground by a single strong wooden mast in the centre of the dome. Furthermore, Nelli states that the necessary trestles required to bring the bricklayers to their working place can then be erected on top of that solid platform.

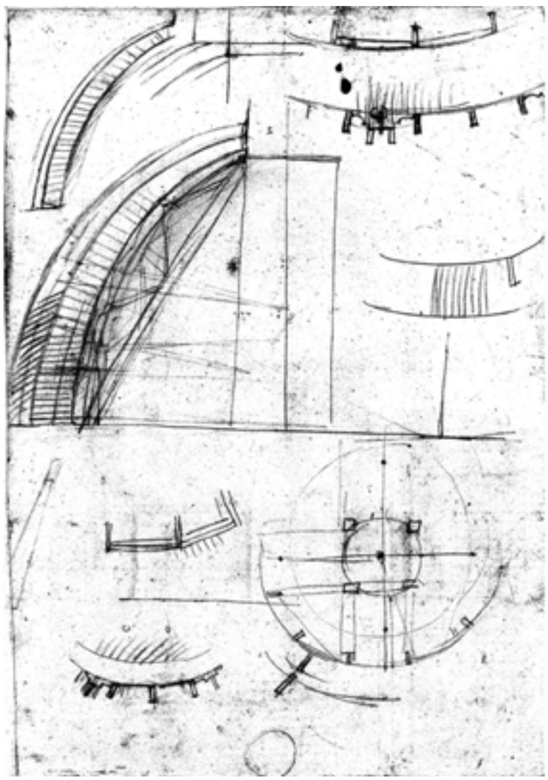

Figure 2: Sketches relating to the erection of the cupola of the Church of San Tommaso di Villanova in Castel Gandolfo. Gian Lorenzo Bernini, 1659. Biblioteca Apostolica Vaticana, Ms. Chig. P. VII, part I, fol. 13 v., here reproduced after Bauer/Wittkower 1931, plate 91, partly enhanced and redrawn by author.

Similarly, Leonhard Christoph Sturm, in his essay on church architecture cited in the beginning of the present article, also stressed the importance of a working platform, even in case of full formwork, for assembling the centring: "Such a centring cannot be erected unless the whole opening of the dome is covered completely or at least for the larger part of it, by a solid platform which is designed to carry a lot of workers and to permit them to walk on it and move the baulks around and lift them [10]." Sturm deserves a bit of mistrust since he also admitted that he had no personal experience with dome construction; furthermore, he suggested a fancy Serlio floor design for the working platform. In his figures, there is no word about direct vertical support of the platform from the ground. Rather, his work includes a plate showing a dome on a centring which rests on a platform that is supported from below by raking struts [11](Fig. 3).

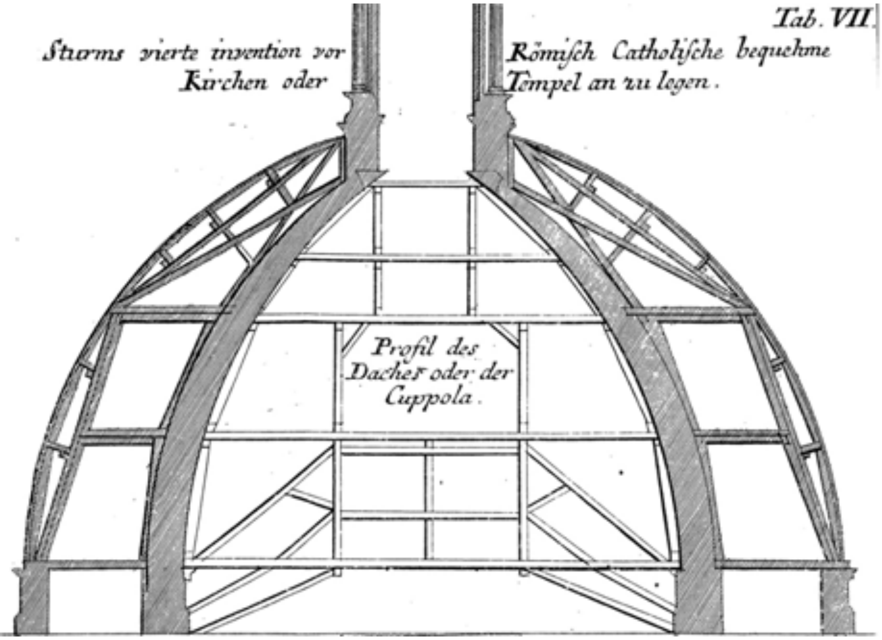

Figure 3. Section of a dome with the centering still in place. Engraving by Leonhard Christoph Sturm 1718, plate VII, detail.

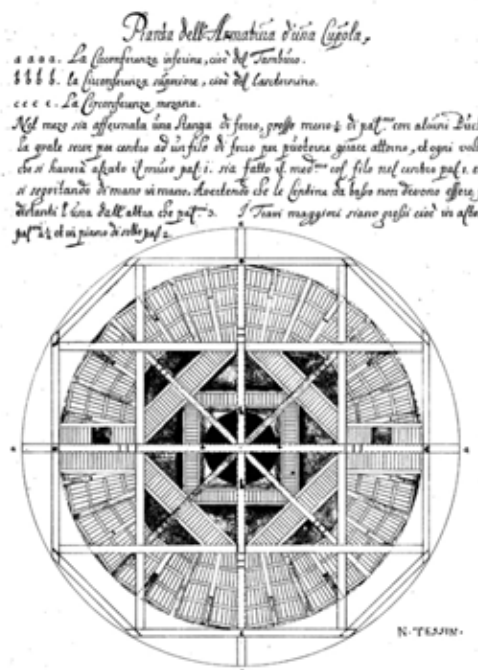

Figure 4. Zenithal view of a dome with scaffolding. Drawing by Nicodemus Tessin the Younger, Stockholm, Nationalmuseum, Cronstedt collection CC 749. Photo: Cecilia Heisser, public domain. Enhanced by author.

Quite likely, the decision whether to construct the working platform in a free-spanning way or rather to erect it from the ground was strongly dependent on the absolute height above ground. For particularly slender cupolas, a free-span platform was probably more practical if more complicated to erect. It appears that Bernini's great contemporary Borromini in fact relied on such a platform when he erected the dome of Sant'Agnese in Agone in Rome, in 1655. The associated centring is depicted in an enigmatic drawing by Nicodemus Tessin the Younger [12](Fig. 4), who may have had access to original documents on the church during a study visit in Rome with Carlo Fontana in the 1680s. From the legend of Tessin's drawing, it does not become entirely clear whether the dome was built on formwork or not. On the one hand, the legend speaks about a dense arrangement of radial circular ribs, indicative of formwork; on the other hand, it also provides details about form control with a metal wire attached to an axis in the centre of the dome, related to free-hand erection. Be that as it may, the drawing definitely shows an interesting view of the working platforms, although it is not easy to understand: The drawing is apparently a reflected plan. At the base of the dome, a grid of orthogonal main beams (3 parallels in each direction) rests on the cornice via an octagonal array of wall plates. This grid of beams obviously constitutes the lowest level of the working platforms. Most of the boarding has already been translated to higher levels. Approximately at the height where the dome needs support and the masonry courses need to switch from horizontal to radial layers, a partly cantilevering platform is installed which rests on a star-shaped arrangement of beams spanning the entire width of the dome. Farther up there seem to be more platforms of the same type. Whether the various levels of platforms were to be supported vertically from below by struts is not entirely clear from Tessin's drawing. Small squares at the principal beams of the lowest platform probably indicate the ends of reinforcement lugs of the large beams, as suggested by the huge scantlings given in Tessin's legend (56 by 45 cm). The presence of the large platform (denoted by the term ponte reale) is attested by documents related to a trial of the contractors against the Pamphili family, the principals of the project: "First of all, one has to keep in mind that, in order to build this dome, a ponte reale was required which covered the entire extent of the dome, employing beams of unusual size, on which the winches for elevating the material were installed, which was then transported from hand to hand to the place where it was needed [13]." Indeed, Borromini himself noted that he left two rectangular openings at precisely that level "for the convenience of the masons who could easily move the material from inside to outside". Tessin's drawing shows two small platforms at the base level, which obviously served to install lifting devices (the only boarded parts of the lowest level of the scaffolding shown by Tessin).

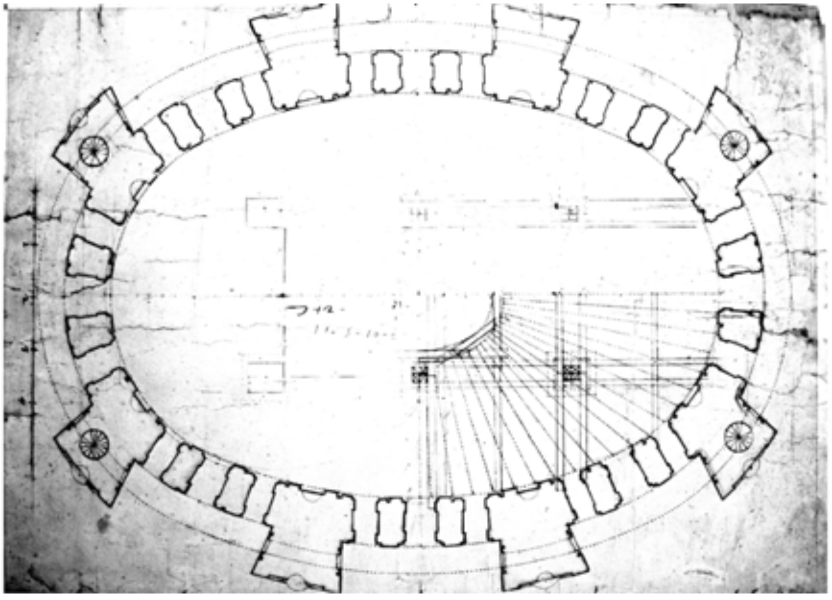

Figure 5. Ground-plan of the drum of the oval dome of the basilica at Vicoforte di Mondovì. Drawing by Francesco Gallo, around 1729. Archive of the basilica. Photo: Martina Diaz, enhanced by author.

The dome of the basilica of Vicoforte di Mondovì

So far, the reconstruction of the temporary works required for the domes has required a lot of guesswork. However, our assumptions are fully supported by the best documented construction site of a baroque dome, namely, the cupola of the basilica of Vicoforte di Mondovì in Piedmont [14]. That Marian pilgrimage church had already been begun in the late 16th century on a fancy large-scale oval plan with principal axes measuring 36 m and 24 m, respectively. However, the main dome to cover that oval nave was not even attempted then. The abandoned construction had to wait until 1728 when new plans for completion were prepared by Francesco Gallo. The dome was now to rise above a high drum added to the original project by Gallo. The falsework for the dome was erected in several steps between 1729 and 1731, interrupted by two winter breaks, but the masonry shell was finally erected swiftly in the fall of 1731, and de-centred in early 1732. The dome is unique in its oval plan. Shape control for an oval dome essentially requires formwork with a fully lagged surface.

In Vicoforte, the shape of the shell was defined by circular 'meridians' which, however, are not strictly radial in groundplan, nor orthogonal to the base oval (Fig. 5). The segmental shape of every single one of the eighty ribs carrying the formwork was constructed separately (or rather individually for every set of four identical ribs, due to symmetry), with different radii for each rib which were directly determined by the boundary conditions of a vertical tangent at the base and a uniform altitude at the oculus bearing the lantern (2 points plus one tangent uniquely determine the arch). The complicated centring was erected on a ponte reale that was once again resting on pairs of parallel principal beams. These beams in turn were supported by six temporary masonry piers rising from the floor of the church up to the cornice level. Fortunately, a whole set of drawings documenting the idea and the details of the temporary works has been conserved in the archives of the basilica.

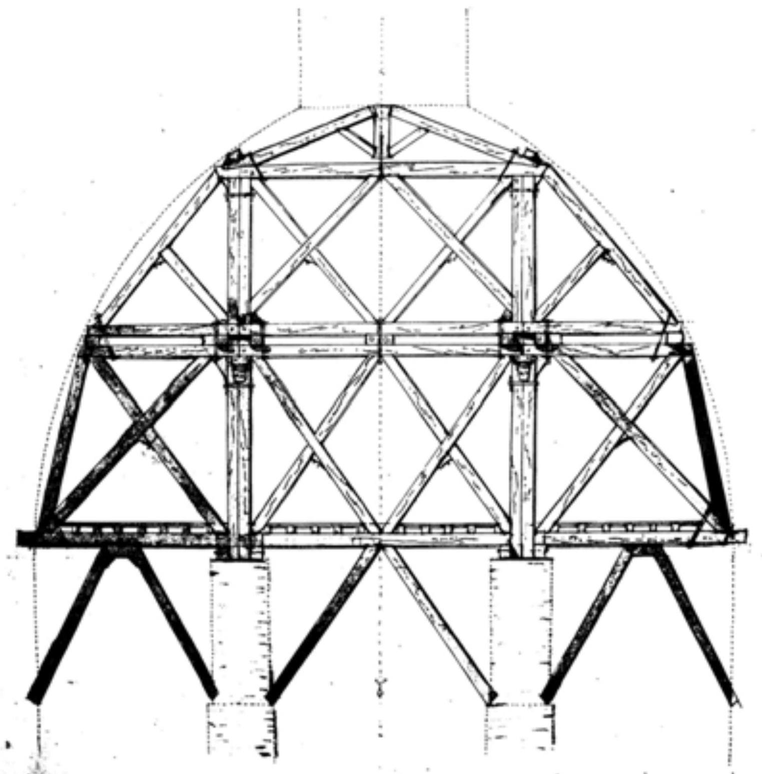

Figure 6. Transversal section of the centering of the dome of Vicoforte di Mondovì. Drawing by Francesco Gallo, around 1729. Archive of the basilica. Photo: Martina Diaz, enhanced by author.

The drawings show that the masonry piers continued as wooden supports up to the masonry shell above the platform (Fig. 6). The truss supporting the formwork was diligently stiffened by diagonal windbracing. The ponte reale was obviously equipped with boarding throughout. This extremely robust and strong centring did not fail to attract the attention of contemporaries: The principle of Gallo's centring was published in two engravings a few years later in Giambattista Borra's treatise on vault erection.

Some 19th century sources

The great age of cupolas was already over when Gallo's dome was vaulted in 1731. However, a certain revival of dome construction happened in conjunction with the neo-classical style in the early 19th century. Among other projects, we note the various imitations of the Pantheon in Rome, e.g. Antonio Canova's memorial church in Possagno, the rotunda of Schinkel's *Altes Museum* in Berlin, or, last not least, the church *Gran Madre di Dio* in Turin, a relatively close copy of the classical model. For the latter project, a very interesting drawing has survived in the municipal archives of Turin [15]. The plan is dated February 26, 1829, and signed by the architect of the building, "professor Ferdinando Bonsignore" (1760–1843). According to the plan, the dome has (in modern units) a diameter of 21.21 m, and a perfect hemispherical shape. Like in Santa Maria della Salute in Venice, the dome is coffered, comprising 5 rings of 24 octagonal coffers each, or 120 in total. Evidently, the complex coffered shape required full lagging again. The drawing comprises two quarter sections of the dome, two quarter plans of the centring, and a plan for the layout of the lead cover (not discussed here).

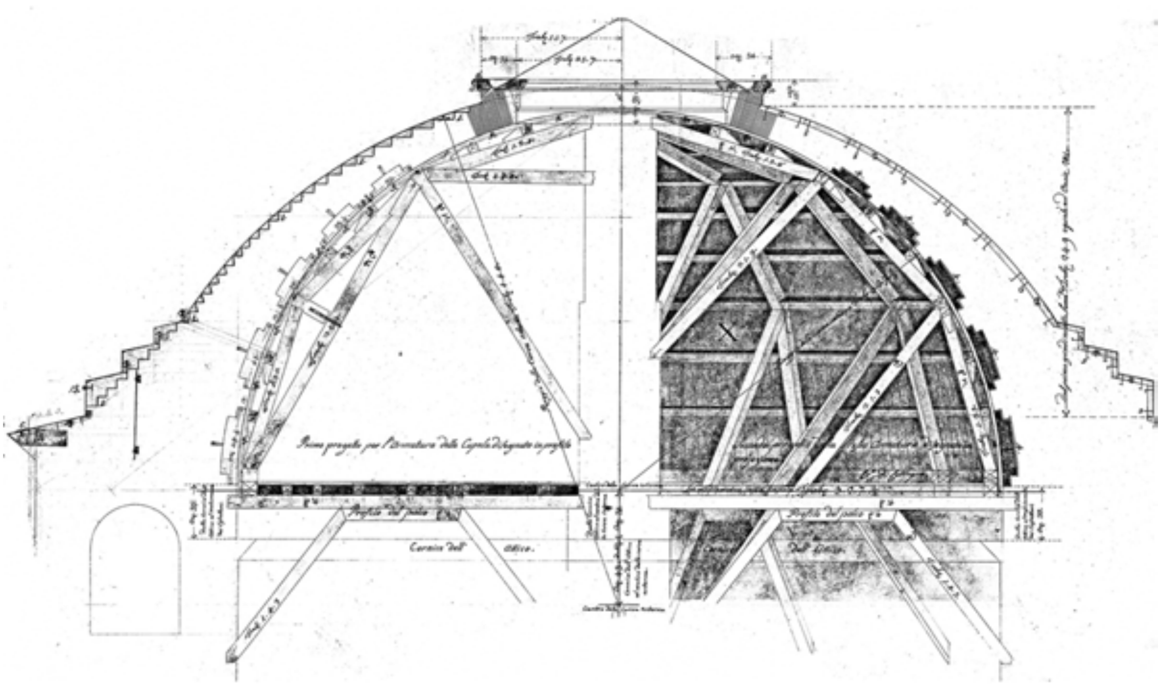

Figure 7. Two quarter sections of the dome of the church of Gran Madre di Dio, Turin. Drawing by Ferdinando Bonsignore, February 26, 1829, detail, enhanced by author. By kind permission of the municipal archives of Turin, TD 10.2.35.

The section (Fig. 7) shows two alternative layouts for the supporting truss. On the left side, the "first project" consists of twelve meridional ribs, each one composed of one raking strut supporting two arrangements of beams similar to a roof truss; on the right side, the circular section of the dome is approximated by three short straight beams, supported by oblique struts at each joint. In both cases, the actual lagging is carried by ring purlins running around the parallels of latitude of the spherical dome. The section also indicates the *palco necessario ai lavori inerenti all'armadura della Cupola*, or "platform required for the works erecting the centring of the cupola". The working platform is supported from below by a system of struts and straining beams.

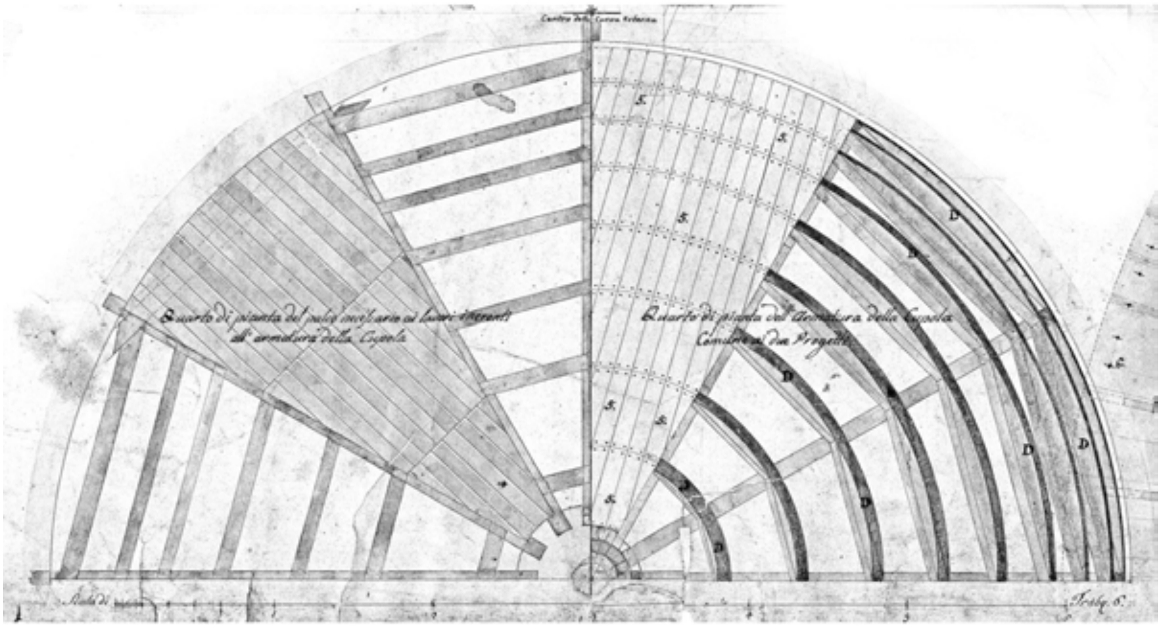

Figure 8. Two quarter plans of the dome of the church of Gran Madre di Dio, Turin. Drawing by Ferdinando Bonsignore, February 26, 1829, detail, enhanced by author. By kind permission of the municipal archives of Turin, TD 10.2.35.

The section and pertaining ground-plan (Fig. 8) reveal that these substructures rest on a central, axial temporary round pillar (according to the colour coding of the plan, a masonry one), which reaches up to the oculus and also receives the struts supporting the centres. The ground-plan shows (on the left side) the arrangement of the joists supporting the floor of the platform. On the right side, the layout of the lagging is shown, as well as the adaption of the ring purlins to the circular form by appropriate distance blocks. In the second project, the platform was to support the lower struts of the centring. Both of Bonsignore's designs are very similar to two centres for domes depicted in an almost exactly contemporary German treatise on carpentry (first edition printed in 1834), Georg Samuel Hörnig's *Sammlung praktischer Zimmerwerks-Risse*[16]. In Hörnig's designs, the platform again plays a key role, while it is supported by a central timber trestle or tower rather than a temporary masonry pillar.

Conclusions

The examples discussed have shown that the presence of a spacious and stable platform at the base of the dome was a key prerequisite for dome construction. Whether that platform was a free-spanning construction or directly supported from the ground depended on the special circumstances of the case. While free-spanning platform constructions were used for the cathedral of Florence and for the Panthéon in Paris (well known from Jean-Baptiste Rondelets engravings), it appears that the more common procedure – at least for cupolas at modest height above ground – was to build a temporary support for the platform in the middle of the domed space. Perhaps it is somewhat surprising that these temporary pillars were even built in masonry. The platform fulfilled a pivotal role in building the actual dome: It could be used to install lifting devices, move the material around on it, assemble the trusses and ribs of the falsework, and erect it. The construction of the actual supporting structure of the lagging was less important than one might expect at first sight, particularly since the loads to be carried by a dome built in subsequent circular ring courses of stones were rather moderate.

Acknowledgements

The friendly permit of the Municipal Archives of Turin to publish Figs 7 and 8 is gratefully acknowledged.

References

[1] B. Sgrilli, Descrizione e studj dell'insigne fabbrica di S. Maria del Fiore metropolitana fiorentina, Florence: Paperini, 1733. Plate IX.
[2] L. Ch. Sturm, Vollständige Anweisung, alle Arten von Kirchen wohl anzugeben, Augsburg: Wolff 1718. p.3: "Von dem Bau der grossen Kuppeln wissen die wenigste, sonderlich in Teutschland, was vor grosse und wichtige Bedencken dabey sind, viel weniger, wie man den Bau veranstalten müsse. In Büchern aber ist biß dato auch noch wenig dienliche Nachricht davon publiciret worden, und halten es die grössesten Italiänischen Bau-Meister noch unter ihren Arcanis."
[3] M. Piana, 'La cupola di S. Maria della Salute e i suoi restauri' pp.114-139 in: Storia e restauro. Studi, ricerche, tesi. Università IUAV di Venezia, Dipartimento di Culture del Progetto. Rome: Aracne, 2014.
[4] Cited after Piana, Cupola (note 3), p.136: "Per sicurazion di tale opera che non si rendi in nulla parte, però tute le armadure anderà da tera, cioè dal piano di essa chiesa fino sotto le cadene sudette sustenta detto pagiolo."
[5] C. Fontana, Il tempio Vaticano e sua origine, Rome: Buagni, 1694. p.321.
[6] H. Bauer and R. Wittkower, Die Zeichnungen des Gianlorenzo Bernini. Römische Forschungen der Bibliotheca Hertziana, 9, Berlin: Keller, 1931, pp.115–118 and plate 91.
[7] N. Carboneri, La reale chiesa di Superga di Filippo Juvarra, Turin: Ages, 1979, p.69 and p.188.
[8] G.B. Nelli, 'Ragionamento sopra la maniera di voltar le cupole senza adoperarvi le centine', pp.51-74 in B.S. Peruzzi, (Ed.), Discorsi di architettura del Senatore Giovan Battista Nelli, Florence: Paperini, 1753.
[9] ibid., p.57: "imperciocchè in luogo elle gran Centine, vi son da fare i Ponti amplissimi, forti, e comodi da trasportarvi per la più breve tutto il bisognevole della fabbrica."
[10] Sturm, Vollständige Anweisung, (Note 2), p.78: "Ein solches Bogen-Gerüste kan aber nicht wohl gerichtet werden / wenn nicht die Kuppel zuvor gantz / oder grössesten Theils mit einer solchen Decke überleget ist / daß die Zimmerleuthe in grosser Anzahl mit Handlangern darauf umlauffen / und die Balcken ziehen und heben können."
[11] Sturm, Vollständige Anweisung, (Note 3), plate VII.
[12] Stockholm, Nationalmuseum, Cronstedt collection CC 749.
[13] G. Eimer, La Fabbrica di S. Agnese in Navona. Römische Architekten, Bauherren und Handwerker im Zeitalter des Nepotismus, Stockholm: Almquist & Wiksell: 1970-71, vol.2, p.637: "In primis si deve considerare che per far detta cuppola è stato necessario a fare un ponte reale per levar tutto il vano della cuppola con legni non ordinarii sopra il quale si sono collocate le burbore per tirar sopra la robba, e da questo sono state transportate da mano in mano dove faceva bisogno."
[14] G. Zander, 'Su alcuni disegni di Francesco Gallo per le armature della cupola del Santuario di Vicoforte', Indice per i beni culturali del territorio ligure, vol.25/26, 1981, pp.19-30.
[15] Turin, Municipal Archives, Tipi e Designi, 10.2.35.
[16] G.S. Hörnig, Sammlung praktischer Zimmerwerks-Risse, 2nd ed., Dresden and Leipzig: Arnold, 1843.