FOUR

THE CONCEPTION AND CONSTRUCTION OF DRUM AND DOME

GIANGIACOMO MARTINES

SPHERE AND CYLINDER: MODELS OF MATHEMATICAL HARMONY AND PERFECTION

Roman architecture can exhibit considerable complexity and sophistication, yet it typically does so by means of elaborating on an elemental geometrical conception.[1] The Pantheon exemplifies this principle. Despite the intricacy of its constructive system, the unity of the composition is easy to grasp, as Georges Chedanne's wonderful cutaway conveys (see Plate XI). In his introduction to the building in his famous treatise on architecture, Andrea Palladio highlights the main geometrical intention behind the design of the interior: "Some maintain it is the same round shape as the world: the height from the floor to the opening in the ceiling, from whence light enters, is the same as its width, that is, the diameter from one wall to the other."[2] The Rotunda is as

This study is dedicated to the memory of Professor William Melczer, of Syracuse University, New York, who taught me the importance of objectivity in research work, during the many visits we made between 1983 and 1995 to the monuments of ancient Rome in the company of students. I would like to thank Giovanni Belardi, director of the Pantheon, of the Soprintendenza per i beni architettonici ed il paesaggio di Roma. Many thanks are also due to Mr. Fred Moffa of the British Institute of Rome, for his care and attention in the translation of this work, and to Cinzia Conti of the Soprintendenza Archeologica di Roma for her help with discussing many questions raised in this study. A special thank you to Mark Wilson Jones for taking my first manuscript to pieces and reassembling it in an improved sequence.

[1] Mark Wilson Jones, *Principles of Roman Architecture*, New Haven 2000.

[2] A. Palladio, *I quattro libri dell'architettura*, Venice 1570, vol. 4, p. 73.

impressive today as it was for Palladio, and it does indeed circumscribe a sphere. The only source of light, the oculus, draws the visitor to the center of the space, where we can wonder at the monumental interplay of a hemispherical dome resting on a cylinder of the same height, a geometry confirmed by modern precision surveys (see Plate XII and Fig. 6.6).[3] This sort of geometry was characteristic of Roman architecture. In his chapter on baths, Vitruvius describes a circular room with a dome in the following terms: "The Spartan sauna and sweating chambers should be joined onto the *tepidarium*, and however broad these are, they should have the same height up to the springing of the dome."[4] The rapport between cylinder and hemisphere is, however, different from that found in the Pantheon. The equality of width to height includes the dome in the Pantheon, but excludes it in Vitruvius's *laconicum*, the total height of which was thus one and a half times its width.[5] Numerous buildings from the Roman period present variations on the theme of a hemispherical dome resting on a cylinder, including nymphaeums, tombs, and bathing rooms.[6] None, though, were as large as the Pantheon.

The geometry of the Pantheon calls to mind the title of an important work of ancient science, as would have been evident to any ancient mathematician standing in the center of the Rotunda. *On the Sphere and Cylinder* is a fundamental work of Archimedes. In this his longest treatise, he established the formula we learn at school for calculating the volume of a sphere, $V = 4/3 \pi r^3$.[7] The subject is the same as Book XII of Euclid's *Elements*, written over half a century earlier, but which gave no rules for calculations.[8] Archimedes' findings on the sphere were totally new for the third century BC and are still definitive today. His procedures came from examining a sphere and a cylinder of

---

[3] Giangiacomo Martines, "Argomenti di geometria antica a proposito della cupola del Pantheon," *Quaderni dell'Istituto di Storia dell'Architettura* 13, 1989, pp. 3–10; M. Pelletti, "Note al rilievo del Pantheon," *Quaderni dell'Istituto di Storia dell'Architettura* 13, 1989, pp. 10–18. In 2005, the Karman Center for Advanced Studies in the Humanities at the University of Bern conducted a new digital survey.

[4] Vitruvius, 5.10.5 (*Vitruvius: Ten Books on Architecture*, trans. Ingrid D. Rowland, commentary and illustrations by Thomas Noble Howe with additional commentary by Ingrid D. Rowland and Michael J. Dewar, New York 1999, p. 72).

[5] L. Crema, *L'architettura romana,* Turin 1959, p. 376.

[6] Mark Wilson Jones, "Principles of Design in Roman Architecture: The Setting Out of Centralised Buildings," *Papers of the British School at Rome* 57, 1989, pp. 106–151.

[7] T. L. Heath, *The Works of Archimedes: On the Sphere and Cylinder* I, Proposition 34, Cambridge 1897; M. Clagett, A*rchimedes in the Middle Ages*, 5 vols., Madison-Philadelphia, 1964–1984; Carl Boyer, Uta Merzbach, and Isaac Asimov, *A History of Mathematics*, New York 1989; A. Frajese, *Opere di Archimedes*, Turin 1974; Archimedes, *The Works: 1. The Two Books on the Sphere and the Cylinder, with Eutocius' Commentaries*, third century BC, ed. and Eng. trans. R. Netz, Cambridge 2004. The notation π is recent and dates back only to the seventeenth century. This is the initial letter of the Greek word *periphéreia,* i.e., "circumference."

[8] Frajese 1974, pp. 51–60. See also Heath 1921; T. L. Heath, *The Thirteen Books of Euclid's Elements*, New York 1956; A. Frajese and L. Maccioni, *Gli Elementi di Euclide,* Turin 1970.

equal diameter, just as in the Pantheon.[9] His breakthrough was linked to the concept of *symmetria*, or mathematical harmony (literally the coming together of measures), an ideal that was intrinsic to ancient architectural design.[10] In the introductory letter, after stating the main relationships between a cylinder and sphere of the same width and height – that the volume and the area of surface of the former are both 3/2 as great as those of the latter – he went on to observe: "Now these properties were all along naturally inherent in the figures referred to, but remained unknown to those who were before my time engaged in the study of geometry, because none of them realized that there exists *symmetria* between these figures."[11] Here, "*symmetria* between these figures" means that they are commensurable and expressible through the relationship of small whole numbers. Attilio Frajese, who published the first complete Italian edition of the work, says, "Archimedes senses that lying beneath complex geometrical facts there must be corresponding simple arithmetical facts."[12] Indeed, apart from the relationships already mentioned, Archimedes proved that the surface of the sphere and the curving surface of a circumscribed cylinder must be equal. Thus in the Pantheon interior, the surface area of the drum is equal to that of the dome it carries. The harmony between these two figures is expressed by the simplest possible ratio of 1:1, both for the radii and the surfaces.

Archimedes also wrote of conoids (i.e., paraboloids and hyperboloids) and spheroids (i.e., ellipsoids), but it was the sphere and the cylinder that he loved best, perhaps because of this elemental symmetria. Cicero found proof of this, it seems, when he was quaestor of Marsala, in Sicily. In 75 BC, he went to Syracuse to find Archimedes' tomb outside the walls: "I remembered certain doggerel lines inscribed, as I had heard, upon his tomb, which stated that a sphere along with a cylinder had been set up on the top of his grave."[13]

The connection between abstract mathematics and physical spatial forms was certainly perceived by Archimedes. His *Method of Mechanical Theorems* relates how he applied the notion of the center of gravity and the lever to the investigation of geometrical figures by dividing solids into straight strips and then "weighing" them on a notional balance, as in the science of mechanics. This approach was as innovative as it was typical of Archimedes. Areas acquire a virtual weight and are balanced against each other, by which means the relative surface areas could be gauged. As he noted in a letter to Eratosthenes, the mathematician and librarian at the Museum of Alexandria in Egypt: "[I]t is easier to

---

[9] Martines 1989.

[10] Wilson Jones 2000, pp. 40–43; P. Gros, "Les fondements philosophiques de l'harmonie architecturale selon Vitruve," *Aesthetics: Journal of the Faculty of Letters, Tokyo University* 14, 1989, pp. 13–22.

[11] Heath 1897; E. J. Dijksterhuis, *Archimedes*, Copenhagen 1956, p. 142.

[12] Frajese 1974, p. 23.

[13] Cicero, *Tusculanae Disputationes*, 5. 23 (trans. J. E. King, Cambridge 1960).

supply the proof when we have previously acquired … some knowledge of the questions than it is to find it without any previous knowledge."[14]

The theorems on the sphere and the cylinder, too, were conceived as problems of mechanics. Thus, the concepts of geometry, symmetria, and balance were related to one another. Until Archimedes' *Method of Mechanical Theorems* was rediscovered at the beginning of the twentieth century by Johan Ludwig Heiberg,[15] his reasoning was only known through the quotations of Hero of Alexandria.[16] Hero, a mathematician from the time of the emperor Nero, also wrote a treatise for architects on the lifting of weights.[17] The central importance of this way of thinking in the creation of the Pantheon seems to be confirmed by the simple dimension, 150 feet (or 100 cubits), that defines the diameter of the ring of its interior columns. What is more, a square inscribed in this circle can be "flipped" over to produce another square that locates the columns of the portico (see Fig. 1.5 and Plate XII).[18]

The coffers of the dome of the Pantheon are divided into five rows of 28, a number that expresses an idea of perfection.[19] The number 28 is in fact a "perfect number," one that is equal to the sum of its factors (28 equals 1 + 2 + 4 + 7 + 14, each of which divides into 28). Perfect numbers are rare; units, tens, hundreds and thousands have one each: 6, 28, 496, and 8128, respectively. Following a tradition going back to the Pythagoreans, it was in Hadrian's time that Nichomachus of Gerasa included in the first book of his influential *Introduction*

---

[14] Dijksterhuis 1956, pp. 313–314.

[15] J. L. Heiberg, "Eine neue Schrift des Archimedes," *Bibliotheca Mathematica* 7, 1906–1907. In 1906, Heiberg discovered in the monastery of the Holy Sepulchre in Jerusalem a tenth-century manuscript copy of Archimedes' *Method*, overwritten with prayers in the thirteenth century.

[16] Hermann Schöne, *Herons von Alexandria Vermessungslehre und Dioptra Griechisch und Deutsch*, Leipzig 1903, p. 80 line 17, p. 84 line 11, p. 130 lines 15 and 25. *Method* translates the Greek word *ephodikón*, i.e. "system."

[17] C. M. B. Carra de Vaux, "Les Mécaniques: ou l'élévateur de Héron d'Alexandrie," *Journal Asiatique* 1893, vol. 1, pp. 386–472; 1893, vol. 2, pp. 152–192, 227–269, 461–514; Hero Alexandrinus, *Mechanica,* ca. AD 50, ed. L. Nix and W. Schmidt, Leipzig 1900; Drachmann, *The Mechanical Technology of Greek and Roman Antiquity*, Copenhagen 1963; G. Di Pasquale, *Tecnologia e meccanica. Trasmissione dei saperi tecnici dall'età ellenistica al mondo romano*, Florence 2004. For the date, see Otto Neugebauer, "Über eine Methode zur Distanzbestimmung Alexandria-Rom bei Heron," *Det. Kongelige Danske Videnskabernes Selskab. Historik-filologiske Meddelelser* 26.2, 1938, pp. 21–24.

[18] Wilson Jones 1989b, p. 129; Gert Sperling, *Das Pantheon in Rom*, Neuried 1999; Wilson Jones 2000, pp. 184–187. Cf. H. Geertman, "Aedificium Celeberrimum: studio sulla geometria del Pantheon," *Bulletin Antieke Beschaving* 55, 1980, pp. 203–229.

[19] Howard Saalman, "The Pantheon Coffers: Pattern and Number," *Architectura* 2, 1988, pp. 121–122; Martines 1989; William C. Loerke, "A Rereading of the Interior Elevation of Hadrian's Rotunda," *Journal of the Society of Architectural Historians* 49, 1990, pp. 22–43. See also K. Williams, *Italian Pavements: Patterns in Space,* Houston 1997, pp. 4–9; Sperling 1999. For a new interpretation of the design of the coffers in terms of perspective, see M. T. Bartoli, "Scaenographia vitruviana: il disegno delle volte a lacunari tra rappresentazione e costruzione," *Disegnare idee immagini* 9/10, 1994, pp. 51–54.

to Arithmetic a discussion of perfect numbers.[20] For Nichomachus, such numbers are associated with virtue, moderation, and beauty; arithmetic, music, geometry, and astronomy are like "bridges" and "stairways" to knowledge.[21]

There are other interpretations of the intentions behind the choice of 28 for the numbers of lines of coffers. Mark Wilson Jones has explained that this is a key ingredient of the interplay of rhythms and alignments – and selective lack of alignment – orchestrated between the pattern of the floor, the articulation of the wall, and the coffering of the dome (see Plate X).[22] As in so many other Roman buildings, a series of subordinate proportions entered into the composition and deployment of smaller units, including the exedras, columns, aedicules and moldings (see Chapter Five).[23] There is complexity, but never does it banish the underlying geometrical simplicity; the two poles of design are kept in balance.

This concept of balance, neither too much nor too little, is central to the aesthetics of architecture. At the end of the classical era of great Western domes, around AD 560, Procopius of Caesarea described the dome of St. Sophia in Constantinople in these terms: [24] "[I]t proudly reveals its mass and the harmony of its proportions, having neither any excess nor deficiency."[25]

In classical architecture, geometry is like one of Nichomachus's stairways, leading to higher realms of both aesthetic achievement and knowledge. The interior of the Pantheon arouses sentiments on the part of many a visitor similar to those expressed by Procopius, without necessarily knowing the ideas of Archimedes or Nichomachus. Yet knowledge of them gives access to further intellectual pleasures.

DESCRIPTION OF THE STRUCTURE

How did the architect of the Pantheon turn the elemental concept of cylinder and hemisphere into reality on such a scale and build the largest dome that had ever been built? To understand this, we must first understand the structure of the cylinder-drum and the hemisphere-dome, both of which are neither immediately visible nor comprehensible in their three-dimensional entirety.

---

[20] M. L. D'Ooge, *Nicomachus of Gerasa: Introduction to Arithmetic*, New York 1926; J. Bertier, *Nicomaque de Gérase*, *Introduction arithmétique*, Paris 1978; W. Haase, *Untersuchungen zu Nikomachos von Gerasa*, Ph.D. diss., University of Tübingen 1982.

[21] *Nicomaque de Gérase*, 1.3.6. See Martines 1989.

[22] Wilson Jones 2000, pp. 193–196; Martines 1989, p. 8.

[23] Wilson Jones 2000, pp. 182–196. For contrasting interpretations at times, see F. Esposito and A. Michetti, "I criteri di dimensionamento degli organismi a cupola presso i romani, III," *Materiali e Strutture. Problemi di conservazione* 2, 1996, pp. 61–84; Sperling 1999.

[24] V. Hoffmann, ed., *Der geometrische Entwurf der Hagia Sophia in Istanbul. Bilder einer Ausstellung*, Bern 2005.

[25] Procopius of Caesarea, *De aedificiis*, 1.1.29 (*On Buildings*, trans. H. B. Dewing and G. Downey, Cambridge 1971, p. 17).

It would be vain to make this attempt except on the basis of a thorough account of the physical fabric. In Hadrian's time, Lucian of Samosata, a Syrian orator, marked the beginnings of art literature by popularizing the literary genre called *ekphrasis*, which means "description" in Greek. An ekphrasis recreates a work of art in words, stirring the imagination and arousing emotions in the reader; it communicates the idea and the effect of the work to someone far away. To help us understand the structure of the Pantheon, there follows a selection of some of the most concise modern *ekphraseis,* presented not in chronological order but, rather, moving upward from the bottom to the top. These passages, by Adam Ziolkowski, Luca Beltrami, and William MacDonald, respectively, may be further appreciated by viewing the color drawings of the elite nineteenth-century French architects Achille Leclère and Chedanne (see Plate XI). Ziolkowski, author of the entry on the Pantheon in the authoritative *Lexicon Topographicum Urbis Romae*, describes the drum seen from the inside:

> The drum rests on a ring of concrete 7.3 m wide and 4.5 m deep. … Its wall, notionally 6.2 m thick, made of concrete faced with brick, contains cavities arranged on three levels, marked by the three cornices on the outer face of the drum. On the lowest level there are eight large apertures, the entrance and seven exedrae opening to the inside on the rotunda's main and diagonal axes. The four diagonal exedrae are trapezoidal, the other three apsidal. In front of each side exedra there is a pair of columns set in line with the wall; the architraves superincumbent on these columns are continuations of a cornice running round the interior and marking the top of the lower zone. … All these apertures are two storeys high, each of the six side exedrae being topped above the architrave by a sort of unfloored chamber.[26]

On the third story there is another set of large chambers (see Plate IV and Figs. 5.1b, 6.2), this time of uniform configuration, whether they align with the cross axes or the diagonal axes. Beltrami, who directed important investigative campaigns in 1892–1893, explains their geometrical division:

> The exedrae have chambers that are divided into three sections by two radial walls. Vertically these divisions fall over the axes of the Corinthian columns (of the lower level). … These 1.2 metre thick walls act as buttresses and connect the masonry at the springing of the dome to that of the external drum. … The 6-metre perimeter thickness [of the drum] is divided into three: a 1.9 metre thick inside wall, another 1.9 metre thick outside wall and 2.07 metre wide ring chambers.[27]

In alternation with this system of voids is another family of smaller semicircular chambers that occur on all three levels. On the ground floor and also

---

[26] Adam Ziolkowski, s.v. "Pantheon," in E. M. Steinby, ed., *Lexicon Topographicum Urbis Romae*, vols. 1–5, Rome 1995–1999; vol. 4, Rome 1999, pp. 58–59.

[27] Luca Beltrami, *Il Pantheon rivendicato ad Adriano 117–138 d.C.,* Milan 1929, pp. 35–37.

on the top level, they are reached from the outside via small openings shaped like doorways. On account of the great number of all these different types of voids, MacDonald, author of an inspirational introduction to the Pantheon, likens the structure of the drum to a honeycomb and describes its external configuration:

> On the outside the rotunda reads as an almost solid cylindrical wall of brick. There are openings in it here and there, at various levels, that give on to some of the many different chambers that honeycomb the rotunda structure, a honeycombing that is an integral part of a sophisticated engineering solution to the problem of supporting the huge dome.[28]

The exterior of the Rotunda is subdivided by cornices into three parts, or stories. The first cornice lies at the height of the frieze over the Corinthian columns inside the building, the second lies at the springing of the dome, and the third registers the top of the drum (see Figs. 1.12, 1.13, 6.3). Moving on to the dome, MacDonald notes:

> Rather more than half of the exterior rise of the dome is defined by a series of concentric step-like rings that are actually buttresses, masses of masonry placed over the dome's lower part where they are most needed structurally. … Partly because of these ring buttresses, the exterior silhouette of the dome is not hemispherical but bowl-shaped; inside, the hemispherical surface of the dome rises from a level well below that of the outer high terrace. The upper part of the cylindrical wall of the rotunda is built up high, also as a shoulder-like buttress, reducing the prominence of the exterior of the dome. The only exterior spherical portion rises above the highest of the step-ring buttresses, extending upward and inward to culminate in a horizontal circular opening, an oculus, more than thirty feet (9.45 m) in diameter, which is centered over the paving a hundred and fifty feet below.[29]

The above extracts give us a clear picture of the structure of the dome and the distribution of spaces within it. We have now inspected the structure of the cylinder like a bee in the honeycomb described by MacDonald. We have a clear picture of the structure of the building and the spaces within it. We can easily make out eight piers and exedrae in the plan of the building (see Plate IV and Fig. 5.1b). The spaces are made up of exedrae and chambers up to the third story, arranged along the eight axes of the circumference. The vaulted chambers are enclosed by the internal and external walls of the drum and by radial walls. The exedrae look onto the rotunda and reach up to the second story. The third-story chambers are floored at the springing of the dome and open out onto the outer face of the rotunda. The cupola in its hemispherical

---

[28] William L. MacDonald, *The Pantheon: Design, Meaning, and Progeny,* London 1976, p. 33.

[29] MacDonald 1976. Diameter of oculus from Pelletti 1989.

purity is visible only in the interior, while on the exterior it is partly concealed by the step-rings.

THE DRUM

The drum of the Pantheon is an immense structure, roughly 108 feet (32.2 m) tall and 21 feet (6.2 m) in thickness at the base, reducing to 20 feet (5.9 m) at the top. The ratio of the drum to the dome (44.08 m) is about 1 to 7.3.[30] Apart from its huge scale, what is most striking is the presence of the numerous voids that MacDonald likened to the cells of a honeycomb. Giuliano da Sangallo drew attention to them by using a dark tint on his plan in the *Codex Barberinianus* (Fig. 4.1),[31] perhaps to represent the darkness of the empty spaces. Some decades later, Sebastiano Serlio remarked that "I think the spaces are there to avoid using too much material. In any case, being circular they are very strong."[32] The sections of the wall between the apertures (i.e., the entrance and seven exedrae) act as eight huge piers onto which stress is directed by the vaulting over the apertures. The drum can thus be described both as a series of piers connected by walls or as two concentric walls connected by transverse walls.[33] The drum is what in modern terms we call a "diaphragm structure"; this structure is comparatively light and incredibly strong.

In Roman architecture, a beautiful example of a diaphragm structure in the form of a hollow pillar is Trajan's Column, inaugurated in AD 113 (Fig. 4.2). Its shaft comprises 19 hollowed-out monolithic marble drums, with a helical staircase running through them. This hollowing produces a structure that weighs a third less than a similar full column but has virtually the same stiffness.[34]

In the Pantheon the semicircular chambers inside the drum (24 in number, 8 for each tier) are oriented so that they act like arches braced against the outward thrust of the rotunda. The Romans used this arrangement in retaining

---

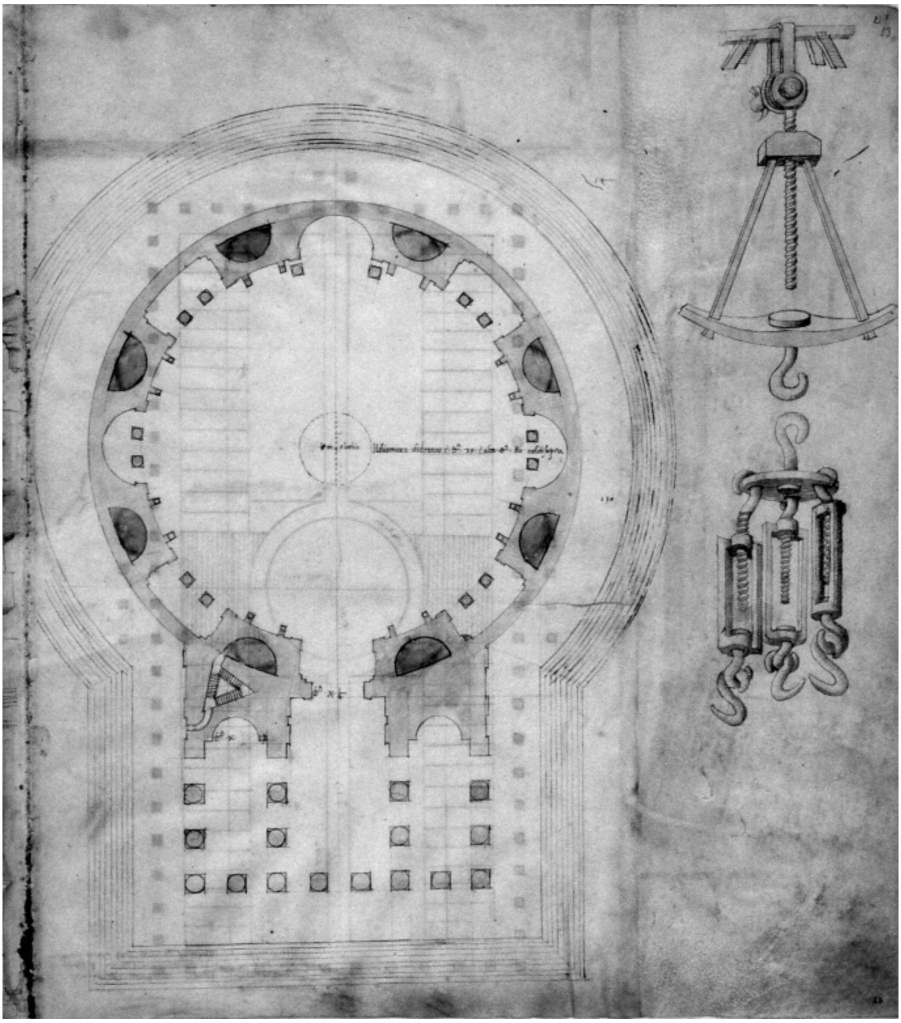
[30] For the ratio of span to wall thickness, see S. Huerta, *Arcos, bóvedas y cúpulas. Geometria y equilibrio en el cálculo tradicional de estructuras de fábrica*, Madrid 2004, p. 3; Janet DeLaine, *The Baths of Caracalla in Rome: A Study in the Design, Construction, and Economics of Large-Scale Building Projects in Imperial Rome* (*Journal of Roman Archaeology*, Supplement 25), Portsmouth, RI, 1997, pp. 56–57; Wilson Jones 2000, p. 82; Lynne Lancaster, *Concrete Vaulted Construction in Imperial Rome: Innovation in Context*, Cambridge 2005, pp. 138–148. Dome span from Pelletteri 1989, p. 12.

[31] C. Hülsen, *Il libro di Giuliano da Sangallo: codice Vaticano Barberiniano latino 4424*, Leipzig 1910, repr. Vatican City 1984, fol. 13; cf. S. Borsi, *Giuliano da Sangallo. I disegni di architettura e dell'antico*, Rome 1985, pp. 94–95.

[32] Sebastiano Serlio, *Il Terzo libro dell'architettura*, Venice 1540, p. 2v.

[33] Ziolkowski 1999, p. 59.

[34] Giangiacomo Martines, "La struttura della Colonna Traiana: un'esercitazione di meccanica alessandrina," *Prospettiva* 32, 1983, pp. 60–71; Martines, "L'architettura," *Autour de la colonne Aurélienne. Geste et image sur la colonne de Marc Aurèle à Rome*, ed. J. Scheid and V. Huet, Paris 2000, pp. 19–88.



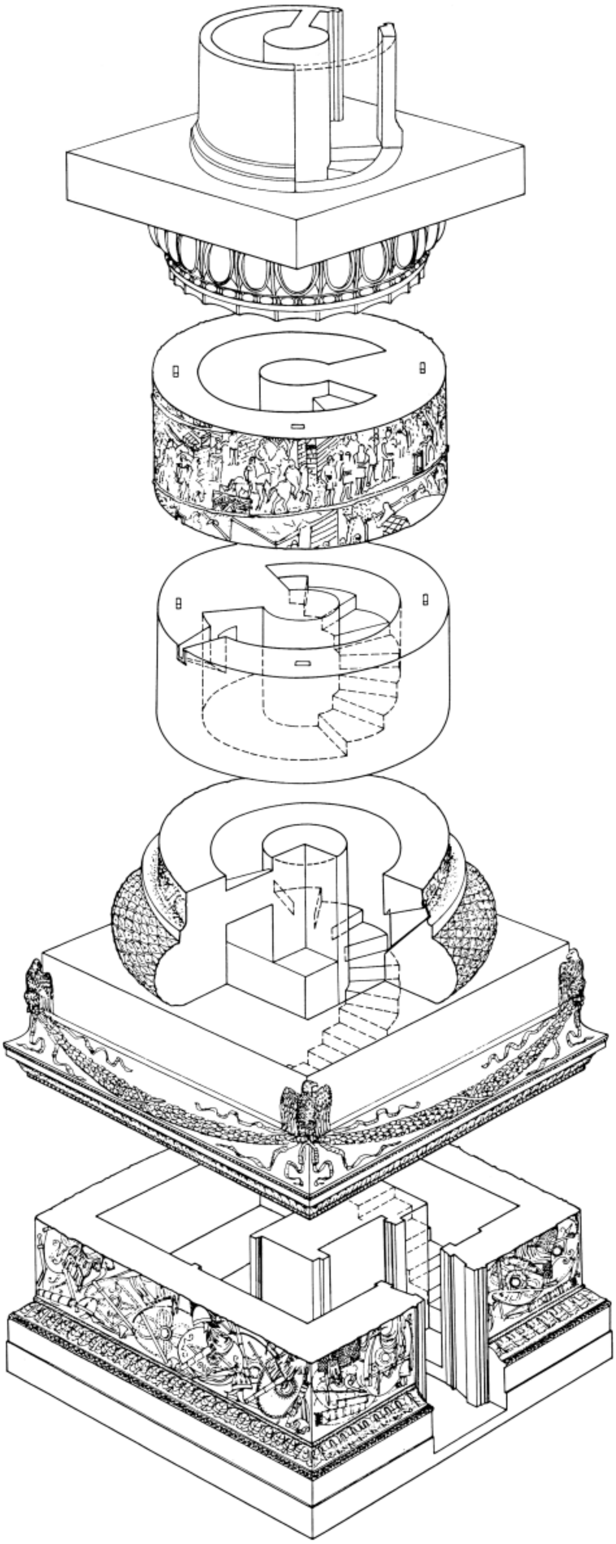
4.1. Plan of Pantheon by Giuliano da Sangallo, after 1465. (Biblioteca Apostolica Vaticana, *Vat. Barb. lat 4424*, f. 13 recto)

structures, as for example at the Mausoleum of Augustus (see Fig. 5.1a).[35] In the third story of the Pantheon (Fig. 4.3, and see Figs. 5.1b and 6.2), the niches are each divided by a radial wall, an arrangement that had also been adopted in the Mausoleum to counter the lateral pressure from the huge core. In Nero's Nymphaeum under the Temple of Divus Claudius, on the Celio in Rome, there are chambers with semidomes that lie on a structure consisting of two walls separated by a semicircular corridor.[36] In Hadrian's Villa, the pumpkin

---

[35] H. von Hesberg and S. Panciera, *Das Mausoleum des Augustus. Der Bau und seine Inschriften,* Munich 1994; G. Ortolani, "Ipotesi sulla struttura architettonica originaria del Mausoleo di Augusto," *Bullettino della Commissione Archeologica Comunale di Roma* 105, 2004, 197–222.

[36] A. M. Colini, *Storia e topografia del Celio nell'antichità* (Memorie dell'Accademia Pontificia 3), Vatican City 1944.



4.2. Exploded perspective of Trajan's Column. (Wilson Jones 2000, Fig. 8.8) semidome of the Serapeum has chambers at the springing, with a system of pillars and niches-openings-windows underneath (see Figs. 5.9 and 5.10).[37] This diaphragm strategy finds its most complete manifestation in the Pantheon.

In the three storys of the Pantheon, the distribution of the masonry and its voids changes subtly. In the lower levels, semicircular voids alternate with the exedrae, while by the third story, above the springing of the dome, the voids are distributed more uniformly along the circumference. The dome therefore discharges its weight relatively evenly, while the drum then concentrates the load on the eight "piers." Piers and interlocking walls work together to support the dome.

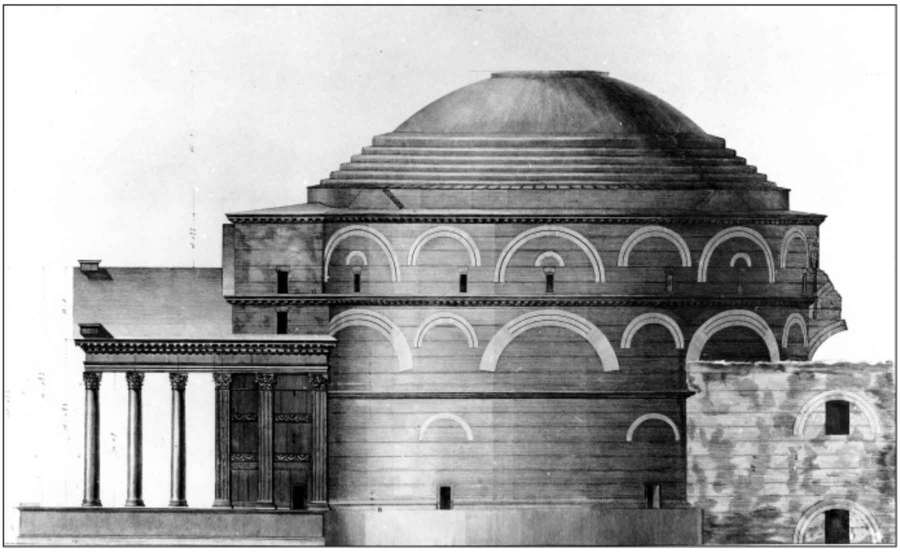
The general idea behind this system for stiffening a structure while lightening it operates in Roman bridges, too. Piers are sometimes hollowed out by a smaller arch in order to prevent the pressure of a river in flood from bringing down the abutments. An example is the Pons Fabricius on the Tiber, built in 62 BC, which joins the Isola Tiberina to the Campus Martius. The two segmental arches have a span of 24.5 meters. The road on top is 5.5 meters wide, almost the same thickness as the Pantheon's drum. In the Pantheon, the system of piers and barrel vaults within the drum can be likened to a circular bridge, or rather, a circular aqueduct with three rows of arches, as in the Pont du Gard near Nîmes.

Let us now focus on the relationship between the spatial articulation of the rotunda and its fabric. The great mass of the drum is concrete encased in brickwork that acted both as formwork and facing (Figs. 4.3 and 4.4, and see Fig. 3.4). The wall of the drum is built in *opus testaceum,*[38] involving *bessales* (bricks about 2/3 ft or 19.7 cm square), *sesquipedales* (bricks about 1 1/2 ft or 44.4 cm square), and *bipedales* (bricks or tiles 2 ft or 59.2 cm square). The latter have a thickness greater than the other two, typically in the range 4 to 4.5 centimeters (whereas bessales and sesquipedales range between 2.5 cm and 4 cm thick). After having been baked in these sizes, bricks were often cut into smaller units. The bessales and sesquipedales were generally cut in half on the diagonal to make *semilateres* that were embedded in the concrete like the teeth of a saw, with the hypotenuse of the triangle on the surface (see Fig. 5.8). When

---

[37] C. F. Giuliani, *Tibur I,* Rome 1970; C. F. Giuliani and P. Verduchi, "Villa Adriana," *Quaderni dell'Istituto di Topografia Antica della Università di Roma* 8, 1975; C. F. Giuliani, "Volte e cupole a doppia calotta," *Mitteilungen des Deutschen Archäologischen Instituts, Römische Abteilung* 82, 1975, pp. 329–342; William L. MacDonald and John Pinto, *Hadrian's Villa and Its Legacy*, New Haven 1995. See also Chapter Five in this volume.

[38] G. Lugli, *La tecnica edilizia romana*, Rome 1957; C. F. Giuliani, *L'edilizia nell'antichità*, 1990; R. Taylor, *Roman Builders,* Cambridge 2003; Lancaster 2005. *Opus testaceum* normally refers to a construction by fired bricks; *testa* in Latin is an object made from clay and baked in an oven. Instead, *opus latericium* refers to a construction made of unfired bricks, which are dried or sunbaked, see Lugli 1957; G. Martines, "Mattoni romani da cortina," in G. Carbonara, ed., *Trattato di restauro architettonico*, Turin 1996, vol. 3, pp. 213–221. For illustrations, see Chapter Five in this volume.



4.3. West elevation of Pantheon; engraving by Francesco Piranesi, Pantheon. (*Seconda parte de' tempij antichi che contiene il celebre Pantheon*, Rome 1790, Plate VII, Istituto Nazionale per la Grafica, Roma)

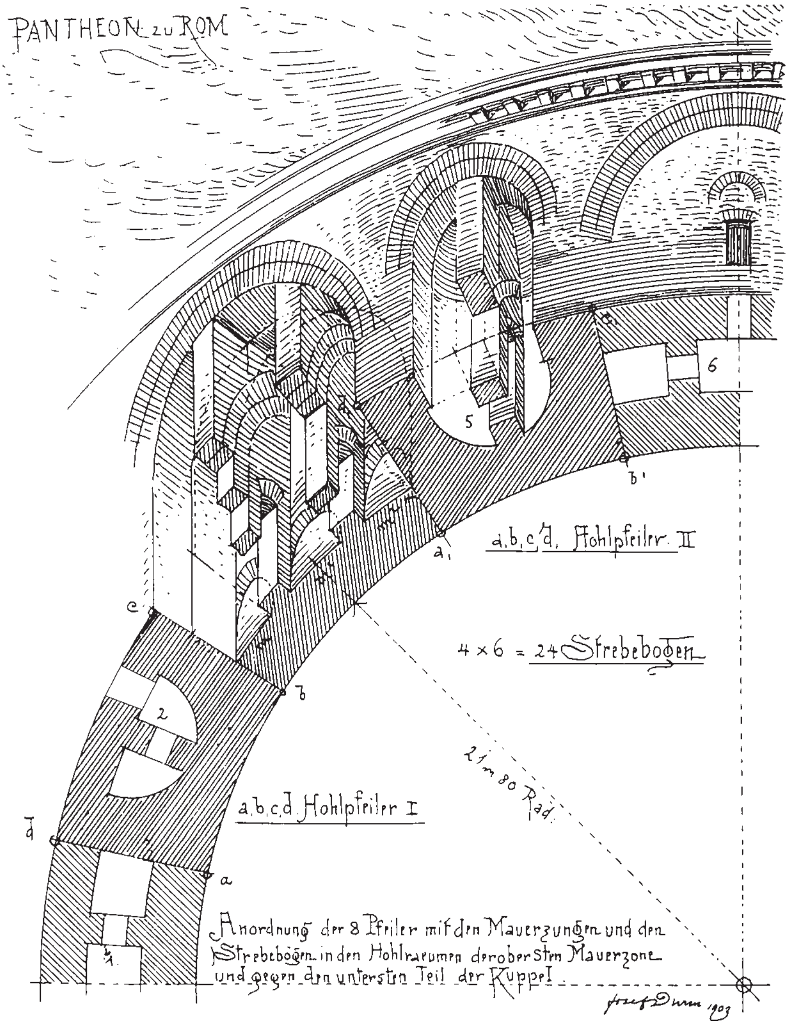
used for the arches of the rotunda, however, the sesquipedales and bipedales were usually employed either whole or as rectangular halves or smaller portions. In this context, individual bricks do not fit a perfectly radial pattern, but tapered bipedales usually alternate with ordinary ones for the sake of economy. The concrete consisted of mortar made of lime and pozzolana into which were laid, not poured, pieces of aggregate, often as large as a fist, made of stone (often tufa) and, to a lesser extent, pieces of broken brick. At intervals, the concrete is divided into horizontal sections by "through" or "bonding" courses made up of a single stratum of *tegulae bipedales*.

The outer face of the drum of the Pantheon has interlocking arches of two kinds, discharging and relieving. Discharging arches and relieving arches differ in that the first have an opening underneath, whereas the second have no opening or none visible at the surface. In their disposition, these arches may be likened to the wicker arches of a basket. The dome is like the upside-down basket seen on the top of the crane of the Haterii,[39] or like the baskets seen on the frieze of Trajan's Column used by Roman soldiers to transport earth, mortar, and *caementa*.

The relieving arches embedded in the body of the rotunda wall are made of bipedales, with a minority of sesquipedales in some cases. These tile-shaped bricks are arranged in one, two, or three superimposed concentric

---

[39] Giangiacomo Martines, "Macchine da cantiere per il sollevamento dei pesi, nell'antichità, nel Medioevo, nei secoli XV e XVI," *Annali di architettura* 10/11, 1998–1999, pp. 261–275.

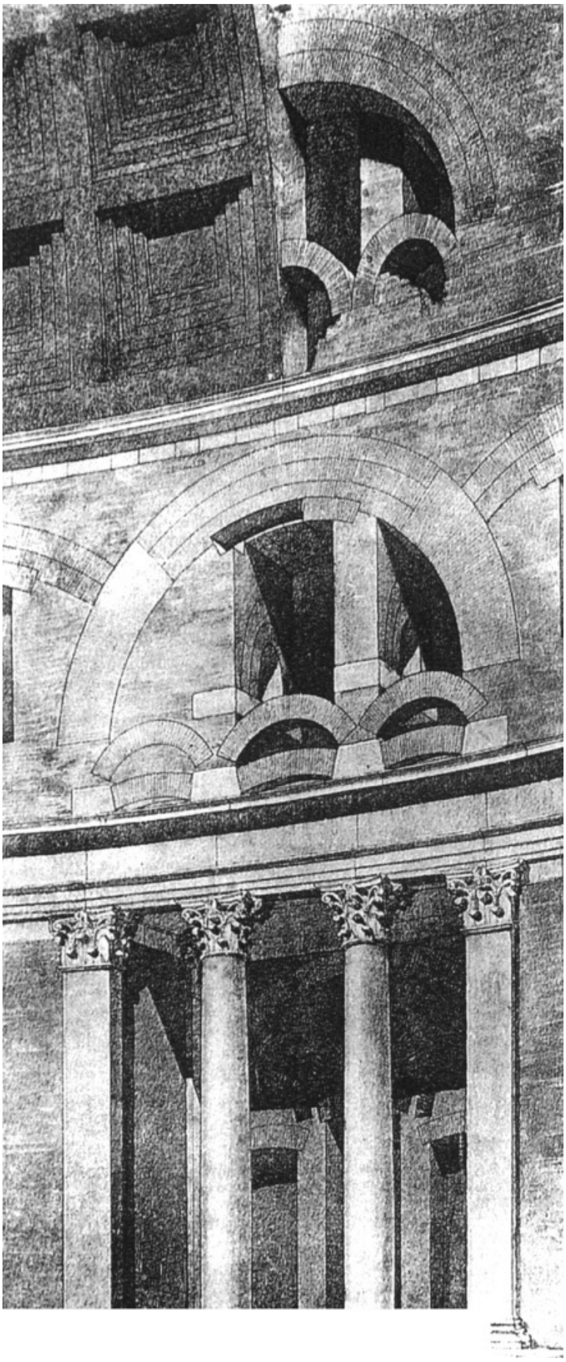


4.4. Study of structure in upper part of drum by Josef Durm. (Durm 1905, Fig. 641)

rings, depending on the strength required (Figs. 4.3 and 4.4). The relieving arches that form part of the eight piers have only one ring of bipedales on the ground-level tier; their intrados correspond to the semidomes of the chambers within (see Fig. 1.13). The arches directly overhead have two rings of bipedales, again arranged to coincide with the chambers behind. The great relieving arches with triple rings (two of bipedales plus one of sesquipedales), also on the second level, correspond to the crown of the vaults over the exedrae; their internal diameter is 11.80 meters.[40] On the third story, arches with double bipedales

---

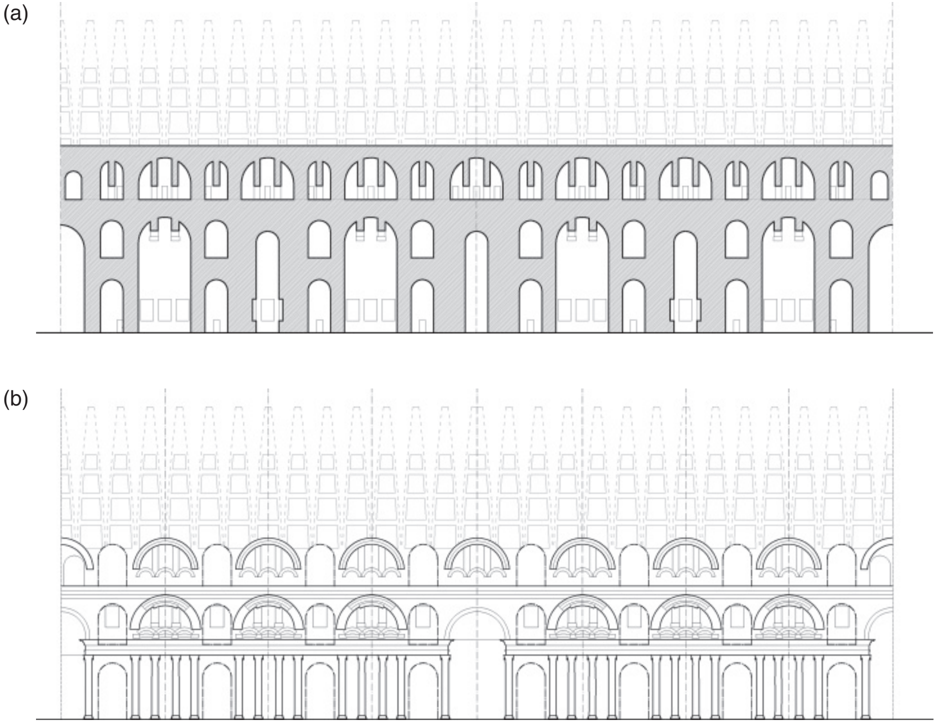
[40] The sizes of bipedales and sesquipedales that make up the arches on the Pantheon's drum were checked with a laser system in 2005 by the architects Benedetto Brattoli and Marco Brunori, whom I gratefully thank for their help.



4.5. Perspective rendering of the structure over an exedra of the rotunda. (Pier Olinto Armanini, in Beltrami 1898, Plate IV)

relate to the barrel vaults of the top tier of chambers (Figs. 4.5 and 4.6).

As just mentioned, the Romans did not generally build arches from whole sesquipedales or bipedales alone, but broke many of them in two for reasons of economy and for better bonding, with the nonbroken edges in view on the exterior faces. As Gene Waddell explains in Chapter Five, whole bipedales often alternate with portions of concrete in between that may be likened to *voussoirs*. This can be seen in many ruined Roman buildings, but we can be less sure of this aspect in the Pantheon because it is intact. We can only catch a glimpse inside of the barrel vaults through a few cracks in the dome. I have, however, been able to inspect a high-level chamber of the Basilica Neptuni, immediately to the south of the Pantheon. Where some of the linings have fallen off, it is possible to observe the structure behind. The visible surfaces are made up entirely of bipedales, without rubble, as suggested in the drawings by Joseph Durm (Fig. 4.4). Durm draws the ribs of the dome as if they were made of brick, but this is not certain because we do not see inside the arches. The



4.6. Interior elevations projected flat, showing the bare structure (a) and the structure in relation to principal marble elements (b). (Drawn for the author by Roberta Zaccara in 2007)

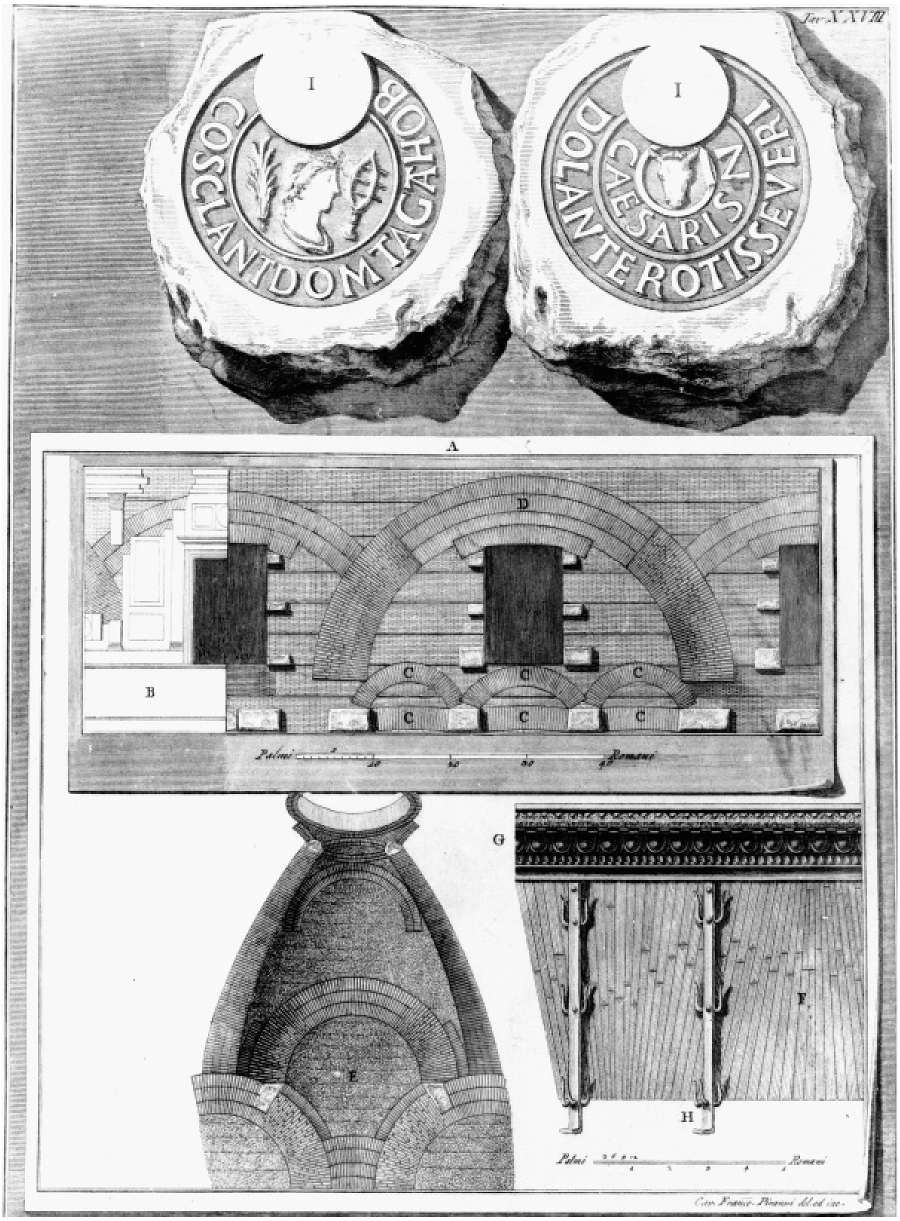
impressive arches that once bridged the Pantheon and the basilica at high level are in any case definitely made of solid bipedales (see Fig. 7.5). Perhaps all third-story barrel vaults were built with a high density of bipedales and relatively little rubble.

The lower level of chambers in the piers open onto the exterior of the rotunda with apertures crowned by flat tile arches; above each of these there is a semicircular relieving arch (Fig. 4.3). The second-story chambers have no openings toward the outside, except for the ones that correspond to the stairs.[41] At the same time all of the chambers sit behind the blind attic windows. The third-story semicircular chambers have an outside aperture that is not in the center so as to avoid the radial wall that bisects them.

Inside the rotunda, the trapezoidal exedrae on the diagonal axes have barrel vaults, while the exedrae on the cross axes have semidomes. The extrados of both attain a level just beneath the springing of the cupola. The relation between the architectural volumes and the fabric at attic level can best be seen in drawings that relate to the works that Pope Benedict XIV authorized after

---

[41] The stairs between the portico and the rotunda give access to a pair of semicircular chambers on the third level, corresponding to the second story of the rotunda (see Chapter Seven). The other semicircular chambers at this level are presumed to be the same.



4.7. Engraving illustrating brick stamps (top), construction of attic level (middle), brick skeleton for a portion of the dome, and an elevation detail of the oculus (bottom) by Francesco Piranesi. (Rome 1790, Plate XXVIII)

the Jubilee of 1750 to repair damage to the interior of the dome, which had been caused by infiltration from rain. During 1756–1758, adjustable scaffolding was put up, and Giovan Battista Piranesi had an opportunity to make firsthand observations.[42] His studies were collated by his son Francesco (Fig. 4.7), which

---

[42] Susanna Pasquali, *Il Pantheon: architettura e antiquaria nel Settecento a Roma*, Modena 1996.

appeared as part of a set of engravings in 1790.[43] The upper part of the plate contains reproductions of two brickstamps from Hadrian's time, found in the dome.[44] In the center there is a drawing of the brickwork in the attic, which was temporarily visible on account of the removal of areas of defective covering. The attic wall has a continuous series of main and secondary relieving arches, relating to the exedrae and the piers, respectively. Under the intrados of each main arch there is a framework of minor arches. This system lightens the load while directing it over the columns below (Fig. 4.5).[45]

The function of the relieving arches of the Pantheon, like those of numerous other Roman buildings, is rather enigmatic. Having been built over and filled with masonry, they cannot behave like real arches. What purpose, then, do they serve?

One of our sources for such arches is the sixth book of Vitruvius, on private buildings:

> Likewise, make certain that arches relieve the weight of the walls [*ut levent onus parietum fornicationes*] onto their voussoirs [*cuneorum divisionibus*], and that they are centered over the opening. For if arches spring from voussoirs that begin beyond the wooden beam or the head of a stone lintel, in the first place the wood will not bend because its load has been relieved, and secondly, if in time it begins to develop flaws, it can be replaced easily, and without piling up braces.[46]

Toward the end of the period of classical Roman architecture Procopius of Cesarea provides us with some interesting information on the construction of Hagia Sophia in Constantinople. He writes of the decision of the Emperor Justinian to complete one of the four main arches in the face of the danger that the centering would collapse:

> And the props [Greek *pessoi*], above which the structure was being built, unable to carry the mass which bore down upon them, somehow or other suddenly began to crack, and they seemed on the point of collapsing. … And straightway the Emperor … commanded them [Anthemius of Tralles and Isidorus] to carry the curve of this arch to its final completion. "For when it rests upon itself," he said, "it will no longer need the props [*pessoi*] beneath it."[47]

---

[43] Francesco Piranesi, *Seconda parte de' templij antichi che contiene il celebre Pantheon,* Rome 1790, Plate XXVIII. The system of arches and ribs supposedly embedded in the dome shown in the bottom left of the plate was redrawn by Auguste Choisy (*L'art de bâtir chez les Romains*, Paris 1873, Fig. III).

[44] The two brickstamps were found during works to the ancient windows of the attic. After their discovery, the brickstamps were sold to antique dealers; see Pasquali 1996a, p. 128. The first brickstamp (*Corpus Inscriptionum Latinarum*, XV, no. 276), transcribed incorrectly by Piranesi, reads "Rosciani Domit(ii) Agathob(uli)." The second is CIL XV no. 811b.

[45] Lancaster 2005, pp. 97–101.

[46] Vitruvius 6.8.3.

[47] Procopius, 1.1.69–71. See also Robert Ousterhout, *Master Builders of Byzantium*, Princeton 1999.

In 1985, I had new bipedales made for the restoration of arches in the Domus Tiberiana on the Palatine.[48] A dry bipedalis weighs 30 kilos but, when laid wet, and so much heavier due to water absorption, two bricklayers are required to shift it. As the wall dries, bipedales gradually release water, and this helps to even out the curing process and reduce the extent of shrinkage cracks. Due to the viscous quality of the mortar and the capillary nature of the terra-cotta, the union between wet bipedales and wet concrete is extremely strong. The porosity and surface area (0.36 m^2) of a bipedalis is far greater than ordinary bricks. As a matter of fact, when an arch is closed by laying the final, key bipedalis, even though the masonry of the arch is still wet it immediately acquires stiffness (which gradually increases as the mortar dries). Once the crown of the arch is in place, the weight on the props diminishes as the thrust on the haunches begins, just as described by Procopius of Cesarea.

It is also significant that the amount of mortar used with the bipedales is much less than in the main body of concrete, this being another reason why relieving arches gain strength more quickly. This made relieving arches particularly effective in terms of constructional procedure, since the centering could be struck earlier than otherwise would be the case. It can further be supposed that having the vaults gain their strength quickly would have been a great advantage for proceeding with the construction at a higher level.[49]

Relieving arches confer greater stiffness to a wall because an arch of bipedales is stiffer than an equal mass of either normal opus testaceum or concrete. And as Lynne Lancaster notes: "The idea of using arches to control how a structure supports its load is related to the idea of reinforcing the parts of a building that support the greatest loads with the most durable materials."[50]

Furthermore, stress is placed along a line going from one extremity to the other, as in a bridge. This advantage is useful in cases of differential subsidence of the terrain under the foundations. Some of the cracking in the Pantheon is

---

[48] Martines 1996, p. 228; A. Giuffré and G. Martines, "Domus Tiberiana: dissesti antichi e provvedimenti nuovi," *Il Palatino area sacra Sud-Ovest e Domus Tiberiana*, ed. C. Giavarini, Rome 1998, pp. 409–426. In 1858, the architect Francesco Fontana had new bipedales made just for the Pantheon's restoration; see P. d'Orsi, "Pantheon, Portico degli Dei Consenti, Colosseo. Tre monumenti antichi restaurati a metà Ottocento," *Ricerche di Storia dell'Arte* 52, 1994, pp. 72–77.

[49] DeLaine 1997, p. 164; Lancaster 2005, p. 98. C F. Giuliani 1990, p. 83; Lynne Lancaster, "Building Trajan's Markets 2: The Construction Process," *American Journal of Archaeology* 104, 2000, pp. 755–785; Giangiacomo Martines, "La struttura del Pantheon velut regionem fornicatam," *Quaderni dell'Istituto di Storia dell'Architettura* 41, 2004, pp. 3–16.

[50] Lancaster 2005, pp. 86–87. On the phases of execution of a relieving arch, see R. Volpe, "Un antico giornale di cantiere delle terme di Traiano," *Mitteilungen des Deutschen Archäologischen Instituts, Römische Abteilung* 109, 2002, pp. 377–394. Cf. E. Bianchi, "Le nervature nelle volte massive di età romana," *Bullettino della Commissione Archeologica Comunale di Roma* 101, 2000, pp. 105–162.

almost certainly due to settlement.[51] It can be surmised that Roman architects believed that such cracks, which slowly get bigger over the life span of a building, would be checked or even averted by the use of relieving arches.

Thus, we have seen how inside the drum, voids are overlaid by either semidomes or barrel vaults, which on the outside are echoed by series of relieving arches. Built on three levels, these trace the logic of the 20-foot-thick diaphragmatic structure: arch-pier-arch, like a bridge or an aqueduct (Fig. 4.6).[52] The voids give the structure lightness while the vaults in bipedales confer stiffness. The relieving arches brought advantages, too, in terms of both the performance of the structure and the speed with which it was put up.

ABOUT THE DOME

Ammianus Marcellinus, describing a view of Rome during a visit by Costantius II in AD 357, expressed his admiration for the Pantheon: "The Pantheon is like a rounded city–district, vaulted over in lofty beauty."[53] This feat of engineering is underlined by the great weight of the masonry above the springing of the dome (shell of the dome + the third story of the drum), which, according to MacDonald, is about five thousand metric tons.[54] The wonder of the building also raises other questions: what theoretical notions lie behind the construction of the dome? What technical criteria were used? Were there any precedents?

A book written during the greatest period of Roman architecture is *The Mechanics* of Hero of Alexandria, mentioned earlier. It is not a treatise like Vitruvius's *De Architectura* but a textbook for students of architecture and engineering, which includes study exercises. It includes a foreword on geometry

---

[51] G. Croci, *The Conservation and Structural Restoration of Architectural Heritage*, Boston 1998, p. 125. According to Croci 1998, p. 211, and G. Croci, *Conservazione e restauro strutturale dei beni architettonici*, Turin 2001, p. 461, compression vertical stresses at the springing of the dome are less than 0.5 MPa while tensile annular stresses are less than 0.05 MPa (MPa stands for the Mega Pascal, a unit that corresponds to 10 Kg/cm^2). According to R. Mark, "Reinterpreting Ancient Roman Structure," *American Scientist* 75, 1987, p. 146, the maximum levels of compression stress could rise to about 0.3–0.6 MPa around the wall openings of the drum. According to Kjeld De Fine Licht, *The Rotunda in Rome: A Study of Hadrian's Pantheon*, Copenhagen 1968, p. 92, the pressure on the top of the foundation is 0.45 MPa and on the ground 0.52 MPa. See also G. Croci, M. Cerone, and A. Viskovic, "Analysis from an Historical and Structural Point of View of the Domes of Pantheon, Hagia Sophia and St Peter," *Studies in Ancient Structures*, ed. G. Özsen, Istanbul 1997, pp. 295–304.

[52] Figures 4.6a and 4.6b were created for the author by architect Roberta Zaccara, to whom I am most grateful, on the basis of Pelletti 1989, Fig.7, and Wilson Jones 2000, Fig. 9.21a. The idea for Figure 4.6a I owe to the architect Hyppolita D'Ayala Valva, whom I thank for showing me drawings from her degree thesis.

[53] Ammianus Marcellinus, *Rerum gestarum libri*, 16.10.14, fourth century AD (trans. J. C. Rolfe, Cambridge 1956).

[54] William L. MacDonald, *The Architecture of the Roman Empire*, vol. 1: *An Introductory Study,* London 1965, 2nd ed. rev. New Haven 1982, p. 109.

and kinematics, and describes lifting equipment for heavy weights on building sites and the straightening of a wall twisted by an earthquake.[55] The heavy weights to be lifted are columns and stone blocks of *opus quadratum,* and so the book is not concerned with constructions using mortar, brick, and caementa. Hero writes with precision, and his work contains a formula relating to inclined planes that was not improved upon until Galileo Galilei.[56] Unfortunately, we do not have an analogous source for the arch and the vault as yet, but Hero gives us an idea of Roman engineering science, which was evidently empirical but neither improvised nor approximate. We also know that Hero wrote a treatise *On Vaulting*, which was the subject of a commentary in the sixth century AD by Isidorus of Miletus, one of the architects of Hagia Sophia.[57] Hero and Isidorus lie at either end of five centuries of written tradition on building vaults.

According to Robert Mark, an important source of Roman engineers' knowledge was the observation of constructional failures – which may have been quite numerous – along with any remedies employed.[58] Theory, therefore, was based on observation of deformation, displacement, and collapse, as in modern limit analysis. Reading Hero, we can appreciate how the concept of statics was based on mechanics and, furthermore, how architectural techniques made use of experience from a variety of other contexts including stone quarries, olive presses, and docks.

The biggest domes in the Roman world apart from the Pantheon have interior spans as follows:

- The Temple of Mercury in Baiae, diameter 21.4 m
- Temple of Venus in Baiae, 26.2 m
- Temple of Diana in Baiae, 29.8 m
- Temple of Apollo at Lake Avernus, 35.5 m[59]
- Caldarium of the Baths of Caracalla, over 35 m.

---

[55] Martines 1998–1999. *The Mechanics* has reached us in its entirety only through copies made by Islamic writers, and it only became accessible after the late nineteenth-century French translation by Baron Carra de Vaux of 1893.

[56] M. Clagett, *The Science of Mechanics in the Middle Ages*, Madison 1959.

[57] Archimedes repr. 2004, trans. Netz, p. 290. See also G. Downey, "Byzantine Architects: Their Training and Methods," *Byzantion* 18, 1946–1948, pp. 99–118; A. Cameron, "Isidore of Miletus," *Greek, Roman, and Byzantine Studies* 30, 1990, pp. 103–127. Probably we can see other clues of Hero's *On Vaulting* in Hero's *Stereometrica*, for which see *Heronis Alexandrini Opera quae supersunt omnia*, vol. V: *Heronis quae feruntur et de mensuris*, ed. J. L. Heiberg, Leipzig 1914 (repr. Stuttgart 1976), pp. 105–119; E. M. Bruins, *Codex Constantinopolitanus Palatii Veteris N.1,* Leiden 1964, pp. 139–147. For a synthesis, see Ousterhout 1999, pp. 70–76. See also Giangiorgio Martines, "Isidore's Compass. A Scholium on Hero's Treatise on Vaulting," *Nuncius* 29, 2014, pp. 279–311.

[58] R. Mark and P. Hutchinson, "The Structure of the Roman Pantheon," *Art Bulletin* 78, 1986, pp. 24–34; Mark 1987.

[59] Guglielmo De Angelis d'Ossat, "La forma e la costruzione delle cupole nell'architettura romana," *Atti del III Congresso Nazionale di Storia dell'Architettura*, Rome 1938, pp. 223–250;

Four of these buildings are located above Capo Miseno, near Naples, in the same volcanic region, from which derived their function as part of thermal complexes. Furthermore, the common constructional feature is that all of these domes are made from light volcanic material.

A most unusual vault is that of the Octagonal Hall in Nero's Domus Aurea.[60] There is no comparison in size with the Pantheon because it has a diameter of only 13.35 meters. Yet it is worth dwelling on the Octagonal Hall because its vault is exceptional in the history of Roman architecture (Fig. 4.8, a, b, c).[61] The rotunda of the Octagonal Hall must have produced quite an effect on its privileged visitors. It was highly unusual in many ways beyond the extensive use of gilding,[62] but what would really have impressed Nero's guests was the way light was scooped in from above. This was something totally unexpected and must have produced great wonder: the walls were empty, whereas in other *rotundae* they were full; there was light where others were dark.

The Neronian vault did not rest on a full drum but on an octagon with solid corners and open walls. The vault is very slender, and where it does thicken toward the base this is not achieved by means of external concentric stepped rings. Despite these differences, some structural elements of the Octagonal Hall of the Domus Aurea are similar to those of the Pantheon. The dome rests on eight piers, which are connected by a system of bipedales, that is, eight flat arches. The crown is lightened by an oculus 5.6 meters wide. Examination reveals that the concrete vault is formed by two different, superimposed, geometrical figures, a calotte on top of a domical vault. In the lower half, eight webs, separated by clearly visible groins over the piers, spring from the eight flat

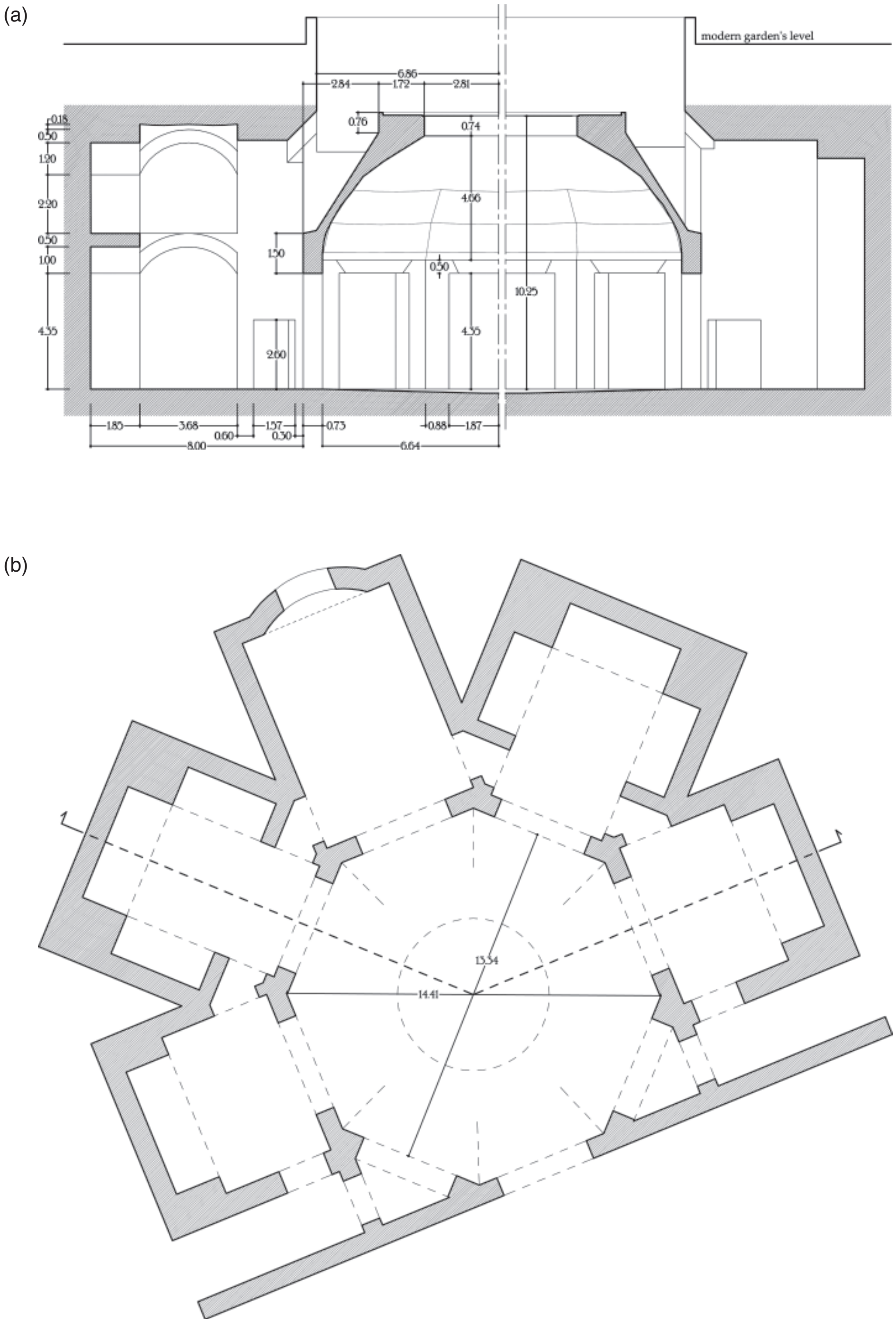
---

repr. in *Realtà dell'architettura. Apporti alla sua storia 1933–1978: Guglielmo De Angelis d'Ossat*, ed. L. Marcucci et al., Rome 1982, pp. 53–77. De Angelis d'Ossat dates the construction of the Temple of Diana to the time of Alexander Severus (222–235 BC). M. Borriello and A. D'Ambrosio, "Baiae-Misenum," *Forma Italiae Regio I,* p. 14, Florence 1979; S. De Caro and A. Greco, *Campania*, Bari 1981; Jean-Pierre Adam, *La construction romaine. Matériaux et techniques*, Paris 1984; Friedrich Rakob, "Römische Kuppelbauten in Baiae. Die Gewölbeprofile," *Mitteilungen des Deutschen Archäologischen Instituts Römische Abteilung* 95, 1988, pp. 257–301.

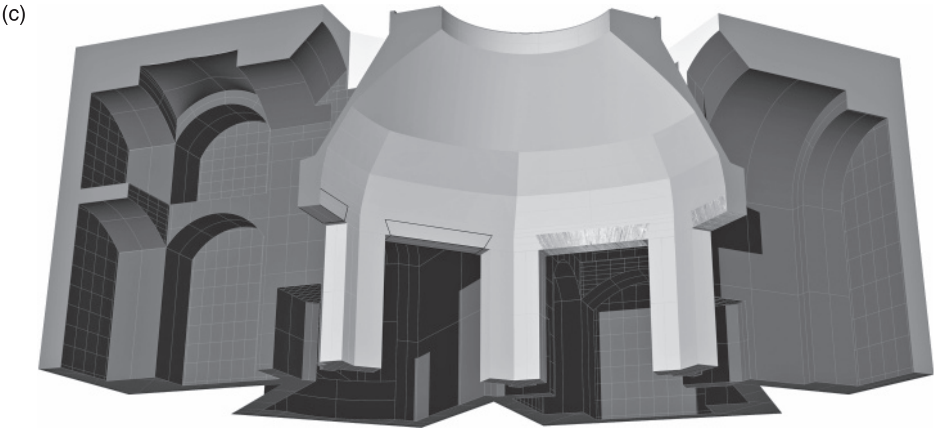
[60] Laura Fabbrini, s.v. "Domus Aurea: il palazzo sull'Esquilino," in Steinby 1995–1999, vol. 2, 1996, pp. 56–63; H. Prückner and S. Storz, "Beobachtungen im Oktagon der *Domus Aurea*," *Mitteilungen Deutschen Archãologischen Instituts, Römische Abteilung* 81, 1974, pp. 323–339; Larry F. Ball, *The Domus Aurea and the Roman Architecture Revolution*, Cambridge 2003, pp. 207–218.

[61] G. Giovannoni, "La cupola della *Domus Aurea* neroniana," *Atti del Congresso Nazionale di Storia dell'Architettura*, Rome 1936, pp. 3–6; Ball 2003, pp. 207–218; Lancaster 2005, pp. 42–43. The three-dimensional model reproduced here was created for the author by Filippo M. Martines, from his original survey, in 2006.

[62] Suetonius, *Nero* 31. See David Hemsoll, "The Architecture of Nero's Golden House," *Architecture and Architectural Sculpture in the Roman Empire*, ed. M. Henig, Oxford 1990, pp. 10–36; Ball 2003, p. 208, p. 218 and fig. 79; Lancaster 2005, pp. 42–43; Giorgio Rocco, "Alcune osservazioni sul valore architettonici dell'antica decorazione parietale: la *Domus Aurea* di Nerone," *Palladio 1*, June 1988, pp. 121–134. Further information is emerging from the ongoing restoration works on the Octagonal Hall under the direction of Cinzia Conti of the Soprintendenza Archeologica di Roma.



4.8. Section (a), plan (b), and model (c) by Filippo M. Martines of Octagonal Hall in the Domus Aurea, Rome. (Drawn for the author in 2005–2006)



4.8 c.

arches. The calotte begins where the groins end. We have already mentioned that the dome of the Pantheon is also made up of two superimposed systems: eight barrel vaults over the third-story ring chambers supporting a calotte with an oculus. Thus the structural idea is similar to that of the Octagonal Hall.

The architects Severus and Celer, *magistri et machinatores*, built the Domus Aurea before AD 68; Tacitus praises their talents: "[T]hey had the ingenuity and the courage to test the force of art even against the veto of nature."[63] Contemporaries said that Nero's architects had surpassed nature in feats of construction, just as Parrasius had done in painting.[64] This marvel was no longer visible by the time the Pantheon was built. In fact, in AD 104 a great mound of earth sealed the *damnatio memoriae* of Nero and his Domus Aurea. But as the architect who, ancient sources tell us, was responsible for creating the Baths of Trajan, the complex that subsumed Nero's Domus into its massive substructures, Apollodorus of Damascus could have seen the renowned octagonal hall. What is more, he would have seen it without the decorations that camouflaged its constructive inventions when the Domus Aurea had been in use. In a highly original study in 1975, Wolf-Dieter Heilmeyer attributed to Apollodorus the design of the Pantheon as well. His hypothesis has found subsequent support and amplification (see Chapter Seven), though we still await definitive proof of it.[65]

---

[63] Tacitus, *Annales*, 15.42 (*The Histories and the Annals*, trans. Clifford Moore and John Jackson, repr. London 1956, p. 279).

[64] Pliny the Elder, *Naturalis Historia*, 35.65.

[65] Wolf-Dieter Heilmeyer, "Apollodorus von Damaskus – der Architekt des Pantheon," *Jahrbuch des Deutschen Archäologischen Instituts* 90, 1975, pp. 316–347. Heinz-Otto Lamprecht, *Opus Caementitium. Bautechnik der Römer*, Düsseldorf 1985, p. 175; Martines 1989; Wilson Jones 2000, pp. 192–193; Alessandro Viscogliosi, "Il Pantheon e Apollodoro di Damasco," *Tra Damasco*

MacDonald has suggested a comparison with another innovative piece of Roman vaulting:

> There is a certain similarity between the structure of the aula of the Markets of Trajan and that of the Pantheon in spite of the basic difference in plan. The abutting tabernae barrel vaults and the gallery arches of the aula appear at the Pantheon in a more complex arrangement, disposed around a central vertical axis.[66]

Nero's Octagonal Hall, the *aula* of the Markets, and the Pantheon share a static concept: central vault equilibrium is produced by a system of barrel vaults and abutments. This concept is different from the great domes of Baiae; it reminds us of the statics of gothic cathedrals. However, arches of bipedales in Roman vaults are not autonomous ribs but, as we have seen, are embedded in the concrete.[67]

Apollodorus's best-preserved work is Trajan's Column, the structure of which may be attributed to him as part of his authorship of Trajan's Forum as a whole.[68] The Column and the Pantheon are very different, yet they have similar characteristics. Firstly, they are gigantic, the biggest examples of their kind. Apollodorus's experience of large-scale structures also included authorship of Trajan's renowned bridge over the Danube.[69] The Column and bridge set two world records in vertical and horizontal dimensions.[70] The bearing structure of the Column is, like the drum of the Pantheon, a diaphragm (Fig. 4.2).

Both monuments are gigantic constructions with tiny passages (the spiral in the Column, the honeycomb in the drum). This relationship (giant building/tiny space) is mentioned in the *Poliorketica*, Apollodorus's treatise on siege warfare, in a passage describing the excavation of niches to undermine enemy walls.[71] Finally, with its height of approximately 130 Roman feet, without the

---

e Roma: L'architettura di Apollodoro nella cultura classica, ed. Festa Farina et al., Rome 2001, pp. 156–161.

[66] MacDonald 1965, 2nd ed. rev. 1982, pp. 108–109.

[67] J. Durm, *Die Baukunst der Etrusker. Die Baukunst der Römer*, Stuttgart 1905; Bianchi 2000; Lancaster 2005, pp. 86–112.

[68] F. Lepper and S. Frere, *Trajan's Column, a New Edition of the Cichorius Plates*, Gloucester 1988; S. Settis, A. La Regina, G. Agosti, and V. Farinella, *La Colonna Traiana*, Turin 1988; S. Maffei, s.v. "Forum Traiani: Columna," in Steinby 1995–1999, vol. 2, Rome 1996, pp. 356–359; Martines 2000b, pp. 19–88; Martines, ed., *Colonna Traiana. Corpus dei disegni 1981–2001*, Rome 2001.

[69] Dio Cassius, 68.13; G. G. Tocilescu, *Fouilles et recherches archéologiques en Roumanie,* Bucarest 1900, pp. 140–141; D. Scagliarini Corlàita, "Per un catalogo delle opere di Apollodoro di Damasco, architetto di Traiani," *Ocnus – Quaderni della Scuola di Specializzazione in Archeologia* 1, 1993, pp. 185–193; A. S. Stefan, *Le guerres daciques de Domitien et de Trajan. Architecture militare, topographie, images et histoire,* Rome 2005, pp. 641–642. See also Chapter Seven in this volume.

[70] Martines 2000b.

[71] Apollodoros, "Poliorketica," 143.6–145.6, in *Griechische Poliorketiker*, ed. Rudolf Schneider, Berlin 1908, pp. 14–15; G. Commare, "La Poliorcetica di Apollodoro: traduzione," *L'arte dell'assedio di Apollodoro di Damasco,* ed. Adriano La Regina, Rome 1999, pp. 51–77; Martines 2001, pp. 20–30.

statue,[72] the Column would fit neatly into the Pantheon, with its clear height of 147 feet. These observations are no proof for attributing the Pantheon to Apollodorus but they are indicators. Two very different buildings use similar ideas. The architect of the Pantheon was certainly closer in artistic sensibility to Trajan's era than Hadrian's, and he must have seen the great construction sites at the beginning of the second century AD: the dome of the Venus' Temple in Baiae, and Trajan's Forum and Baths in Rome. On the basis of these indications, it may be assumed that he belonged to Apollodorus's circle if he were not indeed Apollodorus himself.

BENEATH THE PLASTERWORK OF THE DOME

Plaster covers the inside surface of the dome of the Pantheon, while the outside is protected by a dressing of lead that replaced the original system of bronze tiles. Unlike that of many other ancient domes, which lie in ruins, its structure cannot be directly observed. We must therefore rely on data from previous inspections to an even greater degree than for the drum, many parts of which are still accessible today.[73]

The earliest document we have is a drawing, U 69A, by Antonio da Sangallo the Younger, which shows a section of the Pantheon on the right, while on the left there are studies for Villa Madama and, below, for St. Peter's.[74] Antonio's interest in the construction of the Pantheon evidently sprang from his concerns for the building of St. Peter's, in which he had been involved since 1507, some years before he made this drawing. The study of the Pantheon highlights two important high-level structural elements, relieving arches at the internal springing of the dome and bonding courses (of bipedales) capping the arches.

Another valuable, if problematic, source of information is the set of drawings by Francesco Piranesi, mentioned earlier, that was based on the surveys

---

[72] The height of Trajan's Column from the bottom to the top of the original marble structure is 38.57 meters; see Martines 2000b, p. 75, Plate 1. The ancient statue of the emperor is missing: cf. Martines 2000b, pp. 64–68; Wilson Jones 2000, Chap. 8.

[73] In 1929–1934, Alberto Terenzio directed an important restoration of the entire monument, with direct observation of the extrados under the lead roof, which revealed the layer of *opus signinum* for waterproofing. In ancient times, the dome was further lined with bronze and perhaps gilded tiles, but these were removed by Costans II in 663 and then taken by Saracens; see P. Tomei, "Le vicende del rivestimento della cupola del Pantheon," *Bollettino d'arte* 32, 1938, pp. 31–39; Licht, 1968, p. 136. All that remains of the bronze are the plates forming the ring round the oculus, which are certainly from Hadrian's time. Furthemore, the dome's lowest step-ring still has 34 marble tiles in situ, see Lucos Cozza, "Le tegole di marmo del Pantheon," *Città e architettura nella Roma imperiale: atti del seminario del 27 ottobre 1981 nel 25° anniversario del Accademia di Danimarca*, Odense 1983, pp. 109–118.

[74] C. L. Frommel and N. Adams, eds., *The Architectural Drawings of Antonio da Sangallo the Younger and his Circle*, vol. 2, New York 2000, pp. 90–91.

made with his father, Giovan Battista. In the lower third of Piranesi's plate reproduced here as Fig. 4.7, on the left, the perspectival drawing is entitled "Dimostrazione dell'ottava parte della cupola, come si vede quando fu spogliata dell'antica intonacatura" (an eighth part of the dome viewed without the ancient plasterwork). The arches depicted at the bottom are the same as those drawn by Antonio da Sangallo the Younger. Above them Piranesi drew a system of ribs and compartments, which would have numbered eight in all. This engraving by Piranesi conditioned subsequent studies and publications on the Pantheon for over a century, but the web of arches above the first row is mere conjecture. As a matter of fact, subsequent inspections confirmed only the existence of the arches drawn by Sangallo. Piranesi's web reflected the building techniques of the 1700s but not the dome of the Pantheon.

In 1892–1893, the Italian government commissioned repair work to "some coffers near the springing of the dome, on the right of the main altar."[75] Scaffolding was installed up to eight meters above the level of the springing of the dome. In charge of operations were Giuseppe Sacconi and Luca Beltrami. The French architect Chedanne was given permission to make sketches of the dome from the scaffolding.[76] Beltrami discovered that the arches at the springing of the dome do not follow its spherical curvature but rise vertically. In fact, he made an opening for inspection in the concrete at the level of the second row of coffers. He found the brick key of the arch one and a half meters from the surface of the recessed central field of the coffer (Fig. 4.9).[77] In addition, he discovered 1) that the arches are built with two rings of bipedales; 2) that under each arch there are three minor arches, corresponding to the spacing between the Corinthian columns far below; and 3) that there are no other arches in the dome or ribs of the kind that Piranesi envisaged.[78]

Photographs show the ribs of the coffers without the plasterwork. Some are faced in brick, others appear to be concrete, but this aspect does not seem to have been adequately investigated (the brick may be modern). To return to the drawing on the bottom right of Piranesi's plate (Fig. 4.7), this shows a detail of the ring of bricks around the oculus. The bipedales are not arranged vertically but into flat arches. The veracity of this document has been confirmed by modern inspections and photographs, and a schematic drawing by Guglielmo De Angelis d'Ossat shows eight flat arches in all.[79] The oculus of

---

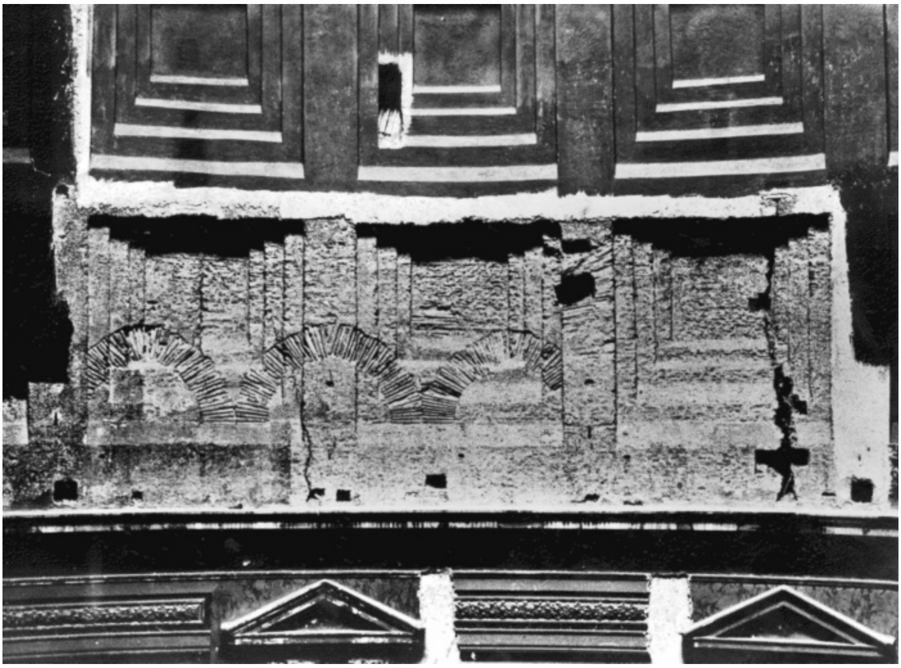
[75] Luca Beltrami, *Il Pantheon: La struttura organica della cupola e del sottostante tamburo, le fondazioni della rotonda, dell' avancorpo, e del portico, avanzi degli edifici anteriori alle costruzioni adrianee. Relazione delle indagini eseguite dal R. Ministero della Pubblica Istruzione negli anni 1892–93, coi rilievi e disegni dell' architetto Pier Olinto Armanini*, Milan 1898, p. 17.

[76] Beltrami 1898, p. 17. See also P. Ciancio Rossetto, G. Pisani Sartorio, F. C. Uginet, eds., *Roma Antiqua, "Envois" degli architetti francesi (1786–1901). Grandi edifici pubblici,* exhib. cat., Rome 1992, pp. 124–130.

[77] Beltrami 1929, pp. 23–24.

[78] Beltrami 1898, p. 71.

[79] De Angelis d'Ossat 1938.



4.9. Detail of dome intrados at the springing with plaster knocked off, 1892. (American Academy in Rome, Fototeca Unione, no. 3595)

the Tempio della Tosse in Tivoli has a similar arrangement; here, the flat arches push against each other with the springer bricks embedded like ribs in the concrete shell.[80]

The oculus was a structural device, too. Its rigid perimeter ring of bipedales acts like a boss in a vault or the keystone in an arch, except that in being a void, it simplifies the difficult problem of building the crown. Indeed, it replaces a stretch of vault 9.1 meters wide. Thus, the critical part of the dome is reduced to the portion from the top of the third story to the edges of the oculus (see Plate XI and Fig. 1.12).[81]

To conclude, investigation carried out under the plasterwork of the Pantheon dome has revealed a series of eight relieving arches resting on the exedrae; they rise vertically rather than following the curvature of the dome and are embedded in the concrete vault. These arches are actually the faces of the barrel vaults that cover the ring of chambers of the third story of the drum (Figs. 4.5 and 4.6). The tops of the arches rise to 8.4 meters above the springing of the dome. So the dome is embedded in the drum for almost 40 percent of its height, taken from the springing to the oculus. A further 25 percent of the height is

---

[80] Giuliani 1970; Bianchi 2000.

[81] For further detail see Giangiacomo Martines, "The Structure of the Dome," in Grasshoff, Heinzelmann, and Wäfler 2009, pp. 99–105; Pelletti 1989; Beltrami 1898; Alberto Terenzio, s.v. "Pantheon," *Enciclopedia Italiana* 26, 1949, pp. 212–214; Licht 1968; Martines 1989.

masked on the exterior by the step-rings, and only from above that level does the dome correspond to a simple calotte. The dome embedded in the diaphragmatic drum was the architect's trick.

MATERIALS

As in most construction in Rome, the mortar used is a mixture of lime[82] and *pozzolana*. This is a volcanic powder named after the town of Pozzuoli, between Naples and Baiae, while a similar material can also be found in Rome itself.[83] Vitruvius describes its exceptional qualities:

> There is also a type of powder that brings about marvellous things naturally. It occurs in the region of Baiae and in the countryside that belongs to the towns around Mount Vesuvius. Mixed with lime and rubble, it lends strength to all the other sorts of construction, but in addition, when moles [employing this powder] are built into the sea, they solidify underwater.[84]

Concrete made with pozzolana can cure without drying, even in water and in the absence of air. It is perfect, therefore, for walls of great thickness. To the mortar are added types of aggregate, such as brick fragments, tufa, and volcanic slag. On the basis of detailed inspections by Gioacchino De Angelis d'Ossat and other scholars, we know this material to be graded carefully for the sake of performance,[85] as illustrated in Figure 1.12 and summarized in words by Kjeld De Fine Licht:

> Up to 11.75 metres above the level of the springing the cupola is composed of layers of brick fragments set in mortar. Six through–courses of *bipedales*, which slope 1 in 10 inwards are set in this zone at irregular intervals. The unit weight of the mass of concrete is calculated to be about 1600 Kg/m^3. Above this there is a belt 225 cm high which at the top and bottom is delineated by courses of *bipedales*, and in this belt the layers of brick alternate with layers of tufa. In that section about 9 m high which makes up the top part of the cupola, there are alternating layers of light tufa and volcanic slag in blocks about 20 cm in size, the unit weight being 1350 Kg/m^3. … The thickness of the cupola is reduced from about 590 cm at the foot to nearly 150 cm at the top.[86]

---

[82] According to Pliny the Elder lime was best after maturing for three years (*Naturalis Historia* 36.173). See also C. Conti, G. Martines, and C. Usai, "Gli interventi di conservazione su materiali e superfici," *Trattato di restauro architettonico vol. III*, ed. Giovanni Carbonara, Torino 1996, pp. 199–205.

[83] D. Moore, *The Roman Pantheon: The Triumph of Concrete*, Wyoming 1995.

[84] Vitruvius, 2.6.1.

[85] Guglielmo De Angelis d'Ossat, "Le rocce adoperate nella cupola del Pantheon," *Atti della Pontificia Accademia della Scienze, Nuovi Lincei* 83, 1930, pp. 211–215. Cf. Lamprecht 1985.

[86] Licht 1968, pp. 134–136. See also Terenzio 1949; Lamprecht 1985, p. 176.

The distribution of the materials is an expression of a conscious and rational arrangement. The heavier brick and tufa with a greater resistance to stress is placed at the foot of the dome. Above this follow layers of filling of increasing lightness: *Cappellaccio*, *tufo giallo*, pumice, and volcanic slag.[87] Volcanic slag (or scoria), such as is used in the vaults of the Baths of Caracalla, is a light material that at first floats if immersed in water since it contains air pockets. The judicious use of volcanic slag reflects the building traditions of Baiae and its great domes. The benefits of this approach are threefold: 1) the weight of the material lessens as the structure rises; 2) this reduces compression on the underlying layers, and 3) this produces less thrust.[88]

MASONS' CRITERIA

In traditional Italian terminology, "*volta romana*," that is, Roman vault, means a vault filled with masonry from the intrados to the crown. This construction technique is completely different from that of medieval or Renaissance vaults, where the abutment is not made of concrete masonry but simple earth or rubble and the structure formed by voussoirs, or wedge-shaped stones. In medieval and Renaissance vaults, the stones are, as a rule, arranged radially on a centering, so that each row of stones forms an arch or rib. The mass of earth filling on the extrados helps stability. On the other hand, in Roman concrete vaults, a radial alignment of aggregate in sympathy with the curvature is rare. It is found in the dome of the Temple of Mercury in Baiae,[89] the barrel vaults of the Sanctuary of Fortuna Primigenia in Praeneste, and the Temple of Hercules in Tivoli.[90] The stones, or caementa, of Roman vaults are generally arranged in horizontal layers, even where they run up against the centering. This is the case in the original vaults on the radial *cunei* of the Colosseum, in the Domus Aurea, and in many other ruins.[91] For us today, this arrangement seems illogical because the caementa do not follow the curvature or the stress flow. The method is, in fact, more reminiscent of corbeling techniques, as noted by Gustavo Giovannoni:

---

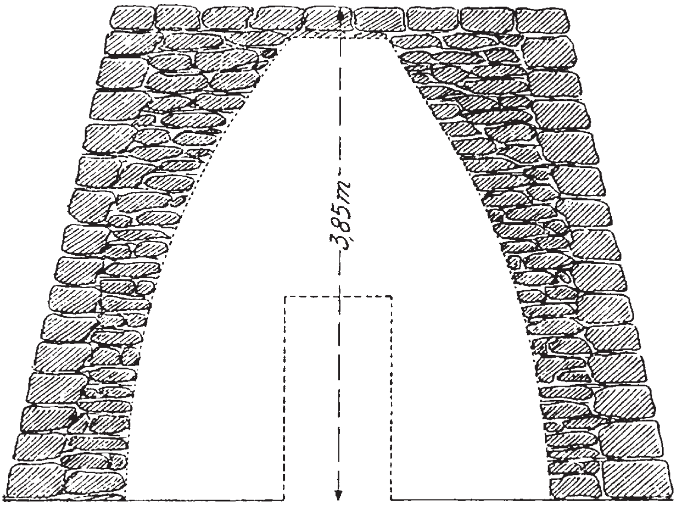
[87] Moore 1995; Lancaster 2005.

[88] Lamprecht 1985, p. 176.

[89] De Angelis d'Ossat 1938, p. 227; De Caro and Greco 1981, p. 58.

[90] The latter is a very rare example of filling abutments on the extrados with earth. For this observation, I am indebted to Professor Cairoli Fulvio Giuliani, during restoration work on the "Tempio della Tosse" in Tivoli, carried out in the summer of 2001 by the engineer Fabio Taccini under the direction of the architect Stefano Gizzi.

[91] Giuseppe Cozzo, *Ingegneria Romana: maestranze romane; strutture preromane, le costruzioni dell' anfiteatro flavio, del Pantheon, dell'emissario del Fucino*, Rome 1928; see also Lancaster 1998, pp. 147–174; Lancaster 2005.



4.10. Section through a *casiddu* near Santa Cesarea Terme, Puglia. (Gerhard Rohlfs, *Primitive costruzioni a cupola in Europa*, Florence 1963, Fig. 4)

> As a construction concept, a vault of horizontal concrete layers … is far removed from a voussoir vault of cut stone. Indeed, it seems to bear greater resemblance to the Mycenaean false dome, made with horizontal stones, that is, by corbelling layers inwards like cantilevers on rings below.[92]

Studies by Rowland Mainstone come to similar conclusions.[93] The principle of corbeling can be seen in certain types of vault indigenous to the Mediterranean. In Apulia, in southeast Italy, the *casella*,[94] or *casiddu* (Fig. 4.10), is a kind of beehive house "built of rough stones set in projecting courses to form a dome."[95] Similar shelters are also found in Liguria, the island of Minorca, and the Basque region.[96] The *casiddi* and the *trulli* in Apulia go back to the sixteenth century and are built without any mortar. But the tradition goes back to former times. Another very ancient building type similar to the casiddu is the cyclopean nuraghe, built in Sardinia from circa 1800 BC until ancient Roman times.[97] Aristotle mentions such constructions in a minor work entitled *On Marvellous*

---

[92] G. Giovannoni, *La tecnica della costruzione presso i Romani*, Rome 1925, p. 42.

[93] Rowland Mainstone, "Le origini della concezione strutturale della cupola di Santa Maria del Fiore," *Filippo Brunelleschi. La sua opera e il suo tempo. Atti del Convegno Internazionale per il sesto centenario della nascita, 16–22 Ottobre 1977*, Florence 1980, pp. 883–892.

[94] G. Rohlfs, *Primitive Kuppelbauten in Europa*, Munich 1957; G. Simoncini, *Architettura contadina di Puglia*, Genoa 1960; E. Allen, *Stone Shelters*, Cambridge, Mass. 1971; P. Oliver, ed., *Encyclopedia of Vernacular Architecture of the World*, Cambridge 1997; L. Lago, *Pietre e paesaggi dell'Istria centro-meridionale. Le "casite,"* Trieste 1994.

[95] J. Fleming, H. Honour, and N. Pevsner, *The Penguin Dictionary of Architecture and Landscape Architecture*, London 1999, p. 47.

[96] Oliver 1997.

[97] Massimo Pallottino, *La Sardegna nuragica*, Rome 1950; see also G. Lilliu, *La civiltà nuragica*, Sassari 1982; Franco Laner, *Accabadora. Tecnologia delle costruzioni nuragiche*, Milan 1999.

4.11. Nuraghe "Is Paras," near Ìsili, Sardinia, detail of corbeled dome. (Photo author)

Things Heard: "In the island of Sardinia they say that there are many fine buildings arranged in the ancient Greek style, and among others domed buildings (Greek *tholos*), carved with many shapes."[98]

The largest nuraghe corbel vault, Is Paras (fifteenth century BC) located in Isili near Barúmini, has a span of 6.4 meters and a height of 11.8 meters, and inside the corbel vault is made by 37 rows of rough stones (Fig. 4.11). It is reminiscent of the "Treasury of Atreus" in Mycenae, a *tholos* of the Greek Bronze Age (thirteenth century BC), except that this has a far greater extension: a 14.5 meter span and a height of 13.2 meters, while inside the false dome is constructed by 33 rows of much larger hewn blocks. In terms of size, this bears comparison with the domical vault of the Octagonal Hall, which spans 14.40 meters at the diagonal and rises 10.25 meters on the extrados. Tholos-type structures can also be seen in other Mediterranean lands and civilizations. The stonework of the Etruscan "Tomba dei Carri" in Populonia (seventh century BC) is quite remarkable.[99]

Just as props and centering were not needed to construct any of these structures mentioned, the same could be the case for the lower portions of the dome of the Pantheon. Here, the horizontal layers of mortar with tufa and brick fragments were built up as a series of corbels in structural terms, while the profile would probably have been defined by a system of wooden boards

---

[98] Aristotle, "De Mirabilibus Auscultationibus," *Minor Works*, fourth century BC, trans. W. S. Hett, Cambridge 1955, p. 281.

[99] For the "Tomba dei Carri," see S. Di Pasquale, *L'arte del costruire*, Venice 1996, pp. 229–237.

tied back to the intrados. There was no need for solid props beneath for this, the lower part of the dome.

To be more specific, the method of progressive corbeling, without props, would have encompassed an angle of approximately 40 degrees to the center of the sphere (see Fig. 7.4), that is to say, up to a height of 14 meters from the springing of the cupola, with an overhanging span of more than 5 meters or so.[100] Since the oculus did away with any structure for the central portion of the dome, only the "doughnut-shaped" portion that lies inside the step-rings would have been built on solid scaffolding centering. In this area, the slope of the dome becomes impracticable for corbeling, while the mixture of volcanic slag, yellow tufa, and pumice cannot exercise thrust before the mortar has completely dried and set. The calotte requiring centering thus measures a rise of 7.4 meters and a span of 12.2 meters. Leaving aside proposals for flying centering favored by Eugène-Emmanuel Viollet-le-Duc,[101] Jean Pierre Adam, and others (see Fig. 7.3),[102] Licht concludes that "only the topmost part of the cupola presumably required a more extensive scaffolding".[103] This view was held by De Angelis d'Ossat and more recently by Lamprecht and Lancaster;[104] Gene Waddell, Mark Wilson Jones, and I are all in agreement on this point. In his recent book on the Pantheon worksite, Gerd Heene comes to similar conclusions.[105]

What relationship is there, then, between the false dome of a casiddu, or ancient beehive house, and the dome of the Pantheon? Is one the forerunner of the other, preserving traces of its genetic heritage? This relationship can better be illuminated by applying Claude Lévi-Strauss's famous comparison of "the engineer and the *bricoleur*" in *La pensée sauvage*.[106] Enrico Comba outlines Lévi-Strauss's concept:

> A bricoleur is a person who can use whatever is at hand to produce something that serves a purpose. Unlike an engineer, he does not have to use specific raw materials or expressly conceived instruments to carry out a task. . . . 'La pensée sauvage' (The savage mind) is not primitive or archaic

---

[100] The third-story drum-barrel vaults are embedded in the dome for up to 8.4 meters from the springing of the dome, halfway up the second row of coffers. At the end of the barrel vaults, the intrados project 1.8 meters from the springing.

[101] Eugène-Emmanuel Viollet-le-Duc, s.v. "Voute," *Dictionnaire raisonné de l'architecture française du XI° au XVI° siècle*, Paris 1875, vol. 9, pp. 471–474.

[102] Adam 1984. Rakob 1988, pp. 280–281, disputes Adam's proposal for the Temple of Mercury at Baiae; see also Taylor 2003, pp. 190–211, and Lancaster 2005, pp. 44–45.

[103] Licht 1968, p. 141.

[104] De Angelis d'Ossat 1938; Lamprecht 1985, pp. 174–177; Lancaster 2005.

[105] G. Heene, *Baustelle Pantheon: Plannung, Konstruktion, Logistik*, Düsseldorf 2004, p. 57. In Heene's view, pp. 28–32, four rings of coffers were built by corbeling whereas, in my opinion, just three were built so. According to Mark 1987, p. 146, the coffering lightens the structure by less than 5% of the total mass of the dome.

[106] C. Lévi-Strauss, *La pensée sauvage*, Paris 1962, pp. 25–27.

> nor does it correspond to a rudimentary state of scientific thought, but is parallel to it. These two forms of thought often coexist and differ only in the way they apply data deriving from experience to build an ordered coherent system of things.[107]

Modern studies on the statics of vaults have distanced us from "the science of the concrete," to use another expression of Lévi-Strauss.[108] As far as vaults are concerned, this came about during the Enlightenment when a distinction started to develop between intellectual science and "concrete science." In Roman architecture, this "concrete science" was a combination of refined design, of which we have some knowledge of principles,[109] and the empiricism of bricklayers, the cognition of which we have lost through lack of experience. Roman construction is a wonderful example of this marriage between the engineers and the bricoleurs.

---

[107] E. Comba, *Introduzione a Lévi-Strauss*, Bari 2000, pp. 82–85.

[108] Lévi-Strauss 1962, p. 25.

[109] Wilson Jones 2000.