Constructions Techniques of Roman Vaults: Opus Caementicium and the Octagonal Dome of the Domus Aurea

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ABSTRACT: Opus caementicium represented a revolution in the history of construction since it allowed Roman vaults to span large areas thanks to the use of innovative structural solutions. A significant example is the vault covering the Octagonal Hall of the Domus Aurea: the lower part starts as a domical vault, while the upper part is a hemispherical calotte ending at the oculus. What is unusual is that the Octagonal Hall is characterized by empty spaces where other rotundae are supported by full walls, and has radial rooms full of light where other rotundae are dark. The aim of this paper is to analyse, illustrate and discuss the construction techniques used to build the octagonal dome of the Domus Aurea, focusing on the innovative used in combining the various elements in a way that guaranteed mechanical behaviour resistant to compression.

INTRODUCTION

From 2006 to 2008 we were lucky enough to have the opportunity of observing the vault of the Octagonal Hall from close range during the restoration directed by the first author of this paper. The paper details the observations that have so far been made on the construction and static behaviour of the octagonal vault and the structural elements connected to it. The last detailed analysis had been conducted in 1934 by students of the Istituto Superiore di Architettura headed by Gustavo Giovannoni, who presented the study in the first History of Architecture Conference in 1936.

The chance to observe at close range the great monuments of ancient Rome, such as the Colosseum and Trajan’s Column, comes once or twice a century, when scholars can view the ancient monuments from the perspective of the scientific progress of their own era, something that has been going on since the time of Piranesi.

The observations we have made on the construction, carried out meticulously at close range from the scaffolding used for restoration, and the extremely detailed - and to some extent new - analysis of the static behaviour follow on from the studies of De Angelis d’Ossat 1938, Zander 1958, Ward Perkins 1974, MacDonald 1976, Ball 2003, Martines 2003 and Lancaster 2005.

For restorers and engineers the vault of the Octagonal Hall is a marvel because it is so slender, being only about 20 cm thin at the thinnest point, and completely undamaged after more than 1930 years of life.

In Nero’s time the vault must have aroused wonder because it revolutionized the architecture that came before it. Where we marvel at the structural innovation and longevity of the structure, the ancients were amazed by the then completely new aesthetic conception. Nero’s guests would have gazed in amazement as they entered a circular room with a vaulted ceiling that had no perimeter walls (Fig. 1).

From the ground, the vault starts as an octagonal prism with full corners and hollow faces; the eight supporting pillars are linked by an equal number of flat arches, built using square bricks (two feet across, thus called bipedales). Larry Ball likens the flat arches to “a spider’s web” because they are so exceptionally slender and long (Ball 2003, p. 218). Above them is a domical vault with eight cells.

In the survey of the vault carried out by Giovannoni, it is shown as a cloister vault right up to the oculus at the top; however, as we shall see, the vault can be interpreted as two vaults on top of each other, the lower part
octagonal and the upper part a semicircular calotte, joined together in a way that serves both a constructive and structural purpose. The dome was built in opus caementicium, a concrete cast of mortar and tufa. The groins of the domical vault can be seen easily and end high up where now there are large holes made by thieves. The intrados surface shows the negative of the formwork: from the impressions left by the wooden boards we can clearly make out the two parts of the vault (Fig. 1, left). Another aspect, which is still a source of wonder today, is the light that pours in from the extrados of the dome: whereas all other rotundae are dark because of the presence of steps, in the Octagonal Hall the light caresses the extrados and comes in through the hollow faces of the octagonal prism (Fig. 1, right). The light descends into the five rooms that surround the Octagonal Hall through the clerestory windows, placed on the perimeter of the vault, where other Roman vaults have steps, such as the Pantheon.

In 104 A.D. the Emperor Trajan began the construction of the Baths on the Colle Oppio, just above the Domus Aurea. The Domus was covered with earth and rapidly all traces of it were lost: this was the damnatio memoriae of Nero. The sculptures, marble lining and everything that could be taken away from the Domus were appropriated; what remained were the frescos that were rediscovered by the Humanist painters. In the Middle Ages the baths fell into ruin and became grazing land and vineyards. Renaissance painters lowered themselves down through cracks in the ruins and copied the paintings, which they called “grotesques” (Dacos 1969). The Laocoon group, now in the Vatican Museums, was part of Nero’s collections, discovered in the Octagonal Hall in 1506 during digs in a vineyard (Settis 1999).

Tacitus (Annales, 15, 42-43) has handed down the names of the designers of the Domus Aurea: the “architects and engineers – magistri et machinatorae – were Severus and Celer, who had the genius and the audacity to attempt by art even what nature had refused, and to fool away an emperor’s resources”.

In effect, the Octagonal Hall seems to fool away the weight of the opus caementicium, namely it seems to overcome the forces of gravity through flat arches as slender as a spider’s web: this is the topic of the next part of our report.

SURVEY OF THE DOMUS AUREA DOME

The vault of the Octagonal Hall can be seen in its bare form, stripped of any decorative elements: but how was it decorated? Frescos or mosaics? Because of the way the light comes in, through the oculus and reflected by the surrounding rooms, Ball came up with the fascinating hypothesis that it was lined with sparkling mosaics. However, we can immediately anticipate one of the observations made during restoration work: the surfaces of the vaults show no trace of decoration or any material other than the opus caementicium used for the structure. The impressions left by the formwork, in part very well preserved, show no sign of any other material apart from the earth used to fill the site in Trajan’s time. However, other traces are to be found on the formwork, which we shall discuss here.

The impressions left by the boards clearly show how the dome was transformed from the octagonal shape at the bottom to the circular shape of the calotte. The wooden boards were placed along the parallels of the dome, the length changing as the height increased until they became of equal size at the top.

From the constructive perspective, the geometrical solution linking the domical vault to the hemispherical calotte was to place over the groins of the cells another eight cell sections of increasing width (like half sections of an orange), so that the octagon is transformed into a sixteen sided polygon, approximating the form of a circumference (Fig. 2): at this level, we can see that the formwork was of a very rough quality compared to the rest of the building. From the structural point of view, the larger eight sections surrounding the groins of the
cells (Fig. 2) and extended to the circumferential base of the calotte are like “squinces”, architectonical elements that connect two vaults of different sections. A geometry professor would have given the architect a fail for such a rough and ready solution to a geometric problem; however, the perfection of the oculus, consisting of 355 carefully shaped bipedales, attracts our attention so that we perceive only the octagon below and circumference high up.

Figure 2: Octagonal Hall: Model and static scheme. The flow lines along the emispherical surface pass over the space above the sides of the octagon; (from a model by F. Martines 2005)

The wooden boards of the formwork were nailed to the centring near the joints. The iron nails used were the traditional clavi muscarii (Vitruvius, De Architectura, 7, 3. 11), or umbrellati, also described by Pliny (Naturalis Historia, 12, 127). Where the groins of the domical vault end high up, there are large holes made by thieves. At the bottom of one of these, between cells 1 and 8, we have seen and surveyed an impression left by a large bar of metal over 24 cm long and 4 cm wide, with another impression, the shape of a buttonhole, in the middle; similar impressions can also be seen, albeit discontinuously, in other cavities. The rectangular impressions and the buttonholes are the negatives of a metal object used as a point of suspension along the vault.

A reading of Latin sources for the Domus Aurea allows us to formulate a hypothesis. Suetonius (Nero, 31) describes Nero’s furnishings: “dining rooms with ceilings inlaid with ivory were made to revolve, and there were holes through which flowers and perfume could rain down; the main hall was circular and revolved perpetually, night and day, in imitation of the motion of the celestial bodies”. Thus, according to the sources, the ceilings were not decorated with frescoes but lined with beautiful false ceilings in wood and other precious materials; in addition, the use of wood allowed for mobile ceilings and revolving floors. Perhaps the eight large suspension hooks supported a sumptuous false ceiling, taken away during the looting which took place in Trajan’s time.

The apparent bearing scheme

Observed from the intrados the dome of the Domus Aurea it is like a structural trompe-l’œil: it is built entirely in opus caementicium and in horizontal layers; it apparently starts as an octagonal domical vault, resting on thin flat arches linking the eight supporting pillars, and ends up as a hemispherical calotte. Its thickness, perceptible only at the level of the flat arches and the height of the oculus, appears to be constant. However, when the vault is seen from the radial chambers, we see that the extrados above the flat arches extends along an inclined plane: this incline allows the light from the splayed windows to illuminate the rooms that extend radially beyond the lunettes of the vault. The surface of the extrados leads us to assume that the thickness is not constant: it must decrease as it moves from the flat arches up to a height where it is at its thinnest and then increase again as it rises to the height of the oculus.

An architectonical survey of the Octagonal Hall was carried out for the authors by Filippo Martines. The main aim of the survey was to identify the thickness and bearing elements of both the vault and walls around the Octagonal Hall. The W-E longitudinal section of the dome is shown in Fig. 2, which confirms the law of thickness variation along the meridian crossing the middle of the flat arches. A new important piece of information provided by the survey is that the intrados outline is a polygon, initially vertical, then oblique up to where the vault is at its thinnest; then the intrados forms a sort of circle arc that extends to about 30° latitude (Fig. 3.b), the thickness increasing until it reaches the oculus.
But is it possible for a dome to infringe the law of decreasing thickness from the springing to the top? The jutting out groins of the cells cannot support, at their thinnest point, the hemispherical calotte, which in turn is characterized by a law of decreasing thickness from the top to the haunches.

If the thickness of the vault were constant, in accordance with the shell theory, the steady incline of the domical vault and the reduced extension of the spherical calotte would guarantee compression both along the meridians and the parallels; however, this analysis would need to take into account infinitesimal dome elements delimited by two adjacent meridians and two parallels corresponding to a radial layout. But the vault of the Octagonal Hall is built in opus caementicium, by means of a series of horizontal casts arranged in such a way as to form a dome.

**VAULTS, PSEUDO-VAULTS AND OPUS CAEMENTICUM.**

Gustavo Giovannoni likens vaults in opus caementicium to the false domes of the Mediterranean’s protohistoric period:

> The system of concretion used to build a vault in horizontal layers, like an artificial monolith, is much removed in conception from the constructive technique of wedges of cut stone, and would appear to be more similar to the Mycenae pseudo-vault of shelf-like projecting horizontal stones or rings placed one on top of the other (Giovannoni 1925, p. 42).

The stability of the false-dome is guaranteed by the great thickness of the perimeter walls and the regularity of the construction, while during construction the equilibrium of the structure, consisting of horizontal layers of stones arranged in a circular fashion, is characterized by the absence of radial thrust since, thanks to the thickness, at any given height along the meridians of the structure, the resultant of the above weight is contained at the base.

The comparison, therefore, is appropriate for vaults that have a thickness similar to the extension of the covered space, such as the annular barrel vaults of the Colosseum. The question is: can we use the same comparison for such a daring vault as the Octagonal Hall of Nero’s Domus Aurea?

In terms of constructive technique the pseudo-vault is very similar to that of opus caementicium, with two differences: the absence of mortar and the absence of radial thrust (Sinopoli, 2008).

The mortar used in opus caementicium is a mixture of water, pozzolana as aggregate, and slaked lime as binder (Conti; Martines 1996, Lancaster 2005, pp.51-53). It is the pozzolana that transforms the opus caementicium into a quasi-continuum which has also a limited resistance to tensile stresses and bending moments; it is not necessary, in vaults and domes, for the elements to be ideally arranged, i.e. radially, as is typical for materials that have no tensile strength. Despite the characteristics of cohesion and adhesion guaranteed in opus caementicium by the ageing of the slaked lime and the hydraulicity of the pozzolana mortar, it seems that the Romans did not have much confidence in the tensile strength of the resulting structure; the constructive solutions adopted in almost all opus caementicium structures seem to indicate, as is the case analyzed here, that the aim was to guarantee compression, as if the material did not have tensile strength.

What is sure is that the switch from a radial arrangement of the elements used in the construction of arches and vaults (such as those of the radial rooms of the Octagonal Hall in Fig. 1) to the horizontal layout typical of the caementa in opus caementicium is in line with the principle of economy and industrialization of the constructive process: the advantage of using stone chips (caementa) instead of bricks, and the need to arrange it...
in a regular manner to ensure homogenous mechanical behavior in all directions, meant that that construction had to be in layers, the thickness of which depended on the working day. Opus caementicium therefore revolutionized construction technique, ensuring rapid work and on site savings; separate layers are piled horizontally in a way that is very similar to that adopted in the construction techniques of the proto-Mediterranean period, when projecting pseudo-vaults were made to cover small areas. Giovannoni’s observation then, rightly hits on the similarity between the opus caementicium technique of the Romans and the proto-Mediterranean pseudo-vaults of Mycenae; however, the revival of the older technique by the Romans was used in typologies characterized by different structural behavior.

Span, thrust and unilateral behaviour

The use of the term vault or pseudo-vault has often been tied to the different construction techniques used to join and position the elements of a structure designed to span a given area, in the absence of intermediate supports: if the building blocks are placed radially, the structure is considered to be a vault; if they are placed horizontally, it is considered to be a pseudo-vault.

However, the basic feature that differentiates the behaviour of the two classes of structure is the presence of thrust, due to the inability of the structure to balance the bending moment generated by the weight along the extension of the covered area: the conflict between the verticality of the weight and the horizontality of the space generates a bending moment and thrust, an indispensable factor to keep the system in balance (Sinopoli 2008).

Structures of great thickness, which are designed to cover small areas, do not generally produce thrust; they can be built using a construction technique of projecting horizontal layers, like the pseudo-vaults of Mycenae and the proto-Mediterranean. In the case of structures spanning large areas, thus with thrust, a radial arrangement means the thickness to be contained, producing, at the same time, compression, particularly useful when using materials with little tensile strength and the dry stone technique.

The vault and the dome represent the most natural and most technically significant ways of covering a given area without using intermediate supports and with minimum consumption of structural material. As a result, they represent one of the most authentic and, not by chance, one of the first expressions of “artificial space”, i.e. space commensurate to the needs of habitation (Pizzetti; Zorgno Trisciuoglio 1980, p. 300).

Roman domes in opus caementicium would therefore seem to be an anomaly in this sense, since they span large areas, as in the case of the dome of the Octagonal Hall of the Domus Aurea, and even more so the Pantheon, despite the fact that they are built by means of horizontal layers. These domes therefore produce thrust and are substantially different from hypogea, such as the tholos of the treasure of Atreus in Mycenae, which spans a great area and is built in horizontal layers but where the radial forces are easily countered and absorbed by the active thrust of the surrounding earth (Sinopoli 2008).

In principle, therefore, building a dome by means of horizontal layers would make it unstable, unless structurally intelligent measures are taken, such as using an appropriate degree of thickness, the addition of a large weight at the top and the control of thrust and flow lines produced by it (Sinopoli 2008).

THE STRUCTURAL SCHEME OF THE OCTAGONAL DOME

The hidden bearing structure

The dome of the Domus Aurea, as already stated, is a sort of structural trompe-l’oeil; the load bearing structure, which is hidden, is very different and reveals not only the control of the mechanical behaviour of a dome built using material which was presumed not to have tensile strength but also an ingenuity that anticipates solutions and inventions generally attributed to later periods.

The architectural survey played an important role at this stage. Following a previous qualitative study by Ball (Ball 2003), a survey was made of the vertical development of the vault and the connections to the radial rooms by elaborating a succession of horizontal sections of the hall from different heights starting from the ground up to the oculus; some of them - the most significant – can be seen in fig. 4. a-f.

Fig. 4.a shows, at the ground level, what we may call a “diagram of the dome’s foundations”: the eight pillars are completely separate from the plan of the radial rooms. At the level of the flat arches, Fig. 4.b reveals the first link between the supporting pillars and the radial rooms: the pillars, connected by flat arches, run radially in the form of an “X” in the direction of the perimeter walls of the rooms, forming a hollow triangular pillar that unloads any thrust from the lunettes of the domical vault onto the walls of the rooms.

Fig. 4.c shows the structural bearing scheme in more detail: the slender flat arches play the “grammatical” role of purely defining the perimeter of the vault, and show the groins to be projecting infill walls; the eight supporting pillars along the octahedral perimeter are connected to the triangular pillars not by means of “struts” as stated by Ball (Ball 2003) but prismatic “wedges”, which as the dome rises get thinner until they come to an end at the height of the clerestory windows (Figs. 4.d,e). At this level, the prismatic wedges and triangular pillars coalesce in a unique full and larger triangular support; Fig. 4.f shows the dome up to the oculus.
The dome of the octagonal dome is therefore not an isolated vault resting on the eight supporting pillars, connected by the corresponding slender flat arches, but a complex and articulated structural system. The lynchpins of the load bearing system for the whole dome are the pillars of the octagonal perimeter, which link up with the walls of the radial rooms through the triangular pillars, and with the hemispherical calotte through the prismatic wedges. From a structural point of view the groins of the cells play an insignificant role and could be removed without damaging the vault; built as projecting walls, thanks to the decreasing thickness, they unload the arch-shaped flow lines spanning the octagon onto the supporting pillars; the slenderness of the flat arches is, therefore, justified by the fact that they mostly have to carry only their own weight.
As for the hemispherical calotte, the reduced thickness over both the flat arches and the groins of the cells shows that the load bearing function of these areas is irrelevant; the flow lines along the hemispherical surface pass over the space above the sides of the octagon, and are channelled into the spandrels and towards the “extended” support made up of prismatic wedges, octagonal perimeter pillars and triangular pillars connected to the radial rooms.

Four centuries before the advent of Byzantine architecture and nineteen centuries before the ingenious solution adopted by Nervi for the Palazzetto dello Sport, the dome of the Octagonal Hall thus behaves as a sail vault - shaped like a “domed wheel” (Ball 2003), which extends from the vault to the walls of the radial rooms.

The relevant role of prismatic wedges and triangular pillars

But how are the flow lines channelled along the meridians of the vault? What role is, in fact, played by the prismatic wedges? And are we sure that the flow lines below the flat arches all go into the extended supports of the octagonal perimeter?

As we can see in Fig. 5, the hemispherical calotte outside the oculus is very flat, consisting of about four layers of opus caementicium; the thick top part bends the flow line due to the thrust and channels it radially to the prismatic wedge and the triangular pillar. However, the flow lines that cross the high vaults of the radial rooms (along the “C” shaped perimeter, which includes the wall with the splayed windows and the two radial walls) are also channeled, coming from the opposite direction, towards the pillars, unloading the weight of about a quarter of the room on each of them, and countering, at the same time, the thrust exerted by the calotte.

Figure 5: Room 125: Longitudinal section through the crown of the vault (SW-NE), including half of the dome of Room 128, looking northwest; (Ball 2003, p. 211)

An additional contribution to the verticalization of the flow lines, lower down, comes from the vaults of the first level of radial walls: they contribute the verticalisation by unloading the corresponding weight and thrust onto the pillars.

The idea of the wedge was very dear to Salvatore Di Pasquale, to whom this work is dedicated. Throughout his didactic and scientific career, he investigated the construction methods of ancient masonry building, structures that typically lacked tensile strength. The wedge is extremely important from the construction point of view: it is the key to the arch, gathering and redirecting the flow of compression tensions; the wedge is a construction element that, once inserted under pressure, increases the level of compression to guarantee stability, thanks to the joint action it produces.

CONCLUSIONS

We do not know of a previous vault similar to the Octagonal Hall: it remains unique in conception and daring. A century later, the vaults of Hadrian’s Villa in Tivoli saw the triumph of opus caementicium; moreover, the static scheme of the Octagonal Hall was again used in the dome of the Pantheon. In our times, the discovery of the hidden behaviour of ancient structures helps in our efforts to preserve them and avoid overburdening the structure during restoration.
REFERENCES