A Brief Overview of the Techniques of Vaulted Architecture in Rome

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Introduction

Vaulted architecture—and its related forms, the arch and the dome—represent some of Ancient Rome’s greatest contributions to the modern world. The impressive accomplishments of Roman engineering and architecture in antiquity are only matched by the lasting power of Roman monumental architecture; we see it still in the Pantheon of Hadrian, the massive Basilica of Maxentius, and in the Markets of Trajan. And while the concept of the vault was not in itself a Roman invention, the Romans did, through their own advances in the fields of architecture, engineering, and construction technique, perfect the vault in its various forms.

The Evolution of the Roman Vault

The Romans were perhaps the first builders in Europe to fully appreciate the versatility and advantages of the arch, vault and dome (Robertson 231). However, they were, by no means the first developers of these structures. In fact, vaulting and arches had been used to great effect in the Near East and Egypt for centuries before the Romans (Robertson 231, Sear 17). We see arches and vaulting establishing a firm footing in Greek Hellenistic and Etruscan architecture in the fourth century BCE (Sear 17, Adam 164), though the earliest examples we see in Etruria are not semicircular arches, but rather polygonal, corbelled ones.

![Early corbelled archway, southern Latium, fifth century BCE](image)

The earliest dome-like structure that we can see in the region is the famed Tholos of Atreus of Mycenae, dated to the middle of the 13th century BCE. The Greek colonies of Magna Græcia are home to the earliest archways and barrel vaults in Italy (Ward-Perkins 28). These were constructed out of stone, with the occasional use of lime mortar.

The general belief is that the earliest archways in the vicinity of Rome were the work of the Etruscans, and that it was a building technique henceforth appropriated by the Latins. Indeed, the earliest archway in Rome proper was considered to be that about the outflow of the Cloaca Maxima at the Tiber. This drainage system had its genesis under the Etruscan Tarquins (and hence, Etruscan engineers) of the late sixth century BCE, and accordingly, the archway present at its outflow is attributed to this period.
(although the Tarquinian date has been challenged, and the archway alternatively dated to an Augustan renovation of the drain) (Adam 158).

Drain of the Cloaca Maxima, Forum Boarium, Rome, either ca. 509 BCE or Augustan

We otherwise see early “true” or *voussoir* archways in the Etruscan towns of Velathri, Aperusia, and Falerii Novi. It is likely that the latter, which was in fact a new Roman town built for the purpose of re-inhabiting the conquered inhabitants of the Etruscan city Falerii Veteres, was built using Etruscan engineers. The town and its archways date to approximately 241 BCE, while the structures at Velathri and Aperusia likewise date to the middle of the third century BCE (Adam 159). *Voussoir* arches are formed by an arc of separate stones, with a keystone at the top of the arch. The arches and surrounding walls were stabilized by utilizing rocks of varying size.

A schematic of the *voussoir*, or true, arch

Following the Roman appropriation of the *voussoir* arch from the Etruscans, we see numerous examples of masonry arches can be found in Rome (e.g. the *Pons Aemilius* (142 BCE) and the *Pons Mulvius* (109 BCE) amongst others). Once, however, traditional masonry arches were eschewed in favor of concrete ones, we are able to see an expansion of the arched form to a much larger scale.
The Development of Concrete

Roman concrete, or opus cæmenticum was a mixture of mortar with stone aggregate (cæmenta) (Lancaster 3). Cæmenta were generally about the size of a human fist, though a great deal of variation is naturally present (Sear 73)\(^1\). This formula in itself was not new and had been used to varying levels of success by the Greeks, who sometimes used a mortar comprised primarily of lime and water. However, the addition of local, "pozzolana" volcanic ash to the mixture represented a breakthrough in the creation of binding mortar. Pozzolana, which is native to the areas surrounding Mount Vesuvius in Campania, possesses a unique chemical composition that gives the resulting mortar a substantial compressive strength (between 5 and 8 times the strength of the pure lime mortar used by the Greeks) and allows it to set even in aqueous environments (Lancaster 51). Moreover, the composition of the cæmenta was highly varied by the Romans, to an effect that will be discussed in several examples later.

This pozolana mortar was used as early as the late 3rd century BCE, though only for walls. The earliest examples of its use in vaulting occur at the Sanctuary of Fortuna at Preneste and the Porticus Æmilia, both of which are dated to the early second century BCE (Sear 19, Lancaster 11). Both the Sanctuary of Fortuna and the Porticus Æmilia are massive structures; the Porticus Æmilia, a large warehouse located on the eastern bank of the Tiber in south Rome, is a long hall measuring nearly 490 meters long and 60 meters wide, with large barrel vaults running the length of the building and smaller archways traversing its width (Sear 19). These early expressions of concrete vaults display a relative unfamiliarity with the material; for instance, the concrete vaults on the Terraza della Cortina at Preneste demonstrate substantial deformation, or “creep”, indicating that the builders assumed that the concrete was in fact stronger than it was (Lancaster 10).

Roman concrete, unlike modern concrete, was not poured, but rather the mortar and cæmenta laid separately by trowel (Lancaster 3). Nonetheless, it is with this innovation that we see the increasingly widespread employ of the masonry arch and barrel vault in Roman Italy by the middle of the second century BCE make way for the monumental concrete structures that would be characteristic of Roman architecture.

\(^1\) Opera cæmentica themselves were often classified according to the type of masonry “facing” that contained the mixture; for more information, please see Sear, pp.74-75.
The Engineering and Physics of the Vaulted Form

Before discussing the further development of the vault in Rome, it is perhaps useful to present some background on the engineering and physics of the vault. The arch and the vaulted form have been so enduring primarily due to the physical superiority of such structures.

From a physics standpoint, the arch facilitates structural integrity by redistributing the weight of the structure that it is supporting about the arced portion (in a line consistent with the said arc) and down through the piers, without inducing points of concentrated force as we see in corbelled or polygonal archways, or in simple post and lintel systems. The extruded arch, or barrel vault, the groin vault (formed by an intersection barrel vaults), and the dome (a revolved arch) all possess structural mechanics of a similar vein.

The stress distribution in a groin vault

It is clear that the Romans did not possess a clear analytical understanding of the physics of the arch (this in fact would not happen until about a millennium after the fall of the Western Empire), although they did have a deep, intuitive understanding of the mechanics involved (Lancaster 11). As is evidenced by the various structural deformations found at Præneste and elsewhere, the Romans tended to rely on on-site experimentation and development, as well as “accumulated knowledge” handed down from earlier generations, although a fundamental knowledge of geometry and structural mechanics (courtesy of Archimedes) was not lacking (Lancaster 10, 166).

Formwork and Centering

A tremendous amount of the success of any vault comes from the frame which is built to support it during the construction phase. The “centering” of a vault refers to the arced wooden frame which outlines the fundamental shape of the form, and which bears the weight of the masonry, or later, concrete laid upon it. The “formwork” of a vault is the portion of the support that sits upon the centering and upon which the concrete is actually placed, within a masonry facing at the perimeter of the formwork. It consists of numerous, straight beams joined together to approximate the circular shape of the vault. The centering and formwork are, after the locking in of the stonework or the curing of the concrete, removed; with large concrete vaults, this time period may be as long as two or three weeks (Taylor 176, Lancaster 27). Occasionally, the formwork may be fitted with insets, so that coffers (stylized recesses designed to reduce overall weight) may be formed within the vaulted structure (Taylor 188).
Just as with modern concrete building, there are usually clear traces of the formwork upon the final concrete structure (Taylor 179, Lancaster 32). Due to the manner in which the centering interacts with the formwork, we can track the evolution of the centering; we see, throughout the course of Imperial Rome, Late Antiquity, and even into the Middle Ages, a better understanding of centering and of truss structures, resulting in less deformation of the vault during the curing process. The proper construction of the centering and the formwork constituted the bulk of vault construction, and, as mentioned before, usually occurred on-site with skilled carpenters playing an important role in the construction thereof (Lancaster 25-26). Moreover, removal of the formwork posed a significant challenge to the carpenters and engineers, and they had to be designed to anticipate this (Taylor 188). The shape and the general layout of the formwork naturally depended greatly upon the sort of vaulted form being constructed, as illustrated below:

![Schematic of general centering and formwork plan](image1)

A schematic of the general centering and formwork plan for a barrel vault (left), and an example of modern centering and formwork nearly identical in form to the Roman method, Olympia, Greece (right)

The formwork for the groin vaults at Trajan’s Markets, 110 CE (upper left) and the frigidarium at the Baths of Caracalla, 216 CE. As barrel vaults came to be intersected, the formwork naturally became much more complicated, and the potential for deformation greater.
Formwork for two different types of groin vaults: the pavilion (left) and the cross (right)

Two different styles of formwork for domes: the so called “horizontal” formwork (left) and the radial formwork (right)

The Monumentalization of the Vault

The Tabularium, or records office, was constructed in the Forum Romanum on the front slope of the Capitoline Hill between 78 and 65 BCE, and demonstrates the foothold that concrete vaulted architecture had taken in central Rome by the middle of the first century BCE (Robertson 240, Sear 27, Lancaster 5). The Tabularium, which covered an area of approximately 230 feet by 140 feet, was full of arches, barrel vaults, and even primitive groin vaults formed by irregular intersections of barrel vaults (Robertson 240-241).

Later, in this vein, we see the extension of concrete vaulting to structures such as the Theatrum Pompeium (52 BCE) and the Theatrum Marcelli (12 BCE) (Lancaster 5, Ward-Perkins 64), where interior concrete vaults are combined with marble and stone architecture on the outside, indicating what Robertson refers to as a “divorce between function and decoration, due partly to the introduction of new structural methods, which is characteristic of Roman architecture” (Robertson 242).

In the Flavian period we see in the Amphitheatrum Flavium (completed 80 CE) and the Domus Flavia (completed 92 CE) a full and successful utilization of the cross or groin vault and the barrel vault on a colossal scale (Robertson 244, Lancaster 38). The former is particularly important, as it demonstrates a maturity of the forms initially investigated more than a century and a half earlier in the Tabularium. [2]
The Groin Vault

Groin Vault in the Amphitheatrum Flavium, 80 CE. Note the horizontal lines indicating original formwork. These lines are the often the only method for reconstructing formwork and centering, as there is no archaeological record of how they were actually employed.

The groin vault is formed by the intersection of two barrel vaults, generally at right angles to one another (Adam 190). Amongst the earliest groin vaults we see are those in the Flavian Amphitheater. By the Trajanic period, the groin vault is in employ on a massive scale, as seen in the Markets of Trajan (110 CE) and the Baths of Trajan (109 CE). The great usefulness of the groin vault, especially as used in the roofing of Trajan’s monuments, is that vaults that intersect along the axis perpendicular to the main length of the building can be used to allow light in. This is seen again in the Baths of Caracalla (see the example in the “Formwork and Centering” section), the Baths of Diocletian (ca. 300 CE), and in the Basilica of Maxentius (ca. 310 CE) (Kleiner 297). Each of these massive structures, intended for mass public use, were well accommodated by the groin vaults and the light they provided.

The Dome

The earliest, preserved concrete dome of note is that belonging to the “Temple of Mercury” at Baiae in Campania, dating to the Augustan period. This particular dome surpassed the Tholos of Atreus at Mycenae in scale, and stood as the largest dome in existence until the construction of the Pantheon.

The dome in general represents numerous challenges in construction, the greatest of which is likely the fabrication of the centering frame, which must consist of an array of the sort of frame required from a vault. Indeed, in the dome of the Temple of Mercury, there are numerous deformations to be found, a sign that the builders encountered substantial difficulties in shaping and positioning the frame for the large, 21 meter diameter dome (Lancaster 42).

[2] The Amphitheatrum Flavium also demonstrates the apparent “divorce” in form and function, as the building’s outer casing of travertine is disjoint from the layered interior array of vaults, both barreled and crossed. This distinction, first seen in the Tabularium, becomes more evident in monuments such as the Forum Traiani and Pantheon—both of the first quarter of the first century CE—which use concrete vaulted architecture with a distinct brickwork facing.
Nonetheless, there is evidence that the builders of the Temple of Mercury attempted to lighten the load that was borne by the dome by using less concrete (Sear 81). A similar thing would be done in the so-called “Octagonal Room” of Nero’s *Domus Aurea*[^3]. This pseudo-domes/ polyhedral banquet hall, which represents one of the few surviving examples of “domed” architecture in the period between the Temple of Mercury and the Pantheon, dates to between 64 and 68 CE, and, as mentioned, uses a cement of lighter composition in order to reduce the weight of the domed structure. This would prove to be a precursor to the technique of “*cæmenta* gradation” that would be used to great effect in the Pantheon.

**Cæmenta Gradation**

The selective grading of the *cæmenta* aggregate is one of the primary reasons for the lasting success of the Pantheon (Ward-Perkins 139). In short, “grading” means progressively using lighter aggregate material in the *cæmenta* at higher altitudes. From a physics standpoint (and mathematics aside), any non-vertical cross-section of a structure must support the weight (or downward acting gravitational force) of everything that sits above it. Consequently, the lowest portion of a structure sustains the greatest stress, while higher portions must bear less; the very top of a structure naturally bears no stress since nothing sits above it.

Understanding this at least intuitively, the Romans spared using heavier (and hence stronger) materials towards the top of the Pantheon’s 43.2 meter-diameter dome, since using heavier *cæmenta* would impose a greater stress burden on the lower portions of the dome. Moreover, since the higher portions of the dome would be supporting less weight anyway, it would be of no advantage to use a higher strength aggregate. The *oculus* that sits at the apex of the dome further reiterates this, by eschewing any structure altogether.

[^3]: The Octagonal Room of the *Domus Aurea* possesses many other interesting architectural features. Its well-preserved state shows, quite clearly, the formwork pattern upon the concrete, allowing for a fairly accurate reconstruction of the formwork used; the formwork, by this point, is of greater stability and certitude than that which was apparently used at *Baiae*, and which would further evolve into the methods employed in the Pantheon. The Octagonal Room’s polyhedral design also removes the necessity of approximating an arced form by removing curvilinear geometries altogether.
Grading seems to have been first used during the Augustan period (in the Basilica Æmilia in the Forum Romanum) and in the Neronian Domus Aurea, although it is not until the latter half of the first century CE that the practice becomes more commonplace (Lancaster 59). Prominent examples, aside from the Pantheon, that feature graded cæmenta include the Flavian Amphitheater, the Basilica Argentaria in the Forum of Caesar (early second century CE), and the Baths and Markets of Trajan, which immediately precede the Hadrian Pantheon chronologically.

As far as the Pantheon is concerned, we see at the lowest levels of the dome, an aggregate composed of broken bricks, while higher up, a mixture of broken bricks and volcanic tufo stone is used. At the highest level, tufo and scoria (Vesuvian pumice) is the aggregate of choice (Lancaster 63). Consequently, the thickness of the dome sees a gradual thinning, from nearly 6 meters thick at the shoulder of the dome, to barely 150 centimeters at the oculus (Ward-Perkins 139).

Ribbed Vaulting and Internal Structural Supports

“Ribbing” a vault refers to the practice of placing an arch within a concrete vaulted structure, ostensibly in order to relieve some of the weight situated directly above the said vault. The practice can first be seen in the polygonal walls at Alatri in Lazio and at the Porta Rosa gate at Velia in Campania, both dating from about the third century BCE (Lancaster 87), the latter of which situates a stone voussoir rib directly above a true voussoir arch.
The practice, in most cases, seems to serve no real structural purpose, since, if a rib is inserted into a solid wall, it no longer acts independently to divert loads (Ward-Perkins 152). Nonetheless, there is a general consensus that the ribs did help divert and manage the concrete which surrounded them. Ribbing is used extensively in the Flavian Amphitheater; in fact, the Colosseum, which features the earliest use of ribbing in Rome itself, utilizes several different kinds of ribbing based on the type of material comprising the rib.[4]

The Pantheon is unique in that it contains a staggered ribbing configuration around the rotunda wall that ultimately serves to dissect the rotunda walls into piers. This is done by placing a hollow, vertical shaft immediately below every other rib. In contrast to the placing of a rib into a solid facing, the system in place in the Pantheon features ribbing that is actually independent of the surrounding structure, acting, in the interior of the building, as a true arch.

[4] The types of ribs used in the Flavian Amphitheater are travertine voussoir, brick-faced filled with concrete (the so-called ladder rib), and solid brick (or “bipedalis”).
In a manner analogous to the spoliation demonstrated in Constantine’s Arch, we see, in a somewhat less crass way, the reclamation of disregarded craftwork being used to save costs in a monumental project.

Exposed amphorae, as used at the Mausoleum of Helena, southeast Rome, ca. 330 CE.

Lastly, one architectural peculiarity, which was commonplace in Rome by the fifth century CE, deserves some mention. Tubi fittili, or vaulting tubes, were specially made earthenware tubes designed to interlock with one another and form an inner frame about which the concrete is laid. This technique, while increasing the weight of the vault minimally, allowed for an increase in the tensile strength of the vault, but also improved the insulation of the structure (Mason).

Conclusion

The evolution of the vaulted form in Rome represents some 800 years worth of architectural development. From the earliest expressions in Italy of the true arch in Etruria and Campania in the fifth century BCE, we see the absorption of this form into Latin hands and mastery a thereof by the second century BCE. With the Roman development of pozzolana-based mortar, the concept of the arch was extended into barrel vaults, groin vaults, and eventually the dome. Moreover, each of these was developed on a massive scale, for mass public use. Indeed, without the perfection of the vault, many of the most long-lived of Rome’s monuments would be non-existent or rendered useless. For without the groin vault, none of the great public bathhouses of the second century CE and beyond would contain enough light for the thousands of bathers within, and without the refinements in cæmenta gradation that eventually made their way into the Pantheon, the famous dome may well have collapsed long ago. Doubtless, vaulted architecture is one of Rome’s more enduring legacies.
References


