Large Freestanding Barrel Vaults in the Roman Empire: a Comparison of Structural Techniques

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Large-freestanding barrel vaults were not common in the Roman world, but the known examples offer a glimpse into the way in which builders in different parts of the empire went about solving the problems of stability introduced by such large vaulted structures.

Each of the three buildings examined below is from a different area of the empire and employs different materials, but they all date from approximately a 100-year period ranging from about AD 100 to AD 200. The buildings include a temple (the Temple of Divine Hadrian in Rome), and a bath complex associated with a cult sanctuary (Sanctuary of Sulis Minerva at Bath, England), a large cult complex which was turned into a bath building (Theater Baths at Argos, Greece). A comparison of the materials and construction techniques used in each of these buildings provides some idea of the innovative ways by which Roman builders managed to accomplish their structural goals using very different materials and methods.

TEMPLE OF DIVINE HADRIAN IN ROME

The Temple of Divine Hadrian (or the Hadrianeum), which is now located on the Piazza di Pietra, was dedicated by Antoninus Pius in AD 145 (*SHA* Ant Pius 8.2, Lucius Verus 3.1) following the death of the emperor Hadrian in AD 136. The remains include the concrete vaulted podium supporting eleven Proconnesian marble columns and the entablature of the north side of the temple, the corresponding peperino block wall of the cella, and the spring of the massive 18 metre concrete coffered barrel vault which covered the cella (Cozza 1982). The temple is unusual in being the first (and one of very few) large barrel vaulted, peripteral temples in Rome or indeed elsewhere in the Roman Empire **(fig. 1)**. From a structural point of view, it is admirable for the way in which the lateral thrusts of the large central barrel vault were controlled. By this time, Roman builders were well aware that their pozzolana mortar, albeit strong, could not be relied upon to resist the cracking which could occur in a vault of this scale. They did not have the modern concept of internal tensile stresses which we use today to explain why such cracks could develop, but they understood that concrete vaults could and did develop lateral thrusts which had to be countered in some way. In this case, the builders accomplished the task by regulating the type of *caementa*, or aggregate, used in the concrete of the vault so that the crown was lighter than the haunches and by combing forms is such a way that the masses were effectively balanced.

For controlling the weight of the different parts of the building, the builders had at hand a number of different materials, most of which were volcanic in origin. One great advantage of concrete is that its weight can be manipulated by varying the type of *caementa* used, and the Romans had already become skilled at this by the time the Hadrianeum was built. For the vault in particular they employed a local tuff quarried north of Rome called Tufo Giallo della Via Tiberina and an imported lightweight volcanic scoria produced by Mount Vesuvius on the Bay of Naples. (This scoria has not been examined petrographically but similar material from other buildings in Rome leaves little doubt as to its origins: Lancaster 2005, pp. 64-7, 222-4). The lower part of the vault is built solely of Tufo Giallo whereas the upper part is built of carefully laid alternating rows of Tufo Giallo and the Vesuvian scoria **(fig. 2)**.

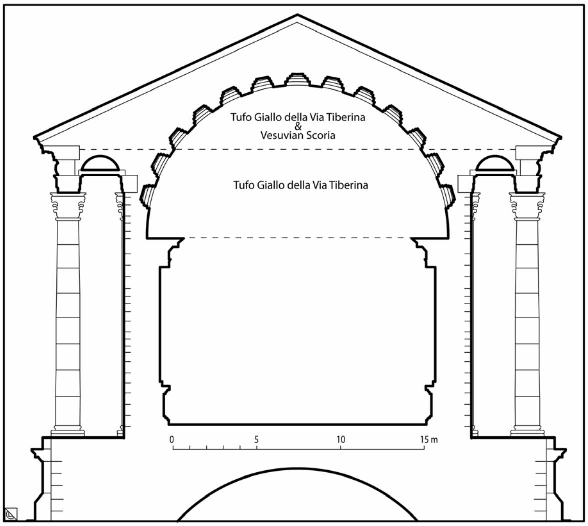

Figure 1. Section through Hadrianeum in Rome showing types of stone used for *caementa* in the concrete.

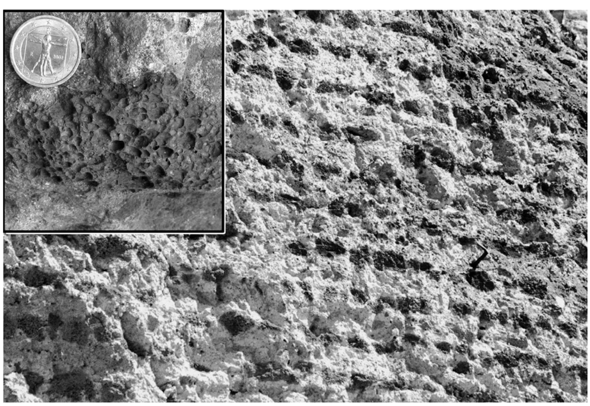

Figure 2. Hadrianeum vault showing alternating rows of Tufo Giallo della Via Tiberina (light) and Vesuvian scoria (dark). Inset shows detail of similar type of scoria (not from Hadrianeum).

The Tufo Giallo della Via Tiberina (1 350 kg/m^3), which is lighter than the more commonly used Tufo Lionato (1 600 kg/m^3), was often reserved for use in vaults. The use of the scoria (800 kg/m^3) is rarer. It is probably the same material mentioned by Vitruvius (*De arch*. 2.6.2-3) which he called *pumex pompeianus,* or "pumice from Pompeii". This material was produced by minor eruptions dating to the tenth/ninth centuries BC which formed the hill on which Pompeii was built (Ranieri 1998, pp. 135-41; Ranieri and Yokoyama 1997, pp. 33-50; Kawamoto and Tatsumi 1992, pp. 92-7). It would have been encountered by builders in Pompeii as they were digging their foundations and can be seen used in the walls there, but the deposits were covered by the products of the AD 79 eruption of Vesuvius which buried Pompeii.

The Hadrianeum was not the first vault in Rome to employ the scoria. It occurs in some first-century BC vaults at the Forum of Caesar (Amici 1991, pp. 52, 162), but it was most commonly used after the AD 79 eruption. Examples occur in imperially sponsored buildings in Rome from the early second century AD: the Baths of Trajan, the Basilica Ulpia, the Pantheon, the Hadrianeum, the Baths of Caracalla, and the reconstruction of the Basilica Julia. Once the deposits of the scoria were covered by the AD 79 eruption of Vesuvius, which also destroyed the river port at Pompeii and the surrounding road systems, there was clearly some substantial effort involved in excavating the material and transporting it to Rome for these imperial vaulted buildings.

Given the effort put into acquiring the scoria, one wonders the degree to which it was effective in helping to stabilize the vault. A simple calculation of the weight reduction in the Hadrianeum vault shows that the addition of the scoria to the Tufo Giallo della Via Tiberina reduced the weight of the vault by only about 6%, so it was probably not critical to the stability of the structure. However, the use of the Tufo Giallo in place of the more common Tufo Lionato yields a 12% reduction, so the combination of Tufo Giallo and the Vesuvian scoria together resulted in an 18% reduction, which is a significant decrease over the typical vault. Preliminary thrust line analyses on the structure have indicated that such a reduction had a significant affect on the lateral thrusts and the overall stability of the structure. The builders did not design the building based on thrust lines, but the idea of controlling the thrusts through the manipulation of mass and geometry was certainly one they understood well. It was a fitting tribute to the emperor who sponsored the Pantheon and was known for an interest in vaulting.

SANCTUARY OF SULIS MINERVA AT BATH, ENGLAND

The second vaulting technique is found at the Sanctuary of Sulis Minerva in Bath England, where there are two large-scale barrel vaults of interest (15.3 m and 10.5 m span), both dating to a phase of reconstruction in the late second or early third century AD. The vaulting technique used there involves hollow terracotta voussoirs, a technique particularly associated with bath buildings. In some examples elsewhere in Roman Britain, they were used to create hollow flues within the vault for the circulation of hot air (Brodribb 1979, pp. 147-8). However, that is not the case at Bath where they are not connected to a hypocaust system. In this case they were clearly used to lighten the weight of these unusually large barrel vaults.

An examination of the natural environment of the complex provides some basis for understanding the structural complexities faced by the builders. The sanctuary and adjacent bath complex were built around a natural thermal spring (producing 250 000 gallons a day at 46.5° C) which rises to the surface in the flood plain formed within a loop of the River Avon. The site provided the perfect location for one of the favorite Roman pastimes, the ritual of public bathing, but the thermal springs were known long before the Roman invasion of southern England in AD 44/45. The site of Bath, or the Roman *Aquae Sulis*, was not an ideal location for a settlement because of the waterlogged and unstable nature of the sands which rose through the fissure supplying the thermal spring. A more permanent settlement (probably of military character) was likely located somewhere to the north of the sanctuary where the soil to either side of the river is more stable. There appears to have been a confluence of roads crossing the river at this point, the most significant of which was the Fosse Way which formed the defensive boundary of the Roman conquests in the first century AD (Cunliffe and Davenport 1985, pp. 79-80; Cunliffe 1984, p. 178-81).

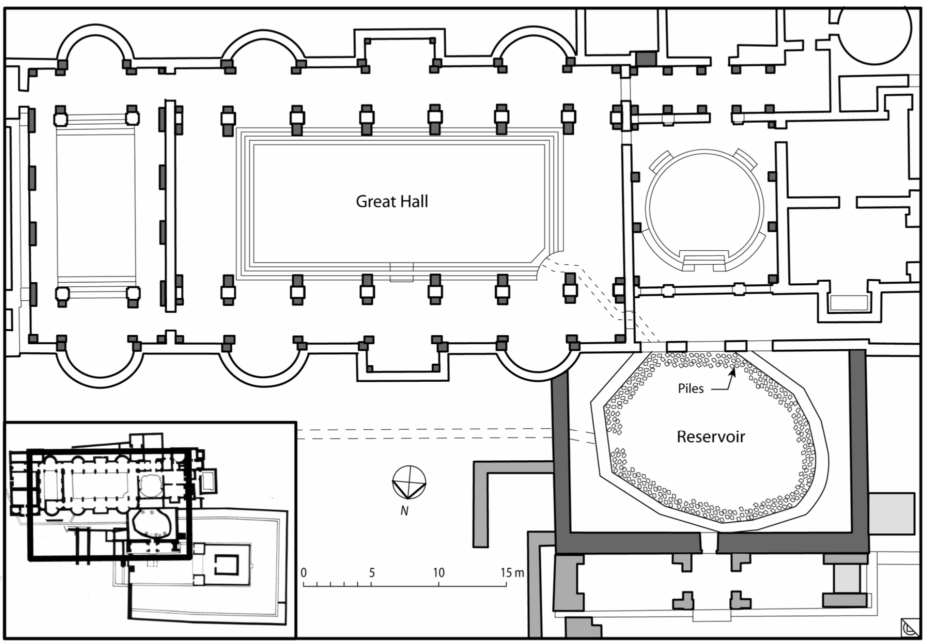

Figure 3. Bath, England. Plan of thermal bath complex. Dark gray: additions made when vaults were added. Medium gray: additional buttressing elements. Light gray: reinforcements of buttressing elements.

The first task in building the sanctuary was to contain the spring water rising from the ground. Excavations begun in 1979 revealed precisely the way in which this was accomplished. In order to contain the spring water, a ring of oak piles was driven into the ground to create a containment basin and to provide a stable base on which to work **(fig. 3)**. Then a foundation trench was dug along the outer circumference of the pile ring, the bottom of which was probably also reinforced with oak piles driven into the muddy soil. The containment wall of the reservoir was then built on stone foundations laid within this trench (Cunliffe and Davenport 1985, pp. 39-42). In its first phase (late first century AD) the reservoir was left open, but later (late second-early third century AD) it was enclosed and covered with a 15.3 metre wide barrel vault. It was buttressed on one side by the adjacent bath building but was left freestanding on the opposite side. These enclosure walls surrounding the reservoir and supporting the barrel vault were therefore built in the least stable areas of the entire complex, i.e., the edge of the spring.

The excavations of the reservoir uncovered substantial remains of the fallen vaulting employing hollow terracotta voussoirs, so a detailed reconstruction is possible. The pattern of the fragments of fallen vault provides a clear indication of its construction. It consisted of a series of radially laid brick ribs between which were placed the hollow terracotta voussoirs. Both the ribs and the hollow voussoirs were built up against a spine of wedge-shaped bricks acting as a long key stone running the length of the vault **(fig. 4)**. (A somewhat similar spine construction albeit with no ribs or hollow voussoirs attached was found in a vault of the bath at Beauport Park of roughly the same date: Brodribb and Cleere 1988, p. 62, Pl. 11b.) As the vault was completely fallen, the precise configuration at the haunch is impossible to know, but the excavators reasonably proposed that the infill between the ribs at the haunch consisted of mortared rubble and that the hollow voussoirs began at some point above the spring of the vault. In this way the lightening effect of the hollow voussoirs would have been concentrated in the upper part of the vault with heavier material at the haunch (Cunliffe and Davenport 1985, pp. 50-3, 134-5).

The north, unbuttressed, wall supporting the vault was 1.65 metres thick built of coursed stone masonry with double courses of bricks placed at intervals. The wall was unusually thick, but evidently the thickness was not sufficient. Sometime during the middle of the third century, a raised porch (0.5 metres high) was added along the north side of the enclosure wall. It supported projecting structures which acted as buttresses. The central one formed a quadrifrons arch in front of the entrance into the sacred spring. A later phase of reinforcement to these buttresses around AD 300 suggests further structural problems arising from the lateral thrust of the vault (Cunliffe and Davenport 1985, pp. 55-65). For all the care which went into the lightening of the vault, this attempt at allowing one side to be freestanding with no form of buttressing was ultimately unsuccessful and had to be remedied.

Another example of the use of the hollow voussoirs occurs in the Great Bath, which was the central showpiece of the complex. It consisted of a rectangular pool 11.5 x 24.3 metres fed directly from the hot water in the reservoir (and was therefore the hottest of the thermal pools). The space was bordered by arcaded aisles on the two long sides and was originally covered by a trussed roof which was later replaced by the 10.5 metre wide vault which employed the hollow voussoirs. The resulting configuration was somewhat similar to that of the Hadrianeum with a central vault buttressed by vaulted side aisles. To support the new vault the builders increased the thickness of the original piers from 0.8 metres to 2.0 metres and added additional piers to the outer wall of the aisles. Fragments of the vault were found in early excavations, but they were not as extensive as those of the reservoir vault (Cunliffe 1969, pp. 98-9).

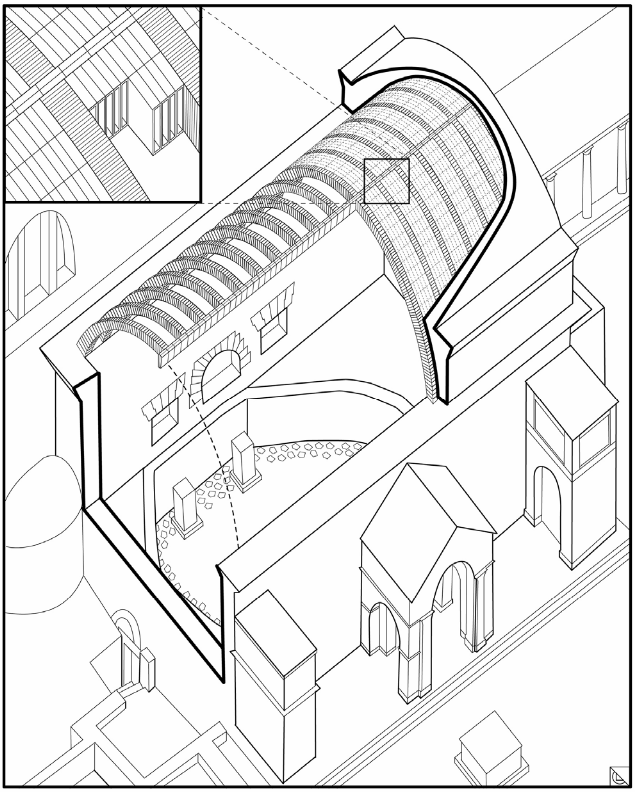

Figure 4. Bath, England. Author's reconstruction of reservoir enclosure showing vault construction (based on Cunliffe and Davenport 1985, figs. 31, 109, 115).

On analogy with the evidence from the reservoir vault, one of the fragments from the Great Bath, now on display, can be placed within the vault **(fig. 5)**. In the few fragments of preserved vaulting, there are no remains of ribs but given the construction of the reservoir vault one can assume they were used in this vault as well. The excavators have reconstructed the hall covered by a barrel vault **(fig. 6)**. The rational for such a tall space lies in a fragment of an engaged column which is reconstructed in an upper order above the enlarged pilasters below. Between these engaged columns they reconstruct semicircular windows which reflect the arcade below and which would have provided light into the space (Cunliffe 1984, pp. 117-18, 129-34; Cunliffe 1969, pp. 98-9). One difficulty with this reconstruction is that the buttressing provided by the aisles is located at a level too low to be effective against the lateral thrusts of the vault, and we have already seen that the lateral thrusts played a role in the modification of the reservoir vault. One solution would be to reconstruct the vault as a series of cross vaults, as in the imperial thermae in Rome, which would bring the spring of the vault down while still allowing for the lunette windows. However, there is no evidence amongst the few surviving fragments to suggest that cross vaults were used. So, for the purposes of this discussion, I use the barrel vaulted reconstruction and explore how this configuration might have been stabilized.

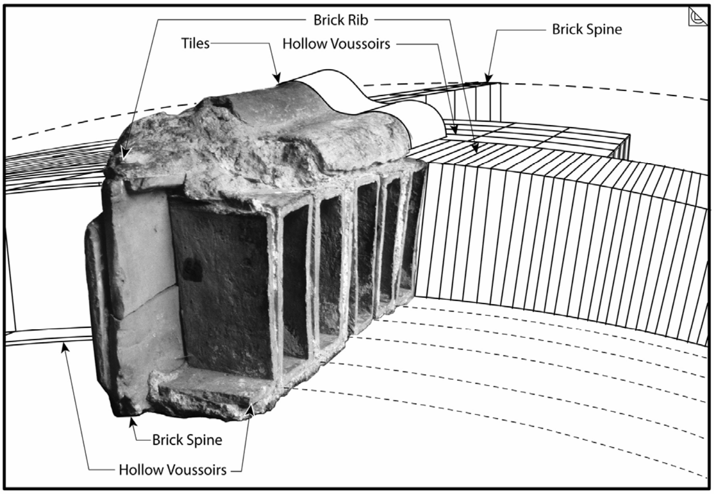

Figure 5. Bath, England. Reconstruction of vaulting of Great Bath with integration of preserved fragment.

In addition to the modifications to the major piers supporting the central vault, the builders also reinforced the corners of the projecting alcoves in the aisles and added projecting pilasters which aligned with the major piers; these additions may provide some clue as to the nature of the stabilization of the vault. Cunliffe (1969, p. 99) rightly points out that the added piers are not perfectly aligned on each side as they would be if they were carrying reinforcing ribs within the aisle vaults. They are, however, positioned symmetrically with respect to the alcove openings, presumably for aesthetic reasons, and in positioning them in this way they are brought closer into alignment with the major piers. One explanation is that they were meant to support a structure above the aisle vaults, which would not have been visible from below, namely some type of external buttressing as was common on bath buildings in the imperial thermae from at least the early second century AD **(fig. 6)**. The addition of external buttresses above the aisles would have provided the greater stability at the spring of the vault and served to channel the line of thrust through the structure onto the outer walls. The brick ribs in the vault would have been positioned in alignment with the supporting structure so that the lighter bands of hollow voussoirs acted as infill between them.

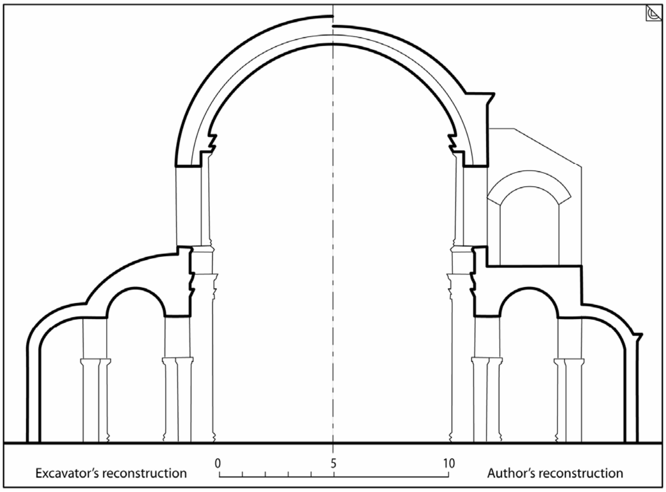

Figure 6. Bath, England. Section through Great Bath showing two proposed reconstructions.

In comparison to the use of the lightweight volcanic materials in the vault of the Hadrianeum, the use of the box tiles at Bath were a less efficient means of reducing the weight. So for example, the hollow terracotta voussoirs would have reduced the weight of the 10.5 metre wide vault over the Great Bath by about 8.6-9.0%, whereas they would have reduced the weight of the 15.3 metre vault over the reservoir by only about 6.3-7.6%. (The detailed measurements of the bricks were not given in the excavation report, so I have assumed a size of 35 cm high by 20 cm wide for the purposes of the calculations). The larger the vault the less effect the hollow voussoirs have unless they are manufactured proportionally larger.

CULT COMPLEX AT ARGOS, GREECE

The third vaulting technique to be examined occurs in cult building (late first/early second century AD) into which was later incorporated a bath complex (mid second century AD) in the center of Argos, Greece. Unlike the previous two vaults, which can be seen as part of a developed history, this one is unique and has no precedents or imitations. It consisted of a brick vault (10.6 metre span) covered by a concrete roof structure containing hollow voids. Moreover, no buttressing of any sort was provided in the first phase. The details of its construction have evidently been examined (Aupert 1984, p. 850) but have not yet been published, so in what follows I have had to rely on my own photographs of the building taken in 1994 together with the series of annual excavation reports which came out in *Bulletin de correspondance hellénique* from 1974 through the early 1990s.

The original building complex consisted of the large vaulted main hall with a raised podium in the semicircular niche on the back wall. It was fronted by a porch, flanked by two rooms, facing onto a sunken, colonnaded peristyle accessed by means of a 12.4 metre wide stairway **(fig. 7)**. The character of the building, a chamber elevated above its surrounding structures containing a raised platform at the back and fronted by a peristyle court, is characteristic of a cult building, but there is no clear evidence as to the nature of the cult. The suggestions include Sarapis, Aesclepius, and the imperial cult or some combination of them (discussed further below). The structure has been dated by the excavator, P. Aupert, to the late first or early second century AD, based on the ceramics (AD 80-90) found in the fill under the floor of the north portico and in a trench in main vaulted hall (Aupert 1977, p. 669; 1982, pp. 637-9). The vault of the main hall belongs to this early phase. In the mid second century, the peristyle was converted into a bath complex, and the main hall was incorporated into it, presumably retaining some type of cult function **(fig. 7)**. The dating is less secure for this phase. The primary evidence consists of finds of fragments of an imperial dedication inscription noting an emperor with the *cognomen* of Parthicus, which could refer to Hadrian, Antoninus Pius or Marcus Aurelius. Because Hadrian constructed the aqueduct at Argos and an inscription with similar lettering was found at the Hadrianic Nympheum at nearby Larissa which was supplied by the aqueduct, Hadrian is considered the most likely candidate to have added the baths (Piérart 1974, pp. 777-9).

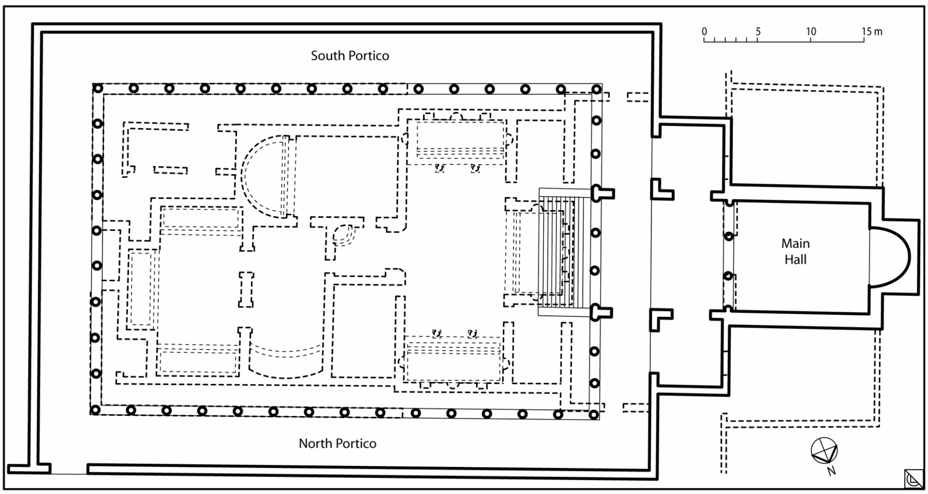

Figure 7. Argos, Greece. Plan of cult building (later turned into the bath complex known today as the Theater Baths). Dashed lines indicate bath complex built into courtyard of cult building.

The vault was built onto supporting walls ca. 1.4 metre thick giving a ratio of wall thickness to vault span of 1:7.6, which corresponds to the outer limits of the ratio typically found in barrel vaulted structures in Rome (Lancaster 2005, p. 133), though the comparisons are rarely freestanding. The vault was constructed of a series of arches made by laying bricks upright, on edge, side by side **(fig. 8)** (as opposed to the more common method of laying them radially like voussoirs). A few of the bricks remain in place **(fig. 9)**. Also constructed in the same manner was the smaller vault (ca. 4.7 metre span) forming the raised podium in the apsidal niche. The roof structure above the brick vault is truly unique, though it represents the same approach seen in both the Hadrianeum and the vaults at Bath: an attempt to control the form and mass of the barrel vault by lightening the upper zone. At Argos the builders constructed a pitched concrete roof over the curved brick vault leaving voids in the area above the haunch **(fig. 10)**. To create the voids they used wooden formwork, which presumably remained in place once it was sealed between the extrados of the brick vault and its concrete shell. The formwork boards inside the outer concrete enclosure are still visible. To provide support for the flat slabs making up the pitched outer roof, low walls were built above the extrados of the brick vault to create the five separate hollow spaces which served to lighten the load **(fig. 11)**.

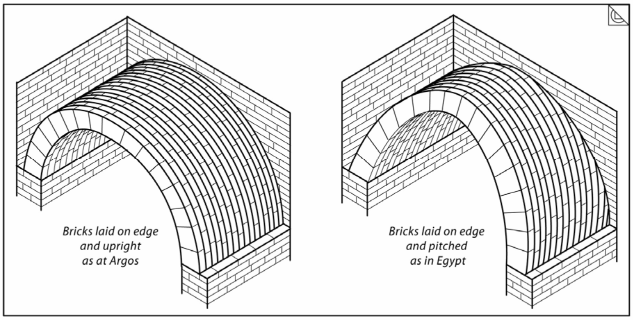

Figure 8. Two methods of brick vault construction employing bricks laid on edge.

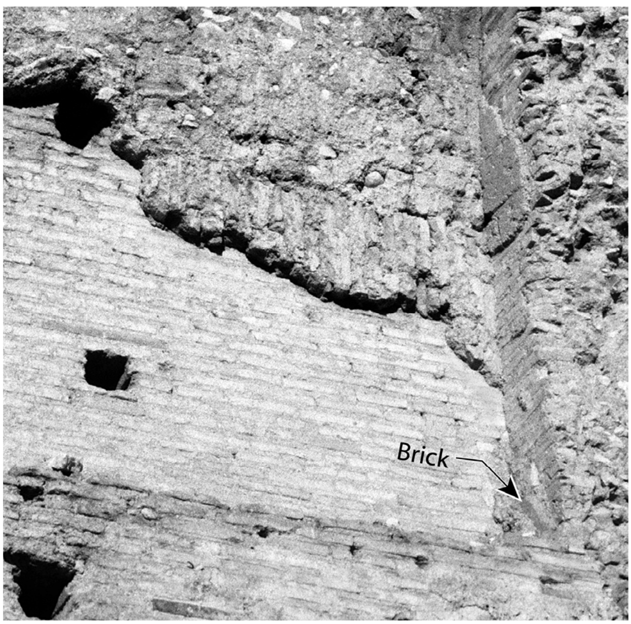

Figure 9. Argos, Greece. Detail of remains of brick vault in main hall.

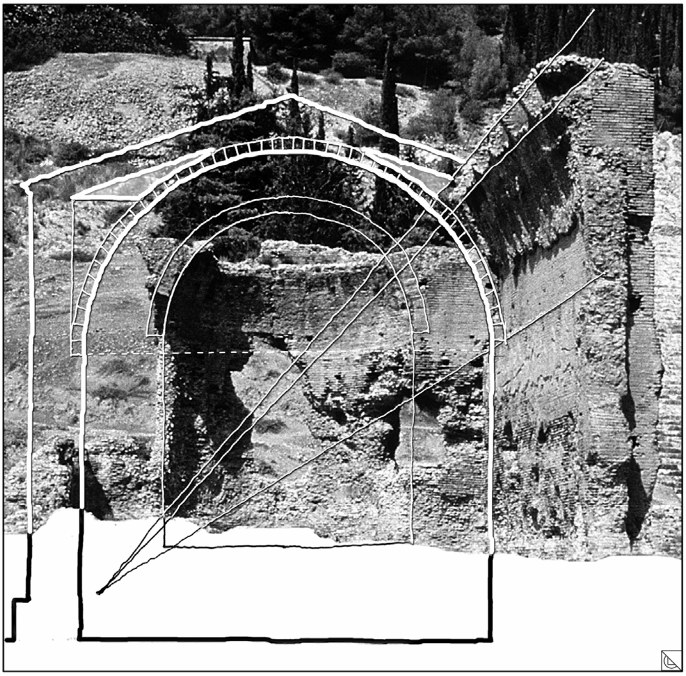

Figure 10. Argos, Greece. Remains of main hall with section sketch showing section and voids in vault.

Figure 11. Argos, Greece. Detail of remains of vault of main hall showing voids divided by low walls over haunch.

At first glance, the placement of the voids over the haunch may seem counter to the principle discussed at the Hadrianeum whereby the haunch was made heavy and the crown light, but a comparison of the two vaults shows that the hollow zones in the Argos vault actually begin at a higher level than the change to lightweight scoria in the Hadrianeum so that the mass was, in fact, concentrated above the lower haunch and lightened on the upper part. Unfortunately the upper part of the Argos vault does not survive to reveal how the intersection of the brick vault and the concrete shell was handled at the crown.

As noted by the excavator, the way in which the bricks were laid in the vault is very similar to the method often called "pitched brick vaulting", a technique commonly used for mud brick construction in Egypt and the Near East since at least the second millennium BC. It was a method which required very little wooden centering and was first adopted in areas where wood was scarce. In this type of construction, the first few arches of brick were slightly canted, or "pitched", against the back wall to form the curve of the arch **(fig. 8)**. The following arches of brick could then be "glued" to the next using quick setting mortar, often of gypsum. The combination of quick setting mortar with the slight incline of the bricks prevented them from sliding down due to gravitation force. The vault at Argos is somewhat different than the traditional method in that the bricks are placed upright rather than pitched and regular lime mortar was used. These details suggest that the main objective of the builders was not simply to avoid the use of wooden centering, as some form of centering would still have been necessary, especially for a vault of this size. Another explanation is that they thought this method of laying the bricks would help reduce the lateral thrusts. The typical method of laying the bricks radially is based on the assumption that the bricks act as voussoirs and distribute the thrust to each side as described by Vitruvius (*De Arch*. 6.8.4). In Rome, this was used in structural situations to channel the loads to particular points within the structure (Lancaster 2005, pp. 88-97). At Argos, perhaps the builders believed that by effectively "gluing" the bricks side by side they were creating a system which was stronger and more crack resistant so that the thrusts would not develop (?).

By creating voids above the upper haunch of the vault, the builders managed to reduce the weight of the vault by about 11.5 % and at the same time keep the weight above the lower haunches. This method is still not as effective as the use of the lightweight materials in the vault of the Hadrianeum, but it was more effective than the use of the hollow box tiles at Bath because it created a more advantageously placed void. The advantage of using the volcanic material is that there is greater control over the weight in all parts of the vault.

The cult building at Argos is the earliest large-scale, freestanding barrel vaulted structure yet known, and it represents the earliest example of vaulting using the method of laying bricks on edge (albeit not "pitched") in the Empire outside of Roman Egypt. Aupert and Ginouvès (1989) have interpreted the cult building as a temple to the Egyptian god Sarapis and suggest that the decision to build the brick vault using bricks laid on edge instead of laid radially was because Egyptian workers were imported for the construction of the temple to an Egyptian god. The identification of the deity as Sarapis, however, is based on an analysis of building typology and votive finds in the area relating to Egyptian deities and cannot be considered definitive. Aupert goes on to argue that the building was later known as the temple of Aesclepius, which was mentioned by Pausanius (2.21), due to a syncretism of the two gods (both associated with healing). In this scenario, the baths would then have been added to the Sarapis/Aesclepius sanctuary as part of its curative function (Aupert 1985; Aupert 2001, pp. 448-9). Aupert's argument regarding the attribution of the building to Sarapis/Aesclepius is complex, and there is no direct evidence to confirm it, but in relation to the construction techniques used, the building itself need not necessarily be dedicated to an Egyptian deity to explain the use of the vaulting technique. The worship of various Egyptian deities is attested in the area (Vollgraff 1958, pp. 556-70), any of which could have brought people familiar with the native land to the area. Alternative explanations, such as the presence of ex-soldiers from Egypt experienced in building, could also be posited. Unfortunately the evidence for a definitive explanation is lacking.

Another possible attribution of the building is that it was related to the imperial cult. Fragments of an inscription with bronze letters (the use of which is usually associated with the imperial family: Rose 2003, pp. 65-6) were found rebuilt into both the cult building and the later bath building. The inscription was a dedication, apparently by a priest of the imperial family, for the base of a series of statues (Piérart 1974, pp. 776-7; Aupert 1978, p. 773; Aupert 1982, p. 639). The fact that it was destroyed fairly soon after it was erected during the first century AD is unusual and could imply that the building in which the pieces were re-employed was under imperial sponsorship itself. The temple complex was among the largest structures in the center of Argos and was therefore of great importance. The use of such an unusual building techniques for the vault would be in keeping with an imperially sponsored project with significant resources.

CONCLUSIONS

The three vaults examined demonstrate that the Roman builders throughout the Empire understood the basic principles involved in reducing lateral thrusts by manipulating the mass of the vault. More interesting, however, are the different ways in which they accomplished similar goals given the available materials in each location.

The Hadrianeum was part of a development in the use of lightweight volcanic stones to control the mass of large-scale vaults in Rome. The *systematic* importation of scoria from Vesuvius for large imperial structures began under Trajan at the beginning of the second century (at about the same time as the vault at Argos was built), culminated in the Pantheon dome, and continued to be employed until the late third century. The Hadrianeum follows this development but represents a new turn in the combination of architectural style with building techniques and materials. It was the first example of a traditional peripteral temple to employ a barrel vaulted cella, and given the 18 metre span of the vault it was quite a daring endeavor which in some ways reflects the level of confidence attained after the success of the Pantheon dome.

The vaults at Bath using hollow voussoir tiles also represent a developed form which had earlier precedents. The method adopted to lighten the vaults came directly from the terracotta industry and was inherently related to bath technology, both of which were introduced into southeast England by the Roman military. The scale of military production of terracotta (both building materials and table ware) can be seen in the remains of the large kilns at the Holt depot outside of the legionary fort at Chester (the baths of which also employed hollow tile voussoirs in the vaults: Mason 1990). Direct military connections with Bath do not exist, but a number of inscriptions indicate the presence of soldiers who were either buried there or came there to make a dedication (Cunliffe 1984, pp. 183-7), so it was not devoid of military minds. The principle of regulating mass to control lateral thrusts was one that developed in the volcanic areas of central Italy, but as Roman influence spread the principle was adapted to the different technologies available, and the military was often a primary agent for the spread of building technology in some parts of the Empire.

The vault at Argos is unique, but it was built at a time when in Rome the use of the lightweight scoria to control the mass of concrete was being perfected in such structures as the Baths of Trajan and the Basilica Ulpia. Unlike the Hadrianeum, which took the form of a traditional peripteral temple, the complex at Argos was based more on the Hellenistic precedents of cult buildings for hero and ruler worship (for parallels, see Yegül 1982, pp. 13-7, esp. figs. 5-6). So, both the architectural typology and the building techniques were drawing inspiration from eastern sources. The suggestion of Egyptian influence for the brick vault construction is possible, but the construction of the concrete shell and the fired brick wall facing is decidedly Roman. The combination of the two together represents the way in which different building traditions within the Roman world could be combined to create unique solution to the problem of reducing the lateral thrust of a freestanding barrel vaults. One hopes that the final publication of the structure will provide additional insight into its mysteries.

In sum, the three buildings examined demonstrate the ingenuity of the Roman builders in applying their accumulated structural knowledge to the construction of buildings with different functional requirements, each by means of large-scale barrel vaults employing sophisticated and creative solutions to control their stability.

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