Auguste Choisy and the Economics of Roman Construction

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In the presentation of the Gold Medal by the Royal Institute of British Architects to Auguste Choisy in 1904 and in his obituary in the journal of that same institution in 1909, Choisy is repeatedly praised for insight into Roman construction and his emphasis that «economy in expense was one of their principle considerations» (Spiers 1909, 741). Indeed this was a primary theme in the first of his major works, *L'art de bâtir chez les romaines* (1873). His focus on the economics of construction colored the understanding of Roman building throughout the twentieth century and into the twenty-first. His work can be considered the intellectual ancestor of the chapter called «Economy of Construction» in W. L. MacDonald's *The Architecture of the Roman Empire* ([1965] 1982) and later of J. DeLaine's study, *The Baths of Caracalla: A Study in the Design, Construction, and Economics of Large-Scale Building Projects in Imperial Rome* (1997). Choisy's work is listed in the bibliography of every major handbook of Roman construction, yet specific references to his ideas are often critical or non-existent. His examination of Roman construction methods in relation to the economy as a whole was his lasting legacy, but ultimately it also led him to propose some problematic interpretations. His determination to explain the monumentality of Roman construction in terms of economic efficiency acted as a filter through which he understood Roman building sometimes to the exclusion of other evidence and approaches. On the other hand, his training as an engineer gave him an understanding of material properties and structural principles that provided an insightful perspective into the construction process. Unfortunately, this aspect of his work did not have the lasting influence of his economic theory even though the

two were interrelated, and it did not pass down to many of the 20th-century archaeologists, who were ultimately responsible for shaping our understanding of Roman architecture and construction.

Choisy and the idea of the monolithic concrete vault

One of the great advantages that Choisy brought to the study of Roman construction was his understanding of the way materials and structural systems interact. He is probably one of the first scholars to come to a logical explanation of the structural behavior of Roman concrete in response to the structural techniques employed by the ancient builders. One can see in his works that his understanding of the material developed over time. *L'art de batir romaine* (1873) was published when he was only 33 years old and was the first of his major works. By the time he published his capstone work *Histoire d'architecture* in 1899, some 25 years later, his explanation of the behavior of Roman concrete was somewhat more nuanced. In both works, he was struggling to deal with the concept of the monolithic nature of concrete vaults that was current in his day.

The concept of the monolithic concrete vault is based on the idea that Roman concrete, due to the use of the volcanic ash, pozzolana, was so strong that it acted as a «monolith», or a rock, and therefore transferred no lateral thrust onto its abutments. Choisy himself uses the term «monolithe» to describe Roman concrete when he raises the issue of lateral thrust of vaults. He notes that «It is, apparently, one of the great advantages of monolithic vaults that they can be supported without any auxiliary abutment». He then concludes that the Romans could see the danger in relying too much on the monolithic nature of the material because they took measures to counteract the potential lateral thrust by adding buttresses (Choisy 1873, 92). Later in his 1899 treatise, *Histoire d'architecture*, he adds to his previous observations when he notes that «the concrete vault is an artificial monolith and, as such, it cannot overturn its supports without breaking. In theory one can design a monolithic vault without buttresses if it supports itself, as would a metal arch, by the resistance to tensile forces which develop within its mass» (Choisy 1899, 523). He then explains that in reality masonry does not resist such internal tensile stresses well and therefore the Romans prevented the lateral thrust by countering them with buttresses. Here Choisy is making a distinction between the *theoretical* monolithic properties and the *realistic* fact that the material can and did succumb to breaking («se rompre»).[1] This distinction between theory and reality suggests a level of clarity in his thinking about Roman concrete that was not present in his earlier work.

Unfortunately, the archaeologists who later wrote about Roman structures too often took the idea of the theoretical monolith and presented it as reality, thus leaving generations of students believing that Roman concrete truly acted as monolith with no lateral thrust. These later scholars put much more emphasis on the important strengthening properties the pozzolanic mortar imparted to the concrete, but in doing so, created a type of «cult of pozzolana» that led to the idea that it did indeed create a monolith capable of withstanding whatever tensile stresses developed.[2] This also led to discussions of structure that lacked any coherent logical basis. For example, M. E. Blake, J. B. Ward-Perkins, and J.-P. Adam all refer to Roman concrete vaults as having monolithic qualities, yet each in turn goes on to discuss methods of buttressing employed to counter lateral thrust.[3] *Theoretically*, if the concrete acts as a monolith then it has no lateral thrust and therefore no need of buttresses. If buttressing is necessary to establish stability then the vault is not acting as a monolith. The Roman builders themselves were quite clear that their concrete vaults produced lateral thrusts, and they developed numerous ingenious methods of countering them. Today we understand that Roman pozzolanic concrete can resist some tensile stresses just as a stone beam can, but there are limits to this resistance in both stone and concrete. Just as the stone beam will crack once its span reaches a certain length, so too will a concrete vault. However, the arched form of the vault ensures that it will remain stable even after cracking as long as adequate buttressing is provided to counter the lateral thrust and transfer it to the ground.

Once Choisy had explained why buttressing was necessary, he then examined its use in light of his theory of economy of construction. His conclusion was that the Roman architects cleverly arranged their structures so that buttressing elements were integrated into the design of the building rather than being attached to the exterior (Choisy 1873, 92–95, Choisy 1899, 528–29). The example he uses to illustrate this point is the Basilica of Maxentius, where the thrust of the central cross vault is carried to the ground through the perpendicular walls of the adjacent barrel vaulted rooms (figure 1) So from the exterior, most of the buttressing was disguised and had the dual function of providing both support and extra internal space. This is an example where Choisy's understanding of structural behavior and his theory of economy of construction combined to provide a new insight into the nature of Roman design that has remained fundamental to the understanding of the relationship between structure and design in Roman architecture. It is a principle seen in such structures as the Golden House of Nero, the Colosseum, the Pantheon, and the imperial thermae.

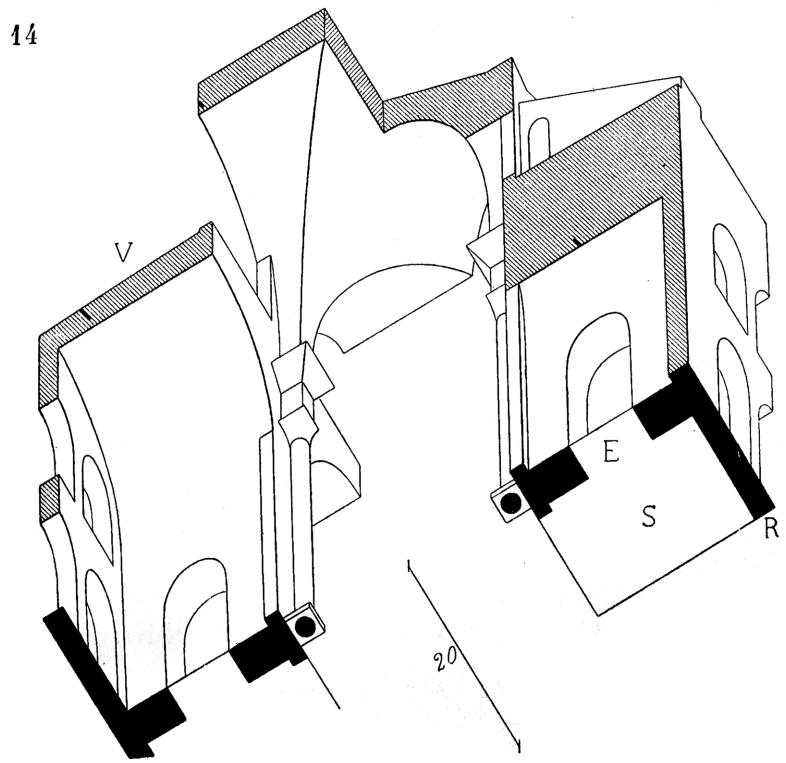

Figure 1
Choisy's drawing of the Basilica of Maxentius showing how wall E of room S acts as an internal buttress for the cross vault of the central nave. (Choisy 1899, 528 fig. 14)

Choisy's interpretation of vaulting ribs as a means to achieve economy of construction

One of the techniques that most captured Choisy's imagination with regard to the economics of construction was the use of brick vaulting ribs. In his Gold Medal acceptance speech to RIBA, Choisy noted that as a youth he was tremendously affected by an article he found in his father's library by Robert Willis, «On the Construction of the Vaults of the Middle Ages», in which Willis distinguished between a structural and a decorative nature of the ribs along the groins of Gothic vaults (Willis 1842). This paper also influenced M. Viollet-le-Duc, who argued that the ribs in both Romanesque barrel vaults and Gothic groin vaults were intended to act as a permanent centering, and in the case of groin vaults they were

critical in carrying the load to the corner supports (Viollet-le-Duc 1854–1868, 4: 14, 21; Huerta 2009, 838). Such ideas about the vaulting of later periods likely influenced Choisy's discussions of ribs in Roman vaults. At one point he makes a direct parallel between the Roman ribs [«armatures»] and the Gothic ribs: «Who doesn't see, indeed, in the ribs of these vaults of the Middle Ages the equivalent of the ancient armatures?» (Choisy 1873, 44). He seems to have been intent on finding precursors to the Gothic ribs that had captured his imagination as a youth.

An examination of Choisy's interpretation of the brick ribbing embedded within the core of Roman vaults reveals how the contemporary discussion of Romanesque and Gothic ribs affected his ideas. Starting from his premise that the Romans were trying to be as economical as possible with their materials, he interprets the Roman vaulting ribs, which often consist of a brick latticework construction (figure 2), as an attempt to reduce the number and size of centering frames. By placing the frames under the brick arches, which would be self supporting once complete, they could be much lighter because the brick ribs would take much of the load off the frames (Choisy 1873, 40–41, Choisy 1899, 525). For this «armature» of arches to work as described by Choisy, the arches had to be completed before the concrete of the vault was laid, and this is how he has illustrated the process in his drawings (figures 3–4). However, a close examination of such lattice ribs reveals that they are not built as carefully as shown in the drawing, which he admits in the following statement: «the aspect of these auxiliary works reveals a very hasty execution; and the inaccuracy of the forms is sometimes so great there that to illustrate the ideas of the builders, I had to give these reinforcements a regularity in my drawings that an examination of the ruins could contradict in more than one case». (Choisy 1873, 41–42). He explains the crudeness of the ribs as a necessity of the process: they had to be built very quickly so that unskilled labor (who he assumed consisted mainly of slaves) would not be idle for long periods while the ribs were constructed by more skilled labor (Choisy 1873, 42–43).

The interpretation of the ribs given by Choisy reflects the differences in approaches to ancient monuments between scholars with different types of training. As an engineer, he is asking how the vault actually behaved, and he developed a rationale for the techniques he saw used in Roman structures based on this understanding. However, from an historical and archaeological perspective one can also ask how the *Roman builders* understood the behavior of their material. The answers to the two questions can be quite different. Further study of the constructional details of the ribs suggests, in fact, that the Romans did not build the ribs separately from the surrounding concrete as suggested by Choisy. One of the monuments that he illustrates is the cross vaulted substructure at the Palatine

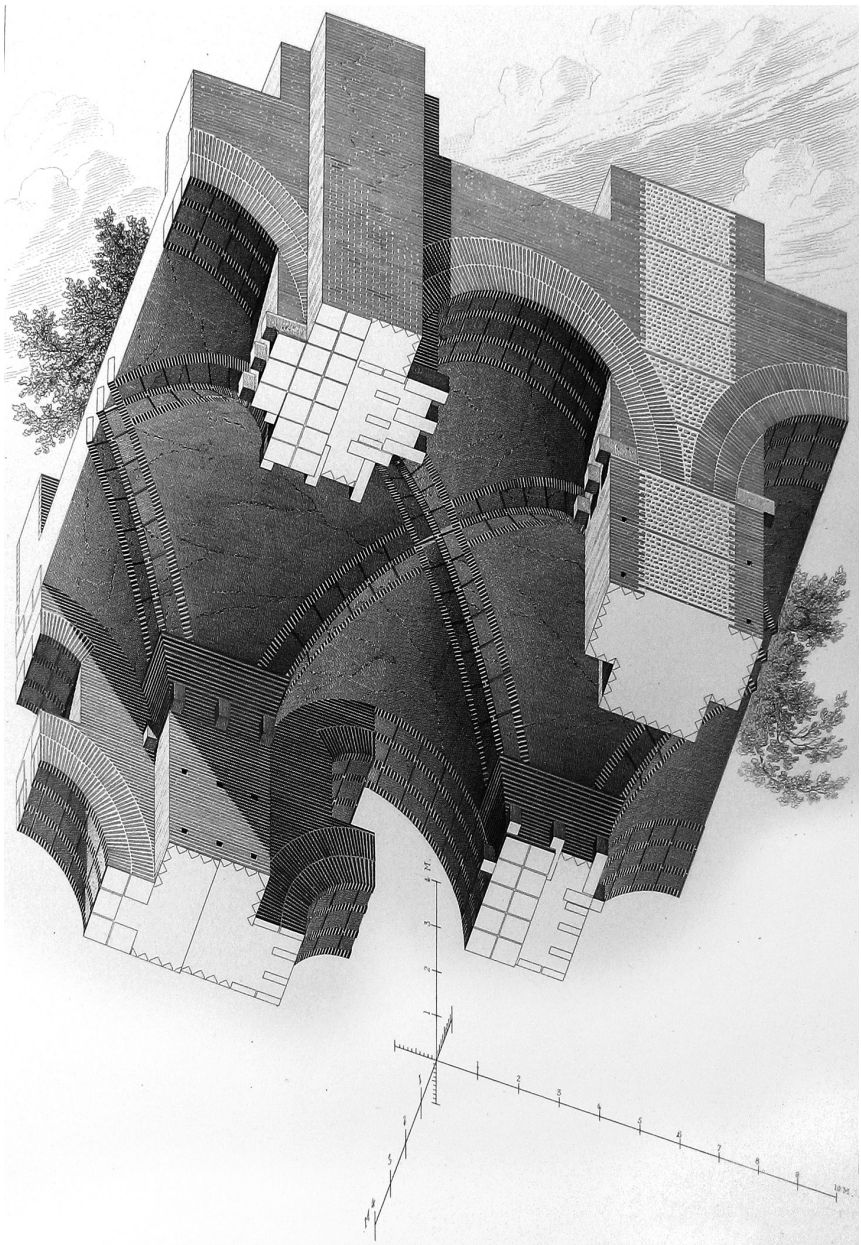

Figure 2
Choisy's drawing of the ribbing in the Maxentian substructures on the Palatine (Choisy 1873, Pl. 8)

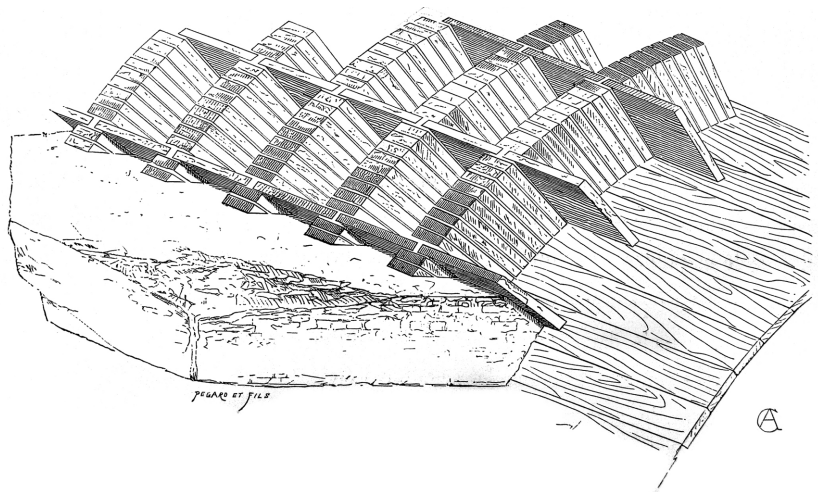

Figure 3
Choisy's proposal for the way in which lattice ribs were constructed in barrel vaults (Choisy 1873, 47 fig. 18)

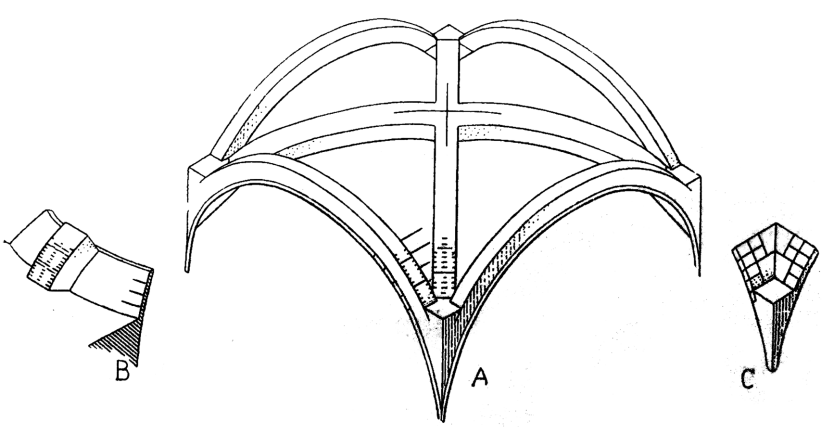

Figure 4
Choisy's proposal for lattice ribbing in cross vaults (Choisy 1899, 526 fig. 12)

(figure 2), which he believed had ribs constructed before the concrete of the vault was laid. But, close examination of the formwork imprints remaining along the intrados shows that the builders applied a thin layer of mortar to formwork before laying both ribs and concrete (figure 5). Since this layer is continuous under the concrete and the ribs, both parts must have been laid at the same time as the vault rose. Another piece of evidence indicating that the Roman builders did not build these lattice ribs independently from the surrounding concrete can be seen in the preserved remains of the decagonal dome of the «Temple of Minerva Medica». The dome has numerous lattice ribs running along the meridians, but some of the ribs do not extend all the way to the crown (figure 6b). At point A in Figure 6, one can also see that one of the large bricks forming a leveling course bridges the rib and the surrounding concrete thus suggesting that both were laid simultaneously. J. J. Rasch's photogrametric study of the dome has shown a correspondence between the ends of the formwork boards and the leveling courses of brick, which indicates that the vault and centering were built together layer by layer as the vault rose (Rasch 1991, 330–35).

One of the great debates in Roman construction is whether the ribs functioned only during construction thereby ceasing to play any structural role after the hardening of the concrete or whether they continued to play an active role during

Figure 5
Photograph of Maxentian substructures on the Palatine (early 4th century A.D.). Arrows indicate formwork imprints that cross under ribbing. Author's photo

the life of the structure. Choisy, followed by many others like Blake (1959, 94, 163), Ward-Perkins ([1070] 1981, 68, 434–35) and MacDonald ([1965] 1982, 159 n. 44) adhered to the former explanation while others, like Giovannoni (1925, 39-41), Rivoira (1925, 144), De Angelis d'Ossat (1940, 239, 47–48), and Lugli (1957, 668), believed the latter. Choisy (1873, 58) stated that «this internal frame was useful during construction only. It allowed the vault to be built up; but it loses its value and its role as the mass becomes solid; finally, once the mortar consolidated, it ceases to have an independent existence, and does not appear any more in the vault but as an integral part of the whole». The engineer G. Giovannoni (1925, 40) later disagreed with Choisy's interpretation of the ribs and asserted rather that they were intended to channel loads through the structure. From a structural perspective this is an important question, but from an historical perspective, the more important issue is how the *Romans* thought about the material rather than how we think about it today given our modern methods of analysis.

Evidence from the buildings themselves suggests that Romans believed that the ribs played an active role in reinforcing the concrete, even after the concrete hardened. The example mentioned above at Minerva Medica where the entire vault, including the ribs, was built in layers indicates that the builders did not intend for the ribs to be «active» during the process but rather after the whole was completed. How long they intended them to be active (during the curing process or for the life of the building) is unclear. By the time Minerva Medica was built in the first half of the 4th century A.D., the Romans had been building concrete vaults for five centuries, so it represents a highly developed understanding of the material. However, even as early as the 1st century A.D. there are indications at the Colosseum that the builders were using elements such as vaulting ribs and relieving arches in walls as a means of channeling loads through the structure, and they apparently perceived such elements to be active elements within the structure (Lancaster 2005b, 64–70).

A criticism that was later made of Choisy's work on Roman construction techniques is that he viewed Roman construction of the imperial period synchronically as a single period rather than diachronically as a developmental process. The archaeologist G. Lugli (1957, 17) in particular criticized Choisy for failing to establish a developmental chronology for the techniques he examined. Choisy himself seems to realize that he was open to criticism on this account when he says «I do not claim to trace the historical sequence of the facts and the true course that the processes followed: the relative date of the various vaults that will be necessary for us to compare is usually rather badly known; so it would be bold to want to find, in the current state of archaeological knowledge, the true development of the Roman ideas; I only propose to demonstrate, through the diversity of the forms, the dominant thought which governs the principal motive allotted to

the permanent frames of the ancient vaults» (Choisy 1873, 49). As an archaeologist, I see this as a critical methodological flaw if the goal is to determine why the Roman builders made the choices they did, in part because their thought clearly changed over time as they gained more experience. Ultimately, Choisy seems to have worked backwards by taking what he understood of the ribs of the Middle Ages as well as his understanding of the behavior of concrete and applying it to interpret the Roman vaults rather than taking Roman vaults on their own terms and examining the details to understand how and why the techniques developed.

Indeed if he had taken into consideration chronology, he would have discovered that the lattice ribs were a late development, largely of the third century and later, and that the precursors were solid brick ribs that were evidently intended to reinforce sections of a vault that supported a dead load above. An examination of the developmental chronology of brick ribs in concrete barrel vaults illustrates

Figure 6
Detail of ribbing in the dome of the «Temple of Minerva Medica» (4th century A.D.). «A» indicates ribs that do not continue to crown. «B» indicates brick crossing between rib and fill, which divided horizontal construction layers. Author's photo.

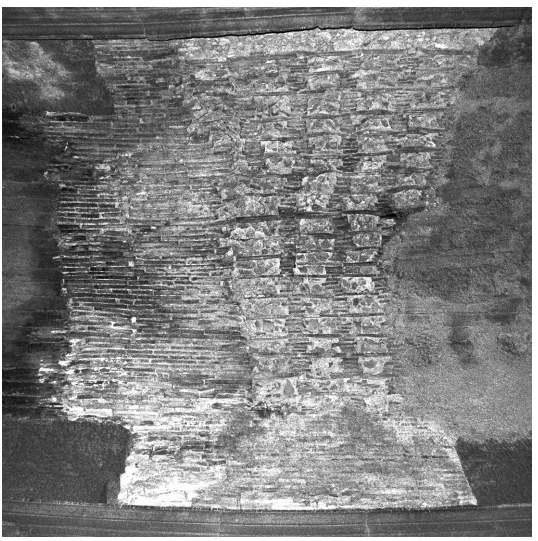

Figure 7
Photograph of rib in outer ambulatory of Level II of the Colosseum. The left half consists of solid brick ribbing from original construction in 80 A.D. and right half consists of lattice ribbing rebuilt after the fire of 217 A.D.. Both types of ribbing act as reinforcing for a stair above at Level III. Author's photo

that many were initially built of solid bricks laid radially and were clearly intended to direct point loads within the structure and that the lattice ribs came later as an economical replacement for the solid type (Lancaster 1998, 154, 171). This is most clearly illustrated at the Colosseum where one of the original solid brick ribs was repaired after the fire of A.D. 217 with the more economical lattice ribbing (figure 7). In fact, Choisy noticed this difference at the Colosseum when he commented: «Either because the vaults were remade at various times, or because construction was shared between various contractors enjoying a certain independence regarding the techniques, one notices in the various vaults of the building [Colosseum], and sometimes in the various parts of the same vault, the most disparate methods» (Choisy 1873, 52). By the 4th century, the lattice ribbing apparently developed into a method of consolidating the mass of concrete in addition to its role of directing point loads, as is particularly evident in the pattern of the ribbing in the dome of the «Temple of Minerva Medica» (figure 8). The developmental chronology also demonstrates a close connection between the change in rib construction and the decline of the brick industry in Rome during the 3rd cen-

tury (Lancaster 2005a, 111–12), a connection that no doubt would have delighted Choisy had the understanding of the brick stamps and the brick industry been so advanced in his day. Choisy's true contribution to the study of vaulting ribs in Roman construction was not so much in accurately explaining the function of the ribs as it was to open a new line of enquiry that focused on the importance of the construction process and to provide a new way of looking at the monuments.

Choisy's interpretation of brick linings on the intrados of vaults

Another technique that Choisy highlighted as a method developed to increase the economy of construction by reducing the amount of centering was the use of brick linings along the intrados of vaults (figure 9). The Roman linings consisted

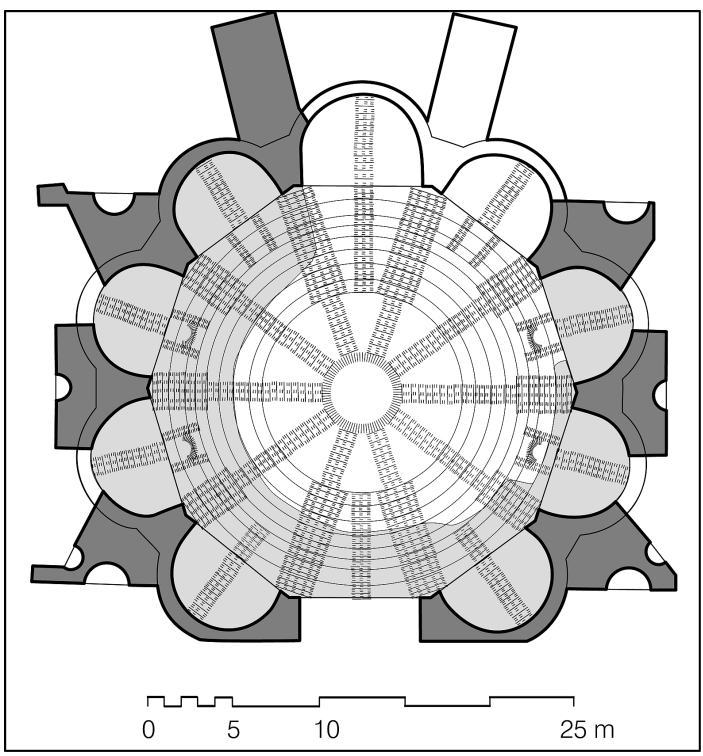

Figure 8
Reflected ceiling plan of the ribbing in the dome of the «Temple of Minerva Medica» (4th century A.D.). Author's drawing

of two layers of bricks laid flat against the centering so that they created a permanent formwork. The first (lower) layer usually consisted of large bricks, bipedales (58 cm square). The second (upper) layer consisted of small bricks, bessales (20 cm square), that either formed a grid covering the joints of the larger bricks or a continuous surface covering the entire layer of large bricks. They were held in place by a layer of fine white lime mortar.[4] Choisy points out that the large size of the bipedales would allow the fewer formwork boards to be used thereby reducing the amount of wood, as shown in figure 10.

He also saw a similarity between the Roman brick linings and a technique used in his day that employed bricks laid flat, which he called *volte alla volterrana* or *volte a foglio* (Choisy 1869, 295), also known as timbrel vaulting today. When he was in Rome during the latter half of the 19th century many of the apartment blocks going up in the city were employing this technique, which involved building vaults without the use of wooden centering by «gluing» small light weight bricks together edge-to-edge with gypsum mortar, which hardens within minutes, so that a thin shell was formed. The shell was then strengthened by using a stronger mortar to adhere a second layer of bricks on top. The lamina-

Figure 9
Substructures of the Terme della Tricrinaria, Ostia (III.16.7) with brick lining along intrados of vault consisting of bipedales with a grid of bessales above. Author's photo

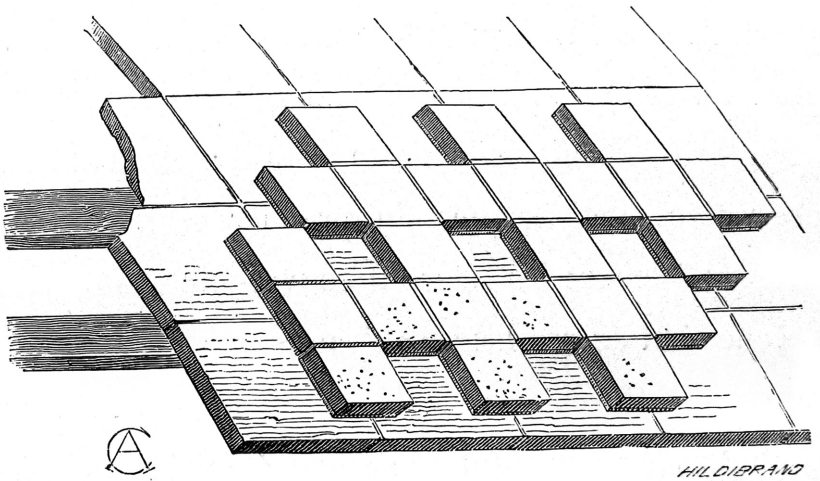

Figure 10
Choisy's drawing of brick lining consisting of lower layer of bipedales and upper layer of a grid of bessales (Choisy 1873, 65 fig. 32)

tion between the two layers resisted shear, and the result was a very thin yet strong and light vault that was built without wooden centering (Collins 1968). The visual similarity between the Roman linings and the timbrel vaulting led Choisy to propose that the Roman technique was also intended to be self supporting at a certain point in the process so that the wooden centering could be removed to be reused for the next vault before the concrete for the first was completely laid (Choisy 1873, 61–62).

His illustration from 1873 (figure 11), which shows how the linings could act as a self supporting shell, is theoretically viable since filling the haunch above the lining would have allowed the line of thrust to remain within the section of the vault, but the idea that the Romans intended the linings to be self supporting at any point during the process is unlikely. The large bipedales used to form the lining each weigh around 25 kg, whereas those developed for timbrel vaulting were small rectangular bricks (15 cm × 30 cm) that weighed only about 1.2 kg.[5] Moreover, the bipedales of the brick linings that remain in situ show no trace of mortar connecting them along the edges. Even those in utilitarian areas that were never covered with plaster show no signs of mortar oozing from cracks other than some traces that seeped in from the lime layer used to glue the upper layer of bessales in place; they were apparently laid next to

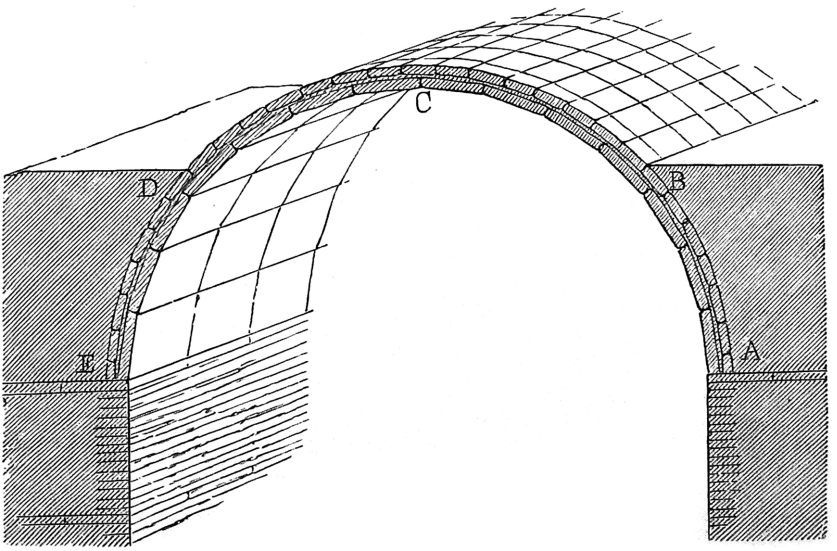

Figure 11
Choisy's proposal for the way in which the brick linings could have been partially self supporting during the construction process (Choisy 1873, 64 fig. 28)

each other completely dry with no attempt to create a continuous rigid shell. The second layer of many of the linings consists of a grid of small bricks covering the joints of the bipedales (figures 9–10), but the use of the grid instead of the solid layer would have reduced the capacity to resist shear by concentrating greater stress within a smaller area. The grid was more likely intended to provide purchase so that the bipedales did not fall off the intrados after the vault was completed.

In his 1899 treatise, Choisy (1899, 524–25) goes further and suggests that for small vaults the linings could be erected without any centering by gluing the large bricks edge-to-edge as in timbrel vaulting (figure 12), but given the weight of the bricks and the fact that there is no mortar preserved along the edges, this is clearly not viable. Figure 13 illustrates a small cistern from Ostia (ca. 1.7 m span) that originally had only four bipedales making up the profile of the vault, yet still visible projecting from the wall are the stone corbels that held the centering frame. In Choisy's day there were few examples where the bipedales actually remained in situ for examination. The examples he illustrates, such as those at the Palatine and at the Baths of Caracalla, are ones where the bipedales have

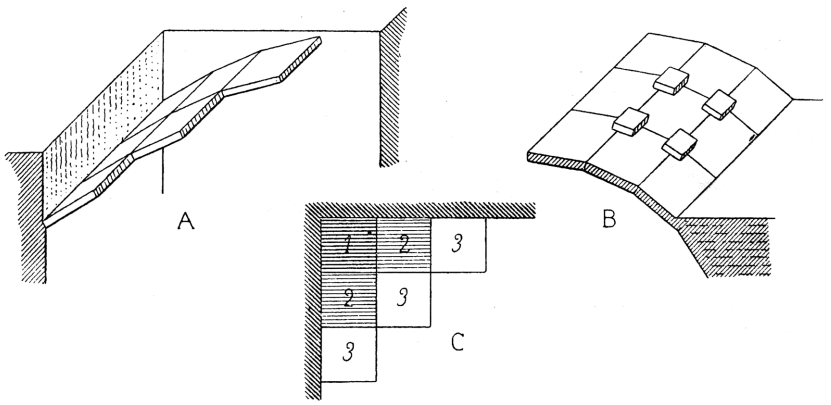

Figure 12
Choisy's proposal for the way in which the bipedales of brick lining could have been laid without centering (Choisy 1899, 525 fig. 11)

Figure 13
Cistern at Casa delle Volte Dipinte, Ostia (III. 5. 1) with brick lining along the intrados of the vault (ca. 1.7 m span). Arrows indicates corbels used to support centering frames. Author's photo

largely fallen away. The best preserved examples can be seen today at Ostia, which was not extensively excavated until after his death. So he did not have the opportunity to examine all the details that are now accessible.

Choisy's overall approach to the linings as a method to facilitate the construction process is surely correct even if some the details are not. In addition to reducing the amount of wood used, they could have also prevented the wood from sticking to the mortar thereby allowing the centering to be removed and reused elsewhere. In spite of my criticisms, Choisy's explanation of the linings as a means of economizing and aiding the construction process is insightful and served to focus attention on the efficiency of the construction process in striving for economical methods.

Choisy's overview of the relationship between economy of construction and society

Choisy ends his 1873 tome on Roman construction with an historical essay in which he relates the building industry to what was known from literary and inscriptional evidence. Choisy was a type of Renaissance man: trained in engineering, skilled in drawing, and adept at Latin. These combined skills allowed him to explore Roman construction from a variety of perspectives and make connections that had not been made previously. In his historical essay he applied his language skills to the original texts that he saw as critical in understanding the society that had created the impressive constructions he had been studying. He was one of the first to ask the following questions, which so concern us today: How much of the construction industry was made of free labor and how much of slaves? From what regions did the people who made up the labor force come? How could their skills be most usefully applied? How did the processes employed relate to the skills of the workforce? (Choisy 1873, 187). These questions are still of critical importance in establishing our understanding of the role of construction in society.

Choisy was particularly interested in the role of the professional collegia and the use of military personnel in construction. He was fascinated by the collegia because he saw in them the forerunners of the medieval guilds (Choisy 1873, 201). The professional collegia were organizations or clubs organized by various trades. Members joined by paying membership fees so they had to be reasonably successful in their profession. The collegia were open to all classes, though a large part of the membership was clearly freedmen, former slaves. During the 1st and 2nd centuries, they organized such benefits as feasts and guaranteed burial plots for their members. Choisy's work was published before the major study of the collegia by Waltzing (1895–1900) at the end of the 19th century, so

he did not have the benefit of a systematic study of the written sources on which to rely. In fact, one of his major secondary sources on the collegia was a Latin dissertation from 1735! Thus he had to use his own Latin skills to read the primary sources, inscriptions and legal codes to understand the role of the collegia in construction.

Choisy argues that the collegia were instrumental in providing the government cheap and available labor. He describes the collegia as representing «a society of workers deeply distinct from the rest of Roman society, and directed by a hierarchical organization and by a system of privileges and constraints within the hands of the emperors» (Choisy 1873, 188). He saw a change from the more independent character of the collegia during the Republic to one of imperial control beginning under Hadrian in the 2nd century and in full force by the 5th century. There was indeed a significant change in the nature of these collegia so that by the 4th and 5th centuries they were no longer independent organizations that one could join at will but rather had become a means of requisitioning and controlling labor. However, the change did not occur as early as Hadrian and was a late antique response to the grave economic conditions that had begun during the mid 3rd century (Jones 1964, 858-64). Choisy's idea that the change occurred earlier was based on his interpretation of a passage by Aurelius Victor noting that Hadrian «enrolled by cohorts and centuries, on the model of the legions, builders, geometers, architects and every sort of expert in construction or decorations».[6] But, this passage refers to Hadrian's building in the provinces and does not actually mention the collegia. The evidence for the change in the status of the collegia is found in various passages of the legal codes of Theodosius and Justinian, which are dated to the 5th and 6th centuries respectively. Thus the largest and most impressive Roman projects, such as the Colosseum, Trajan's Forum, the Pantheon and the Baths of Caracalla do not fit the model he proposes of strict imperial control over the labor force. In fact, during the greatest period of building in the first half of the 2nd century the economy of the building industry in Rome was based on independent contracting (Brunt 1980). Recent work by J. DeLaine (2003, 727–32) on the collegium of the *fabri tignuarii* (literally «carpenters» but more generally «builders») at Ostia has shown that at the end of the 2nd century it did play a role in establishing contacts with wealthy members of society, often magistrates, which in turn could lead to job opportunities. In this sense, the collegium probably was instrumental in the organization of labor by providing a means of networking, but it was not yet in the hands of the emperor. So, again Choisy was very perceptive in focusing on an aspect of critical importance to the building industry even if his conclusions ultimately did not provide an accurate representation of the relationship between the social institutions and the construction techniques.

Conclusions

Choisy was one of the first to study Roman construction taking into account the importance of the process and how it relates to wider social institutions, but despite this fact he is rarely cited in modern literature that deals with the issues he introduced. One reason is that the specifics of many of his proposals have not withstood the test of time as more evidence was unearthed and methodologies were refined. Choisy's training as an engineer is what provided him with the insight to ask the critical questions that he did regarding Roman construction. It gave him the understanding of materials that he could apply to ancient monuments to understand better how they worked structurally. This type of training is precisely what many of the experts on Roman construction in the following century did not have, which led to a lack of logic in discussing the construction and behavior of Roman concrete vaulting. On the other hand, his engineering background also led him to interpret the ancient structures based on how he understood the materials to behave and on how he understood later construction such as the Gothic vaults in his native country as well as contemporary timbrel vaults he saw going up around him in Rome. The very understanding that provided him with new insights sometimes blinded him to examining the details from the monuments that could provide answers to the other question posed at the beginning of this paper: how did the *ancient builders* understand their material?

This clash of approaches between disciplines is one that still exists today. Engineers/architects and archaeologists/historians often work at cross purposes, the former interested in determining how a structure actually behaves, the latter interested in how the ancient people understood their structures to behave. For Greek and Roman construction, the problem of determining what the builders thought is exacerbated by the fact that there is so little literary evidence, aside from Vitruvius, to inform us about their thinking on constructional issues. This is one reason that a careful diachronic examination of constructional details is so important: it is often the only evidence that we have on which to base our interpretations of why a builder chose to use a specific technique in a particular period and context. Ancient construction was a continuum where knowledge was gained through trial and error, and the goals of builders often changed along with their understanding as well as with the changes in economic conditions. One intention in this study of one small aspect of Choisy's work is to highlight the importance of having multiple approaches to the study of ancient construction and of the need to communicate so that the various parties are working towards common goals and if they do not share the same goals so that they are at least aware of each other's differing goals.

In spite of the shortcomings I indicated in some of Choisy's proposals, his work was groundbreaking in that he emphasized the importance of the construction process as a critical aspect of understanding architectural achievement and he then attempted to relate these findings to the social institutions that provided the context in which those processes arose. This provided a broad perspective on the importance of construction in understanding larger societal issues so that the subject itself was relevant to a much wider audience. Many scholars are now emphasizing this approach in an effort to use construction history as means of exploring the economy of the Roman Empire. Today, however, we have the added advantage of much new evidence, both archaeological and written, that has been revealed since Choisy's death in 1909.

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Notes

1. His use of the term «se rompre» is ambiguous as to whether is referring simply to cracking or to a more substantial break in the structure.
2. The addition of pozzolana to lime mortar increases its strength by 5-8 times (Ferretti 1997, 70), and it also creates a hydraulic mortar that will harden under water. Moreover, pozzolana mortar gains its strength much more quickly than simple lime mortar. Choisy was apparently not all interested in the effects of the increased strength of pozzolanic mortar. In his first book, *L'art de bâtir chez les romaines* (1873), he barely mentioned pozzolana and offered no explanation of its significance. Later in *Histoire de l'architecture* (Choisy 1899), he notes that its use was probably the explanation of the hardness of Roman mortar but that in most cases the hardness was simply the result of hundreds of years of curing. Thus, he ignores an important role that pozzolana mortar could play in speeding up the construction process, but this approach also allowed him to focus on the behavior of the material without endowing it with the almost magical properties later attributed to it.
3. Blake (1959, 163) speaks of concrete becoming «monolithic» and then on the next page comments on the need for buttressing thus demonstrating a lack of understand of the material. Ward-Perkins ([1970] 1981, 101) notes that «it stood by virtue of the almost monolithic quality of the finished concrete mass» and speaks of «a concrete . . . which would stand as an almost monolithic unit». Adam ([1984] 1994, 177) notes that «The result is in effect a monolith (assuming the best quality mortar) in which a space has been carved out. The effects of the lateral pressures remain, but are considerably

absorbed by the cohesive power of the bonding agent, preventing the elements from moving».

4. A sample of the fine white mortar from the Cassegiate del Serapide at Ostia was tested to determine if it was lime or gypsum by placing it in hydrochloric acid, which reacts with the calcium carbonate in lime but produces no reaction with gypsum. The sample reacted with the acid by fizzing until it completely disintegrated, thereby indicating that it was indeed lime and not gypsum.
5. I thank John Ochsendorf for supplying this information from his forthcoming book, *Guastavino Vaulting: The Art of Structural Tile*. New York: Princeton Architectural Press.
6. Aurelius Victor *Epitome de Caesaribus* 14.5. Translation from MacMullen 1959, 215.

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