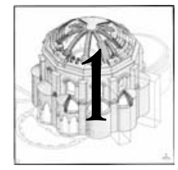


# INTRODUCTION

Concrete vaulted structures represent one of the ancient Romans' most original and enduring contributions to the artistic and architectural patrimony of the Mediterranean world. A combination of factors led to the development of the large spans and curvilinear forms still visible in buildings such as the Pantheon and the Basilica of Maxentius. Rome was endowed with a wealth of natural resources in its immediate environs, and what it could not supply for itself it could bring in from afar through the development of extensive trade networks. Along with the financial benefits of conquest came the architectural, technological, and mathematical expertise of the architects, builders, and engineers from the conquered territories. Augustus, in bringing the civil wars to an end, also brought a vision of urban renewal for Rome that provided incentive for more grandiose schemes than had previously been possible. By that time, the architects and builders had over a century of collective experience with concrete construction, but Augustus's creation of an organizational infrastructure provided a context in which new ideas and larger building schemes were possible. As emphasized by W. L. MacDonald, the fire that devastated much of Rome during Nero's reign in A.D. 64 effectively cleared the slate and provided opportunities to exploit the fireproof nature of concrete and in doing so created a new aesthetic based on the plastic potential inherent in the material.[1] In imperial Rome, all of the natural advantages and cultural influences came together and manifested themselves in imposing concrete vaulted structures, the remains of which are the focus of this study.

My intention is to examine the changes that occurred in the choice of materials and techniques used in concrete vaulted construction in Rome from the time of Augustus to Constantine and to place the results in the wider social, economic, and political context. I document the appearances of particular materials and building techniques and examine the reasons for their use and the ways that use changed over time. In particular, I am interested in techniques that aided in the creation of large and complex structures, such as the use of lightweight concrete, brick vaulting ribs, metal tie bars, and various forms of buttressing. In some cases, the choices of the builders were affected by external factors such as the availability and the cost of materials or the changes in the infrastructure of the building industry itself. The interplay between the decisions made on the building site and these external factors can create a window into the complexities of urban and suburban life in Rome.

### A NOTE ON MONUMENTS AND PREVIOUS SCHOLARSHIP

The monuments included in this study date from the reign of Augustus (27 B.C.), when the resources of the Mediterranean basin became widely available in Rome, to the reign of Constantine, when patronage was diverted to the new capital inaugurated at Constantinople (A.D. 330). The monuments are for the most part limited to buildings in the city of Rome and its immediate environs because I am particularly concerned with the local materials and the economic, social, and political factors unique to the capital city. Many of them are state-sponsored public monuments, such as the imperial thermae, basilicas, and places of public spectacles like theaters and amphitheaters. Some are imperial residential structures such as the palaces on the Palatine, the domed pavilion in the Horti Sallustiani, or the nymphaeum in the Horti Liciniani ("Temple of Minerva Medica"). Some structures in the immediate outskirts of Rome also are included, such as the Villa alla Vignaccia, the Villa di Sette Bassi, and the so-called Villa of the Gordians. Further afield are two imperial villas, Domitian's Villa in the Alban hills and Hadrian's Villa near Tivoli, both of which demonstrated innovative vaulting techniques that relate to developments in Rome itself. During the early fourth century, domed mausolea often located on suburban villas became popular, and these extramural structures are also examined. One monument important to this study is located outside of the immediate environs of Rome. The structure, known as the "Temple of Mercury" at Baiae on the Bay of Naples, is both the earliest preserved concrete dome and the largest spanned dome before the Pantheon and hence must be considered in any discussion of the development of concrete vaults.

One goal of the present work is to provide a synthetic study of the concrete vaulting in Rome by combining my own on-site observations with those of others to create an overview of the developments. This would not be possible without the publication of monographs during the past few decades by scholars conducting fieldwork on some of the major monuments in Rome: K. de Fine Licht on the Pantheon (1968), the Baths of Trajan (1974), and Sette Sale (1990); C. M. Amici on the Forum of Trajan (1982) and the Forum of Caesar (1991); J. E. Packer on the Forum of Trajan (1997); J. DeLaine on the Baths of Caracalla (1997); and J. J. Rasch on a series of late Roman domed structures including the Tor de'Schiavi (1993) and the Mausoleum of Helena (1998). The engineering works of J. Heyman (1995, 1996) and R. Mark (1982, 1990) have been particularly influential in my approach to the structural aspects of vaulting. I also have drawn on numerous articles by archaeologists, geologists, and engineer/architects working in Rome as well as on the invaluable resource of E. M. Steinby's *Lexicon Topographicum urbis Romae* (1993–2000). Although the study is in the spirit of previous works on Roman construction such as those by M. E. Blake (1947, 1959, 1973), G. Lugli (1957), J.-P. Adam (1994), and C. F. Giuliani (1990), my focus is narrower and my inquiry delves deeper into specific issues relating to the construction of large-scale concrete vaulting.

### HOW TO USE THIS BOOK

The book is organized so that it can be used by both general readers and specialists. The material in the remaining sections of this chapter and in the final chapter ("Innovations in Context") is intended to provide general discussions accessible to a wide audience. Each of the other chapters is provided with a brief introduction to the major issues and a conclusion that includes a broader overview and assessment

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of the material discussed within the chapter. A general reader can read the first and last chapters of the book as well as the beginning and end of each chapter to get an idea of the issues discussed and their relevance, whereas the specialist can delve into the details of the arguments presented within the chapters. I also have provided catalogues in Appendix 2 listing all of the documented examples of a particular technique, many of which are not discussed in the text. For those who want to pursue the subject further, these tables provide detailed information about every entry along with bibliographic references. In addition, I have included in Appendix 1 a catalogue of the main monuments discussed in the text and a map with their locations (Map 1, p. 4). For readers not familiar with a particular monument, Appendix 1 provides a catalogue with an introduction to each one followed by a list of the relevant vaulting techniques with cross-references to discussions in the text. A glossary of technical terms used is also provided at the end of the book.

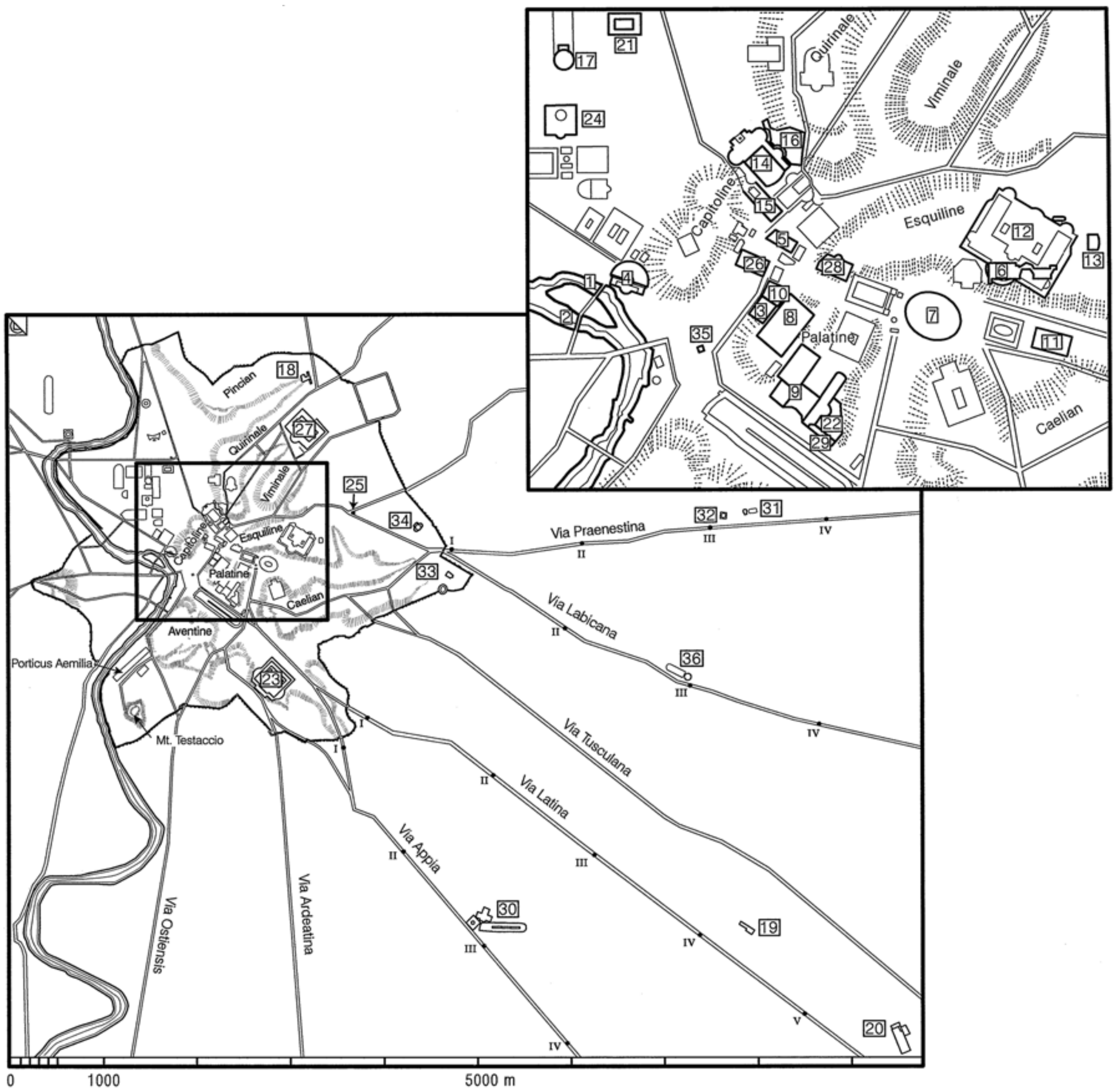
## THE NATURE OF ROMAN CONCRETE

Roman concrete, or *opus caementicium*, is different from what we think of today as concrete. The word *caementa* means rough, unhewn quarried stones and refers to the rubble of fist-sized pieces of stone or broken brick that were used in the mortar as aggregate. As implied by its name, the concrete in ancient Rome is more akin to a type of mortared rubble (Pl. II) than to modern concrete, which consists of mortar mixed with an aggregate of much smaller stones usually ranging in size from a pea to a walnut. The way that ancient and modern concrete is put in place is also different: Modern concrete is literally poured into place over a network of steel reinforcing bars, whereas the *caementa* and mortar of Roman concrete were laid separately, by hand and trowel. In both ancient and modern concrete construction, some type of structure, or centering, is necessary to contain and model the wet mortar until it sets and gains strength.

The mortar of the Romans was stronger than the earlier mortar used in Greek architecture because of the addition of a local volcanic material called pozzolana, which creates a chemical reaction that results in a mortar much more tenacious than simple lime mortar. Furthermore, pozzolana mortar is hydraulic and sets underwater. Mortared construction was used outside of Rome and Italy, but locally available ingredients were often substituted. Because each ingredient has a unique effect on the final mixture, distinguishing between mortars from different areas is critical. For example, both O. Lamprecht and R. Malinowski provide useful studies of ancient Roman mortar, but their samples are not from Rome itself.[2] In recent years, Italian engineers and geologists, often working with preservationists, have become more active in the analysis of mortar and concrete samples from buildings in Rome and Ostia, and, in Chapter 3, I have incorporated these results in an effort to provide the most relevant information regarding the local mortar.

## CONCRETE VAULTING DURING THE REPUBLIC

The development of concrete vaulting during the Republic has been covered admirably by W. L. MacDonald and others,[3] so in what follows I limit myself to a brief introduction of the major developments before the time of Augustus. Pozzolana mortar and concrete walls probably developed as early as the late third century B.C.,[4] but the use of concrete for vaulting came somewhat later. One of the earliest and most spectacular examples of concrete vaulting in central Italy is at the Sanctuary of Fortuna Primigenia at




1 Pons Fabricius
2 Pons Cestius
3 Horrea Agrippiana
4 Theater of Marcellus
5 Basilica Aemilia
6 Domus Aurea
7 Colosseum
8 Domus Tiberiana
9 Domus Flavia/Augustana
10 Domitianic Vestibule
11 Structure under San Clemente
12 Baths of Trajan
13 Sette Sale
14 Forum of Trajan
15 Forum of Caesar
16 Trajan's Markets
17 Pantheon
**18** Pavilion in Horti Sallustiani
**19** Villa alla Vignaccia
**20** Villa di Sette Bassi
21 Hadrianeum
22 Severan Baths on Palatine
**23** Baths of Caracalla
24 Baths of Agrippa
**25** Nympheum Alexandri
26 Basilica Julia
**27** Baths of Diocletian
28 Basilica of Maxentius
29 Baths of Maxentius on Palatine
**30** Villa of Maxentius
**31** Tor de'Schiavi
**32** "Villa of the Gordians"
**33** Sessorian Palace
**34** "Temple of Minerva Medica"
35 Arch of Janus
**36** Mausoleum of Helena

MAP 1. Map of Rome and environs locating the major monuments discussed in the text.

Palestrina (ancient Praeneste). The sanctuary has been known since the Renaissance, but the upper sanctuary was only uncovered after bomb damage during World War II revealed parts that had been built into modern structures. The dating of the sanctuary has been controversial. It originally was assumed to have been built after Sulla's occupation of the city in 82 B.C.,[5] but G. Gullini in a monograph on the monument proposed a mid-second century B.C. date, to which G. Lugli strongly objected.[6] A. Degrassi, in a study of the epigraphic material, supported a pre-Sullan date of the monument but was unwilling to accept such an early one and proposed that the monument was constructed in the last decade of the second century B.C.[7] The weight of the evidence leans toward a late second century date, which makes it the earliest of a series of spectacularly sited, terraced sanctuaries that employed concrete vaulting including the sanctuaries of Hercules Victor at Tivoli, of Jupiter Anxur at Terracina (Fig. 1), and of Hercules Curinus near Sulmona, all of which have been dated to the first half of the first century B.C.[8]

Early examples of vaulting in Rome itself are rare, in part because larger and more impressive imperial buildings replaced many of them. Traditionally, the earliest datable concrete vaulted structure in Rome has been assigned to the remains of a large structure located between the Tiber and Monte Testaccio, but once again controversy reigns. In 1934, G. Gatti associated this structure with a fragment of the Severan Marble Plan that clearly represents the visible remains. A partial inscription [—]LIA survives on the fragment, and he interpreted it as the Porticus Aemilia,[9] which Livy tells us was reconstructed in 174 B.C.[10] Recently, this reading of the inscription and the association of it with the remains of the Porticus Aemilia has been challenged,[11] potentially leaving us with no datable concrete vaulted remains from second-century-B.C. Rome.

1. Sanctuary of Jupiter Anxur (first half of the first century B.C.). View of concrete vaulted platform overlooking the Tyrrenian Sea at Terracina. Fototeca Unione c/o American Academy in Rome, neg. #5139.

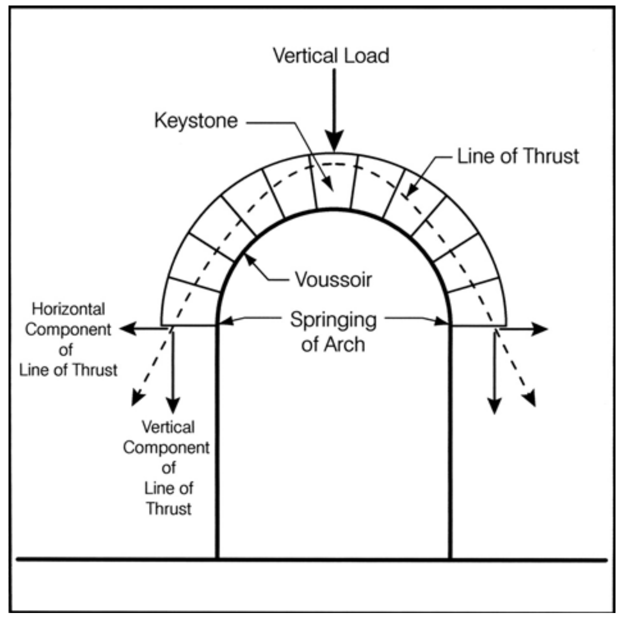
By the first half of the first century B.C., concrete vaulting was firmly established in Rome, as it was in the towns of central Italy. The Tabularium, which is dated by an inscription to 78–65 B.C.,[12] was one of the earliest concrete vaulted structures in the heart of Rome. Like the hilltop sanctuaries, it served the structural purpose of shoring up the face of the Capitoline. Within its façade of peperino blocks, the Tabularium contained a series of pavilion vaults and barrel vaults.[13] Some two decades later, Rome received its first permanent theater dedicated by Pompey in 52 B.C. In breaking a long-standing tradition within the Senate of not allowing permanent theaters or amphitheaters to be built as places for large gatherings, Pompey opened the gates for experimentation in vaulting for the substructures of such buildings. Some early innovations in vaulting techniques can be found in similar structures, such as the Theater of Marcellus and the Colosseum.

So, what prompted the early development of concrete vaulting in central Italy? As seen earlier, the most spectacular early uses were in the hilltop sanctuaries, but by the first century B.C., vaulting also could be found in other types of structures such as the storage/market buildings at Ferentino and Tivoli and in bath buildings at Pompeii.[14] Part of the answer certainly lies in the available natural resources and in the financial resources generated by conquests outside of Italy by this time, but cultural influences also affected the early development. The hillside settings of the terraced sanctuaries were influenced by Hellenistic Greek types, such as the Sanctuary of Athena at Lindos on Rhodes (second century B.C.) and the Sanctuary of Asclepius at Cos (first half of second century B.C.).[15] Incentives to use the new vaulted construction also came from within Italy itself. Concrete vaulting provided both an economical and fireproof means of storage for the goods coming from the conquered territories, and it was a particularly suitable material for enduring the constant moisture present in bath buildings that were becoming increasingly popular.

By the time of the Augustan peace when routes of transport were opened and craftsmen flocked to Rome, concrete vaulting had become common, and during this period the early attempts at more sophisticated vaulting techniques began to appear. The preceding century had provided the context for the acceptance of vaulting, but once the scale of the buildings began to grow and the spans became larger, the builders had to deal with structural challenges that had not been relevant in earlier times.

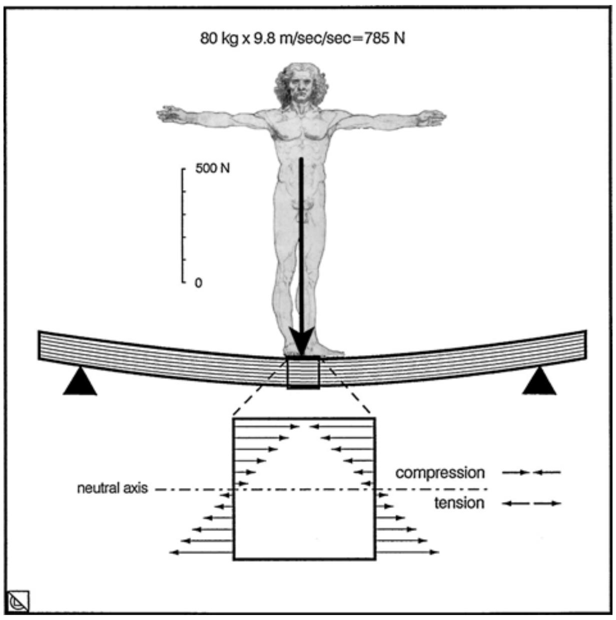
## STRUCTURAL BEHAVIOR OF CONCRETE VAULTS

Roman concrete vaults are known for their longevity, and many visitors to Rome today often ask why our modern reinforced concrete structures seem to have such limited life spans in comparison to ancient ones. The success of Roman concrete structures is often attributed to the strength of the pozzolana mortar. In fact, this is only part of the explanation. Just as important is the relationship between the masses and forms making up the structure. Structural form was a critical factor in the success of Roman buildings. The interplay between form and material was ultimately the key to longevity.




2. Diagram showing principle parts of an arch and its behavior.

The arch, which was originally developed for stone construction, was the basis for the formal development of concrete vaulting. Recent findings show that builders in Rome were using arches of cut stone voussoirs by the sixth century B.C.[16] Voussoirs are wedge-shaped stones that make up an arch (Fig. 2). The radiating joints between the voussoirs serve to direct the weight of the arch and anything it supports toward the sides and away from the opening under the arch. The result is that the arch pushes out at its springing, and this outward thrust must be countered or controlled in some way. If the arch is built into a wall, the



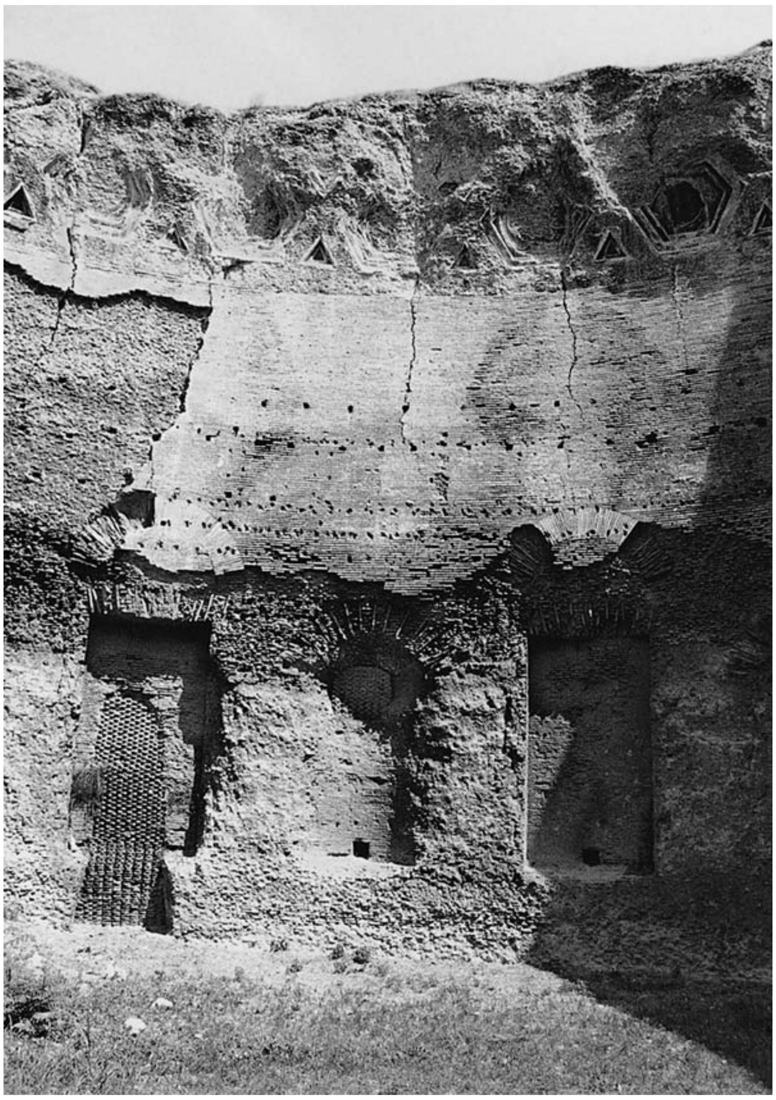

3. Diagram showing the stress patterns in a beam with a point load applied at center.

surrounding masonry acts as a buttress to contain the horizontal thrust.

The strength of any material is measured in terms of *stress*, which can occur as compression (compressive stress) or tension (tensile stress). Compressive stress results when the atoms in a material are pressed together in the direction of the converging forces. Tensile stress results when a material is stretched so that the atoms are pulled apart in the directions of the opposing forces. The example of the man on the beam in Figure 3 shows both types of stresses within the beam. As the beam bends downward under the man's weight, the upper half is in compression because the top surface is squeezed together and becomes shorter, and the lower half is in tension because the lower surface is stretched. At a point in the middle of the beam, there is a neutral axis that is not undergoing tension or compression. The strength of the beam is its ability to resist the different types of internal stresses that occur under various loading situations. Because both concrete and stone are very strong in compression and weak in tension, the arch provides a means of spanning a distance so that the stresses within the material remain in compression. Tension can develop within an arch, but it can be controlled by the form, size, and loading pattern of the arch. The mechanics of arch and vault behavior and methods of structural analysis are explored further in Chapter 8.

Concrete vaults take forms similar to arches built in cut stone, but their behavior is somewhat different. The forces are not transferred by means of the joints between individual voussoirs but, rather, through the mortar between the pieces of *caementa*, which by the imperial period were laid in horizontal courses. As long as the mortar is strong enough to resist any tensile stresses that develop as a result of these factors, the concrete can act as a solid monolithic block once it has cured and gained its strength, and lateral thrusts will not occur. If too much tension develops then cracks occur and the vault begins to push outward, or to display lateral thrust, on its supports, just like the voussoir arch. As long as the thrust is sufficiently countered the structure will remain stable, but if the supports cannot resist the lateral thrust the structure collapses. The success of the Roman builders was in their ability to control the outward thrust of vaulted structures through the choice of form and materials.

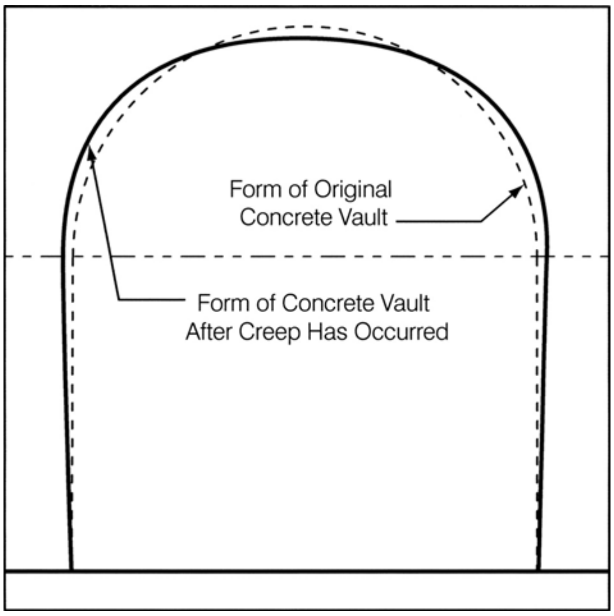
The modern understanding of the behavior of Roman concrete has undergone changes during the past century. J. H. Middleton, writing at the end of the nineteenth century, commented that "the Roman concrete vault was quite devoid of any lateral thrust and covered its space with the rigidity of a metal lid."[17] This idea of the monolithic concrete vault that has no horizontal thrust was repeated by such notable scholars as M. E. Blake, J. B. Ward-Perkins, and J.-P. Adam,[18] but it remained controversial throughout much of the twentieth century. It is based on the assumption that concrete made with pozzolana mortar has the strength to resist any internal tensile stresses that could cause cracks to develop. Both



4. Baths of Trajan (A.D. 104–109). Detail of the exedra at section D showing cracks in wall supporting semidome (29.5-m span).

W. L. MacDonald and G. Lugli were more circumspect in their assessment of the structural behavior of concrete vaulting noting that the monolithic qualities actually depend on the size of the vault.[19] One of the more influential studies affecting the understanding of vault behavior has been the extensive documentation of cracking and deformation in the concrete structure of the Hagia Sophia in Istanbul by R. Van Nice, R. Mainstone, R. Mark, and A. S. Çakmak.[20] With the increased interest in preservation since the end of World War II, more engineers have become involved in the analysis of historical structures. As a result of the analytic approach they bring to the discipline, the traditional view of monolithic concrete long held among some classical scholars has been modified to acknowledge that, in spite of the high-quality pozzolana mortar used by the Romans builders, lateral thrust often occurred and had to be countered.

Roman concrete vaults commonly developed cracks as can be seen in standing remains of many structures,[21] including such imposing ones as the Pantheon, the Baths of Trajan (Fig. 4), and the Basilica of Maxentius. The cracks could occur for a number of reasons. If the tensile stresses within the concrete exceed the tensile strength of the material, cracks will develop. The level of such tensile stresses can be controlled through the judicious design of structural form. However, even when the stresses are normally very low, external factors can cause sudden increases. A common example is a dramatic change in temperature that results in sudden expansion or contraction, which can cause the tensile stresses to spike and a crack to occur.[22] (A similar reaction is observable when a cold egg is dropped into boiling water and immediately cracks.) Moreover, concrete is subject to a phenomenon called *creep*, which is slow deformation over time. In concrete vaulting this usually results in a flattening of the curve of the vault and a spread at the haunches (Fig. 5). The gradual change in form creates changes in the patterns of stresses within the concrete, which can then lead to cracking.




5. Diagram indicating deformation of barrel vault due to creep.

During the second century B.C., when concrete vaulting was in its infancy, the builders were constructing fairly small vaults (typically 5 m or less), which could have acted monolithically, and evidence from the Sanctuary of Fortuna Primigenia at Palestrina (second half of the second century B.C.) suggests that these early builders did not take precautions to counter lateral thrusts.[23] In two places at the sanctuary, vaults were supported on at least one side by a trabeated system of columns and architrave blocks. On the Terrazza degli Emicicli, the concrete vault (3.7 m span) was built of radially laid *caementa* of limestone on the flat upper surface of the travertine architrave (Fig. 6).[24] Metal clamps were not typically used to hold the architrave blocks together, which suggests that the builders did not expect the concrete to push laterally against them but, rather, to bear straight down. A similar condition occurred


6. View of the "Terrazza degli emicicli" of the Sanctuary of Fortuna Primigenia at Palestrina (second half of the second century B.C.).

elsewhere in the complex on the Terrazza della Cortina (Fig. 7), except there the vault was built of *caementa* of the lighter local tuff.[25] Both examples had coffers in the vault, which G. Gullini suggested were intended to lighten the vault while creating a type of ribbing between the coffers.[26] In this early example of concrete vaulting, the builders evidently assumed a degree of strength in the concrete that later imperial builders did not.

By the time of Augustus, the builders clearly realized that once the span of the vaults increased and the support structure became less massive, they had to take some precautionary measures to counter any lateral thrust that could develop. They must have learned (perhaps the hard way) that once cracks developed in a vault, it began to push out on its support structure and would collapse if the thrust was not countered. We have little evidence for those experiments that did not work, but by this time builders had begun to think of ways of reducing the horizontal thrust, such as choosing lightweight stones as *caementa* and using metal clamps to stabilize the stone support structure.

## ROMAN MATHEMATICAL AND ANALYTICAL BACKGROUND

With the adoption of concrete, the methods of calculating the necessary materials for building projects changed. For cut stone vaults, the architect would have calculated the number of blocks needed, whereas for concrete vaults he would have calculated the volume of the vaults and ordered a certain amount of lime, pozzolana, and *caementa* depending on the proportions of each he intended to use in the concrete mixture.[27] This type of calculation would have required measuring units (as opposed to number of blocks), which for the Roman builders was typically in terms of *pedes* (Roman feet = RF), which could be divided into either 12 *oncia* (inches) or 16 *digiti* (digits). Measuring sticks often had two sets of divisions, one for inches and one for digits.[28] The Roman foot varied somewhat from place to place, but it was usually about 29.5 cm, which is somewhat smaller than the modern foot (30.5 cm).

The appearance of concrete vaulting comes after the death of Archimedes (212 B.C.), who provided the mathematical means of estimating volumes of spheres and the areas of conic sections. Such calculations were clearly relevant for concrete construction by the first century A.D. Heron of Alexandria, who gave credit to Archimedes, included a section in his *Stereometrica* explaining how to calculate amounts of materials for the curving forms of various types of vaults.[29] Heron also wrote a treatise called *On Vaulting* (*Camarika*), about which Isodorus of Miletus (mid-sixth century A.D.) wrote a commentary.[30] Unfortunately, neither Heron's treatise nor Isodorus's commentary has survived, but the fact that Heron devoted an entire work to the subject in the second half of the first century A.D. just at the time that concrete vaulting became the norm in imperial Rome is in itself significant. Archimedes was famous for shunning the practical uses of his theoretical discoveries, but the Romans had no such qualms.[31]

Advances in mathematical and geometrical knowledge also would have affected the understanding of the relationships between masses, which govern structural form. One of the fundamental principles for understanding the behavior of masses is the concept of the center of gravity, another Archimedean contribution. The center of gravity of an object is the point at which the object will balance as if the whole weight of the object is concentrated at that point, as on a fulcrum. The development of modern structural theory was ultimately based on this concept (see Chapter 8). By the first century A.D., Heron was concerned with explaining it. In solving various structural problems