On the Structure of the Roman Pantheon

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Since the time of its construction, the bold, brilliantly simple schema of Hadrian’s Pantheon has inspired much emulation, commendation, and even fear. Modern commentators tend to view the building as a high point in an “architectural revolution” brought about mainly through the Roman development of a superior pozzolana concrete that lent itself to the forming of unitary, three-dimensional structures. Other factors cited for the technical success of the Pantheon include the use of a series of massive, concentric stepped rings and the lightening of the dome by coffering and gradated, light-weight aggregates. To investigate these theories, and thereby to understand late Roman design rationale better, a numerical-computer modeling study of the dome structure was undertaken. It yielded several surprises.

Analysis revealed that the stepped rings induced higher, rather than lower, critical stresses in an uncracked dome model. But by allowing the model to crack freely, a salutary effect was caused by the rings. The cracked model closely simulated the behavior of the actual dome, which was discerned to act structurally as an array of arches. In fact, the configuration of the dome seems to indicate that the builders understood this—which points to the conclusion that late Roman architectural development was not so closely tied to structural innovation as has been generally believed.

No other single building has captured the attention of architects, particularly since the Renaissance, as has the Pantheon. Constructed between ca. 118 and 128, it has an interior space of awesome scale (Fig. 1), and it is the most completely preserved building of the Imperial Roman capital. The 43.4-meter clear span of the dome was unmatched for well over a millennium, and not substantially surpassed until the adoption of steel and reinforced concrete in the modern era.1

The enormous influence of the Pantheon is easily traced through numerous buildings from the later Roman period, and again from the beginning of the Renaissance well into the twentieth century.2 Earlier prototypes, though, are not so readily identified. Domed buildings were not uncommon before the time of the Pantheon, but we know of none that even approached its scale. The largest of the earlier, extant domes seems to have been part of a bath complex at Baiae. Dating from the first half of the preceding century, the so-called “Temple of Mercury” has a clear span of 21.5 meters.3

For many historians, the Pantheon represents a kind of culmination of the “Roman architectural revolution” brought to fruition during the course of the first century through the adoption of high-quality concrete that could be more readily used for the construction of curvilinear architectural forms.4 Unlike simple lime mortar, which is produced by adding water to a mixture of quicklime and sand, and sets when all the water has been evaporated into the atmosphere or absorbed into the surrounding masonry, the Middle Ages and the Renaissance," Classical Influences on European Culture AD 500-1500, ed. R.R. Bolgar, Cambridge, 1971, 259ff.). The lesson of Roman architecture for 20th-century design, according to Le Corbusier, was to be derived from "immense cupolas with their supporting drums ... all held together with Roman cement ... absence of verbosity, good arrangement, a single idea, daring and unity in construction, the use of elementary shapes" (Towards a New Architecture [Paris, 1923], New York, 1960, 146-47).

1 The clear span of St. Peter’s in Rome (constructed 1585-90) is 42m. Metal structures in the late 19th century reached spans as great as 113m (for the Galerie des Machines, Paris, 1889), and the maximum clear span of a 20th-century, thin, reinforced-concrete shell is 219m (CNIT Exhibition Hall, Paris, 1958).

2 See, e.g., MacDonald, 1976. During the Middle Ages, the Pantheon was the subject of the “united belief that it owed its existence to sinister forces of demons—the familiar dense row of pillars supporting the vault in Gothic cathedrals was miraculously lacking—and not to the ratio or the genius of its architect” (T. Buddensieg, “Criticism and Praise of the Pantheon in the Middle Ages and the Renaissance,” Classical Influences on European Culture AD 500-1500, ed. R.R. Bolgar, Cambridge, 1971, 259ff.). The lesson of Roman architecture for 20th-century design, according to Le Corbusier, was to be derived from “immense cupolas with their supporting drums ... all held together with Roman cement ... absence of verbosity, good arrangement, a single idea, daring and unity in construction, the use of elementary shapes” (Towards a New Architecture [Paris, 1923], New York, 1960, 146-47).

3 Illustrated in Giedion, 136, 137.

4 This view is exemplified by John Ward-Perkins’ somewhat startling remarks about the structure of the Colosseum, completed only a half-century earlier, and perhaps the only other building of the period to rival the Pantheon in influence. “Built about a framework of squared stone masonry which constituted the essential load-bearing skeleton ... it was not a building of any great originality ... conservative in its structural methods and choice of materials as it was in design ... a strain in Roman architecture that was shortly to be swept away by new techniques and new aspirations” (Ward-Perkins, 68ff.).
Roman pozzolana (after Pozzuoli, where it was first discovered) sets by combining chemically with water in the same way as modern Portland cement. These cements do not need to dry out as does lime mortar; in fact they are "hydraulic" in that they will set even when immersed. In addition to the obvious advantage for underwater construction, large batches of pozzolana cement will cure relatively rapidly, even in damp conditions. It could thus be used for the massive, primary structural elements of large buildings. Furthermore, the early compressive strength of pozzolana cement is far superior to that of lime mortar.

Nonetheless, one must be cautious in characterizing the resistance of concrete to cracking caused by tension forces tending to pull it apart. Although modern concrete based on controlled-cured, high-quality Portland cement exhibits measurable tensile strength (the level of stress causing a material to fail in tension), its tensile strength is taken to be nil in reinforced concrete design. Experience has dictated that reinforcing steel is always required in regions of a structure where calculations indicate that tension will be present. Even more important, in view of our later discussion of the state of the Pantheon fabric, it is also re-
Modeling the Pantheon

Analysis of the Pantheon structure was carried out using a three-dimensional, numerical-computer (finite-element) modeling code developed by Jean-Hervé Prevost at Princeton University. In this approach, the configuration of a building structure is described by a series of coordinates taken at finite intervals. These coordinates define a mesh that becomes the geometric model for the computer. A series of equations related to loading conditions and the properties of the building materials are then used to calculate the displacements of all the mesh points in order to obtain an overall deflection pattern for the model. Through equations of elasticity, the deflection pattern then gives information about the distribution of structural forces throughout the building.

To simplify the analysis, a typical meridional section for the three-dimensional finite-element model of the Pantheon structure was specified. Because of the extensive openings in the cylindrical wall—fully one-quarter of its volume is taken out by statue bays, passageways, and other voids—no typical section actually exists (see Figs. 3 and 4). But since our interest is centered on the functioning of the dome and the conceptual design of the basic structural configuration, we need not here deal in detail with the wall. In fact, it is possible to design a solid wall that provides support to the dome which is similar to that provided by the actual, voided wall. It was determined that a 5.5-meter-thick, solid cylindrical wall provides the same overall structural stiffness as the six-meter-thick actual wall; and this equivalent wall was used throughout the analysis (Fig. 5).

A second simplification made for the modeled, typical building section concerns the structural effect of the dome coffering. The coffering, which forms a waffle pattern beginning just above the springing and ending several meters from the oculus, is actually relatively shallow compared to the full dome thickness, which is taken to be uniform at 1.5 meters above the stepped rings. A volumetric analysis indicated that less than five percent of the total dome weight is taken out by the coffering. And since it decreases the stiffness of the dome to only a small degree, the coffering effect could be neglected in the finite-element model. Another consideration, evident from the building plan, is that the porch plays no role in the supporting structure of the dome. The porch is in fact hardly connected to the rotunda. The base of the rotunda is assumed to be fixed to perfectly rigid foundations, that is, held rigidly against all displacements. The dome itself is assumed to have been erected on timber centering so that, in effect, dome forces were "turned

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5 Modern structural concrete differs from Roman concrete in two important details. First, its mix consistency is fluid and homogeneous, allowing it to be poured into forms rather than requiring hand-layering together with the placement of aggregate, which, in Roman practice, often consisted of rubble. Second, integral reinforcing steel gives modern concrete assemblies great strength in tension, whereas Roman concrete could depend only upon the strength of the concrete bonding to resist tension.

6 See, for example, Giedion, 144.

7 MacDonald, 1982, 110.


9 The actual structure of the wall, which incorporates as well a large number of great relieving arches (Fig. 3), is complex and has received much attention in the literature (see, e.g., MacDonald, 1982, 106ff.). But this construction is not carried into the dome. M.E. Blake and D. Taylor-Bishop draw attention to the fact that "it cannot be emphasized too strongly that the framework of the arches... was part of [the] wall construction and did not follow the curve of the dome. It was these relieving arches that led to so many fantastic but utterly erroneous theories of [internal ribbed] dome construction" (Roman Construction in Italy from Nerva through the Antonines, Philadelphia, 1973, 46).

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required where temperature changes are likely to be encountered.  

Another reason given for the success of the Pantheon dome was the use of a new structural device, the series of concentric stepped rings arrayed about the outer surface of the dome (Fig. 2). According to W.L. MacDonald, "the rings add to the load over the critical or haunch portion of the great vault and function as buttresses, helping to bring the structure into stability through compression." Indeed, the reproduction of the rings on many of the Pantheon derivatives would seem to imply that later designers shared this view. A final, usual observation is that the designer aimed for lightness by coffering the underside of the dome and using a lightweight aggregate in the upper reaches of the building, whose density is significantly less than that of the lower, supporting structure. Our investigation of the dome, based on modern structural analysis techniques, was aimed at evaluating these theories, and thereby gaining some new insight into ancient techniques of large-scale building.
on "all at once with the removal of the centering. Most important, for the first series of model tests, tensile stresses throughout are assumed to be of low enough magnitude so that the structural fabric of the building remains integral; that is, cracking is nowhere permitted. Finally, dimensions and data on the gradation of materials used in the construction were those reported by K. de Fine Licht. The density of the brick-faced concrete used in the cylindrical wall is taken to be 1750 kg/m³. This value is reduced to 1600 kg/m³ in the lower region of the dome, and to 1350 kg/m³ for the upper region of the dome (compared with the 2200 kg/m³ density of the concrete used in the Pantheon foundations, which is also the density of standard modern concrete).

Findings of the Study of Uncracked Models

Five integral models with different geometric and loading modifications were studied in addition to the "full model" of the Pantheon already described. The modifications were made with relative ease using the computer-modeling formulation, and they provide a basis for better understanding the structural behavior of the building itself. The models, rigidities of the constituent materials, were estimated from empirical equations developed for light-weight, modern concrete. (See G. Winter and A.H. Nilson, Design of Concrete Structures, 8th ed., New York, 1972, 8, 16, 26.)
Computer-drawn, finite-element section of Pantheon model in order of geometric and loading complexity, are designated as:

Model 1: Hemispherical dome of constant, 1.5-meter thickness, nine-meter-diameter oculus, 21.65-meter interior radius, the whole formed of uniform, "heavy" concrete having a density of 2200 kg/m³. The base of the hemispherical dome is supported only against vertical loadings; no horizontal buttressing is acting, as illustrated in Figure 6a. Because of its simplicity, this configuration is readily analyzed from shell theory, and therefore it was undertaken to provide a check on the modeling procedure. But since the dome is unbuttressed, it also serves to reveal the limiting, maximum value of circumferential (hoop) tension for a dome of Pantheon scale because expansion of the dome base is here unconfined. (For an explanation of the phenomenon of hoop stress, see the description of the full Pantheon model behavior [Model 6] below.)

Model 2: Hemispherical dome of the same dimensions and the same support conditions as Model 1 (Fig. 6a), except that the density is that of the light, gradated concrete of the actual dome.

Model 3: Hemispherical dome of the same dimensions as above, with concrete density distributed as in the actual dome, but the base of the dome is now rigidly attached to the 5.5-meter-thick, cylindrical wall below it, as shown in Figure 6b. In this case, the heavy wall provides considerable resistance to outward deformation of the dome base. Hence, maximum hoop tension is not experienced there, but rather in a region of the dome well above the base.

Model 4: Same configuration and concrete density distribution as Model 3, except that the attached cylindrical wall is now carried upward along the dome, as it is in the actual building. This configuration is the same as that of the full Pantheon model, but without the stepped rings (Fig. 6c). Maximum hoop tension is experienced in the extension of the cylindrical wall.

Model 5: Same configuration as the full Pantheon model (Fig. 4), except that the entire structure is formed of uniform, "heavy" concrete with a density of 2200 kg/m³. Thus, overall structural behavior is similar to that of the light, full model described below, except that stresses are higher.

Model 6: Full Pantheon model (Fig. 4) with light, gradational concrete density as outlined in the previous section.

The deformations in the full-model section (Model 6) under the action of gravity forces are illustrated, at much exaggerated scale, in Figure 7. Although a hemisphere is not so efficient as a parabolic dome in reducing bending forces from this loading, bending throughout the section was found to be relatively low. Indeed, bending forces were low enough so that when their effect was combined with those of the (meridional) compressive thrusts of the dome, the combined stresses were everywhere compressive in the plane of the section. Furthermore, indicated total levels of stress were moderate for this type of construction. The highest value of compressive stress in the dome itself is 2.8 kg/cm²; the maximum compressive stress at the level of the footings is 8.4 kg/cm². Compressive stresses of the same order of magnitude were found in all the other models as well.

Tension was found to be present, but acting only circumferentially. The major cause of this tension can be discerned from Figure 7. The outward deformation at the base of the dome, and of the upper portion of the cylindrical wall, must be accompanied by increases in circumferential length. This stretching of material in the hoop direction is accompanied by hoop tensile stress. For the full Pantheon model, these stresses are low — the maximum indicated value appears at point (a) on Figure 7: 0.6 kg/cm² — well within the tensile strength of even low-grade concrete. They are also much lower than the magnitudes of maximum tensile hoop stress found in Models 1-5 (Table). But a comparison of the result from the different models is illuminating, particularly in light of the present state of the dome fabric.

One observation is that the light aggregates used for the construction of the dome are indeed quite effective for re-

The Table indicates that if 2200 kg/m³ heavy aggregate had been carried into the full dome, stresses would have been about eighty percent higher than in the actual building. On the other hand, the effect of the coffering in reducing stress is almost insignificant because of the small weight reduction and the fact that it does not extend fully to the oculus. The coffering, then, can be characterized as being mostly an illusionistic device.

Another, more surprising observation from the Table is that instead of increasing, hoop tensile stress is actually reduced twenty percent by removing the stepped rings (as was done in Model 4). Furthermore, removal of the rings does not beget bending-tension stress in the plane of the meridional section taken through the dome; the unringed configuration turns out to be more structurally reliable than the actual configuration. Although the Roman builder did not possess any analytical tools for making this type of evaluation, other studies of pre-scientific structural development lead us to believe that the designer of the Pantheon may well have had sound technical reasons for adopting the stepped rings. Yet the indicated tensile stress levels in both the unringed and the ringed dome configurations, even when raised by a “stress concentration factor” to account for the local effects of wall openings (as discussed below), seem to be low enough so that no further precautions would have been deemed necessary. For that matter, even the limiting, maximum value of tensile stress indicated in the heavy hemispherical dome (Model 1) is not greater than might be expected to be resisted by a high grade concrete. Hence, one may well ask why any device, such as the stepped rings, would have needed to be introduced into the Pantheon design to reduce tensile stress.

One answer is that the rings were not intended to be structural. They have only a constructional advantage: vertical formwork for their outer contour facilitated the placing of concrete in regions where the natural extrados of the dome was highly sloped. Yet, twentieth-century observations of the fabric of the Pantheon itself suggest a more compelling structural explanation. The best report of these findings, though regrettably brief, is a half-century-old paper by Alberto Terenzio, then Superintendent of the Monuments of Latium.

Because of the spalling in 1930 of “small fragments” from the dome, scaffolding was erected and used for a systematic inspection. With the removal of plaster, the pattern of meridional cracks illustrated in Figure 8 became evident.

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**Table**

**Maximum Tension in Uncracked Models**

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Description</th>
<th>Aggregate</th>
<th>Hoop Stress (kg/cm²)</th>
<th>%-increase (decrease)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>hemispherical dome</td>
<td>heavy</td>
<td>4.9</td>
<td>820</td>
</tr>
<tr>
<td>2</td>
<td>hemispherical dome</td>
<td>light</td>
<td>3.3</td>
<td>550</td>
</tr>
<tr>
<td>3</td>
<td>hemi-dome on wall</td>
<td>light</td>
<td>1.0</td>
<td>67</td>
</tr>
<tr>
<td>4</td>
<td>full model w/o rings</td>
<td>light</td>
<td>0.5 (20)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>full model</td>
<td>heavy</td>
<td>1.1</td>
<td>83</td>
</tr>
<tr>
<td>6</td>
<td>full model</td>
<td>light</td>
<td>0.6</td>
<td>—</td>
</tr>
</tbody>
</table>

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13 The more rigid corner of the stepped-ring section probably induces greater bending distortion of the wall under dome loading, and this results in somewhat larger hoop stresses within the wall.


15 MacDonald, 1982, 110.

16 Terenzio, pl. xxvi. Terenzio also identifies fractures “reaching from the base of the rotunda to the summit of the dome” that he thought were brought about by differential settlement from uneven loading of the wall, particularly near the entrance of the rotunda and in the principal niche. Rather than finding the vertical dislocation along wall cracks that usually characterizes differential settlement, we have observed only traces of lateral opening across the cracks — corresponding to the effect of hoop tension. But in any event, Terenzio’s inference should not obscure interpretation of the fairly uniform distribution of dome cracks illustrated in Figure 8.
renzio inferred that the problem must have occurred very soon after construction, because the bricks used for some early crack repairs bore the same stamps as those used in original portions of the building. The cracks are in the lower portion of the dome, in the region analogous to that in the full model which indicated hoop tension (from the springing, to an angle with the springing of about fifty degrees). The distribution of the cracks about the dome generally corresponds to openings within the upper cylindrical wall (as shown in Fig. 8), which serve to increase the magnitude of local hoop stresses by a factor of two to three. Fractures caused by hoop tension would therefore be expected to originate there. Yet the predicted hoop stress levels, which are still an order of magnitude less than the strength of a good quality cement, would not at first appear to cause such fracture. This question will be dealt with at length later on; but for now it is sufficient to note from Terenzio’s findings that the uncracked models already considered in this section may not best represent the actual Pantheon structure. In fact, they may not even represent the actual structure close to the time of construction. To account for the observed behavior, the finite-element modeling code was modified: hoop tension was no longer permitted to develop. In effect, the model would now be cracked along the meridians wherever any tensile hoop stress was indicated, producing an array of wedge-shaped arches.

**Findings of the Study of Cracked Models**

Two cracked-section models were studied. These models are designated as:

Model 7: Configuration and concrete density distribution of the full Pantheon model, but without the stepped rings — corresponding to Model 4 (Fig. 6c).

Model 8: Full Pantheon model with light, gradational concrete density — corresponding to Model 6 (Fig. 4).

The simulated cracking substantially changed the behavior of the dome from that of the first set of models. A three-dimensional, doubly curved dome gains structural advantage from the interplay between the meridional and circumferential forces. If the dome is cracked along the meridians, major internal forces in the cracked region are carried only in the meridional direction. Hence, the dome loses much of its three-dimensional advantage, and behaves instead as an array of arches with a common keystone. Equilibrium demands that this loss of hoop forces is normally compensated for by an increase in meridional forces, which includes also increasing the meridional bending forces within the dome.

In the cracked-section models, dome bending forces were more than twice as great as in the corresponding uncracked model configurations. Indeed, they were now substantial enough so that when combined with the effect of compressive thrusts, tensile stresses developed in the plane of the dome section. For Model 7, which omits the step rings, tensile stress due to bending was relatively high and covered a large area of the dome extrados. The stress reached a peak of 1.3 kg/cm² on the extrados where it joins the raised outer wall. For Model 8, representing the full Pantheon configuration, only highly localized tension was observed—at the inner corners of several of the step rings. Since these small regions of tension are in an area that is predominantly compressive, tension cracks would not tend to propagate and lead to any danger of structural failure.

This factor takes into account local openings in the wall structure as well as the effect of possible stress concentration at the boundaries of the openings. See e.g., S.P. Timoshenko and J.N. Goodier, *Theory of Elasticity*, New York, 3rd ed., 1970, 157ff.

Cracking of the model causes a redistribution of internal forces, so that the final equilibrium of forces must be found from the iteration of a series of models, each carrying the cracking propagation a bit further, until convergence is reached.
The step rings thus make an obvious and, quite possibly, crucial difference in the performance of the cracked-section dome.

The extent of the meridional cracking in the actual dome as shown by A. Terenzio (Fig. 8) agrees remarkably well with the simulated cracking in Model 8. The cracks that he documented continue up the dome to an average of about fifty-seven degrees above the springing. The cracked region simulated in the Pantheon model, by repeated cancelling of the hoop tension as it developed (see note 18), reaches fifty-four degrees above the springing. Above the cracked region, the crown of the dome, including the boundary of the oculus, is entirely in compression with but moderate levels of stress. Below the dome, hoop tension in the rotunda wall would be expected to produce vertical cracks. And although Terenzio does not illustrate cracking in the wall as he does for the dome, the cracking of the supporting cylinder of Model 8 extends all the way down to 7.6 meters above the rotunda floor (see note 16). Hence, the upper portion of the modeled wall is no longer acting structurally as a cylinder, but rather as a circular array of independent piers, which are more than able to support the dome adequately, according to the analysis.

The coincidence of the behavior of the cracked model with that of the actual Pantheon structure indicates that to all intents and purposes, Roman pozzolana concrete could not be counted upon to exhibit any tensile strength. This inference seems to be at odds with the position taken on
As already noted, the reported maximum stress levels due to surcharge from tensile tests of the concrete used in the Pantheon, Hadrian's Villa, Tivoli (design, 118-125), "Teatro Marittimo," cause such extensive cracking. But the presence of even Roman construction by most historians as well as by contemporary technical commentators. It is even at odds, we suspect, with inferences from the results that one might gain from tensile tests of the concrete used in the Pantheon. As already noted, the reported maximum stress levels due to dead loading are all low — too low by themselves to cause such extensive cracking. But the presence of even these relatively low tensile stresses over extensive regions of the structure creates an environment that is particularly sensitive to cracking from other transient loadings that produce tension. One of these is differential temperature. Rapid cooling — as an extreme example, caused by a "sun shower" wetting the surface during an otherwise hot, sunny day — could easily induce tensile, thermal stresses as high as 15 kg/cm² at the surface of the dome. A possible additional cause of large amounts of widespread tension across the dome is the shrinking of the concrete during curving, particularly on rigid form work that has not yet been decentered.

From our analysis and observations, it appears that the Roman builders were well aware of the problem of tensile cracking, and they took steps to cope with it. The performance of the stepped rings in the cracked Pantheon models, unlike their negative role in the uncracked models, is actually close to that described by MacDonald. Because of the meridional cracking, and the consequent behavior of a large portion of the dome as an array of arches, the structural action of the stepped rings can be likened to that of surcharge over the haunch of an arch (or of a barrel vault where every section acts as a simple arch). Such a surcharge, integral with the vaulting, is illustrated in Figure 9, a section through the remains of a barrel vault at Hadrian's Villa in Tivoli that was constructed contemporaneously with the Pantheon.

Evidently the stepped rings are the translation of extensive Roman building experience with planar arches to the construction of a dome of unprecedented scale. The rings may even have been placed as a "fix" intended to stabilize the already-cracked Pantheon structure — a hypothesis supported by Terenzio's identification of the dome cracking near the time of initial construction. The original bronze tile roofing of the Pantheon, too, might have been put in place as an afterthought.

9 Hadrian's Villa, Tivoli (design, 118-125), "Teatro Marittimo." Segment of concrete barrel vault with surcharge (photo: R. Mark)

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19 The idea of a monolithic concrete dome seems to have been first proposed near the close of the 19th century by the then Slade Professor of Fine Arts and Director of the Fitzwilliam Museum at Cambridge, J. Henry Middleton: "It would have been impossible for the Romans to build and vault their enormous spans if they had used vaulting of brick and masonry . . . Roman concrete was quite devoid of any lateral thrust, and covered its space with the rigidity of a metal lid . . . . The construction of the enormous cupola is . . . as free from thrusts as if it were cut out of one block of stone." (The Remains of Ancient Rome, London, 1892, i, 66; ii, 131.) In this account, the massive walls retain little structural function except to provide vertical support for the dome. Nonetheless, the theory was recounted in Anderson and Spies' text (The Architecture of Greece and Rome, London, 1903), which, in a later edition, was cited by D.S. Robertson. Echoing Middleton, Robertson wrote: "Concrete, as the Romans knew it, was in effect a new and revolutionary material. Laid in the shape of arches, vaults and domes, it quickly hardened into a rigid mass, free from many of the internal thrusts and strains which trouble the builders of similar structures in stone or brick." (Greek and Roman Architecture, Cambridge, 1969, 233; originally published as A Handbook of Greek and Roman Architecture in 1929.) By now, acceptance of Middleton's theory is almost universal. For Mario Salvadori, "the Pantheon, a triumph of concrete architecture, could only be conceived and built after the discovery of pozzolana concrete by the Romans . . . the [thickness of the base of the dome] is so large that the tensile hoop stresses in it are well below the resistance of the concrete . . ." (Why Buildings Stand Up, New York, 1980, 230-33). A similar observation had also been made by Henry Cowan: "In the Pantheon the thickness of the concrete is so great in the lower portion of the dome that the tensile stresses are low" (The Masterbuilders, New York, 1977, 74). Rowland Mainstone, on the other hand, is more circumspect: "Structurally the new forms . . . still fell short of a full exploitation of the increased possibilities of action . . . provided that the conditions of support at the base were appropriate and that the circumferential or 'hoop' tensions in the lower part [which Mainstone estimated to be about 5 kg/cm²] could be resisted without cracking" (Developments in Structural Form, Cambridge, MA, 1975, 116, 118). Cowan reported also on the results of modern tests of concrete from some Roman ruins in Libya. These indicated a compressive strength of about 200 kg/cm², not unlike that of modern concrete (Masterbuilders, 56). Based on an empirical relationship developed for modern concrete, the tensile strength of the Libyan specimen could be expected to be almost 15 kg/cm² (Winter and Nilsson, as in n. 11, 22).

20 Cracks caused by transient loadings in regions of a structure already subject to constant (dead-weight) tension will tend to remain open after the termination of the transient. This contrasts with the effect in regions of constant compression where the cracks tend to close. This study is the first instance of our finding large fields of tension extending around an entire perimeter of a building. (In Gothic buildings, tension was found to be present only at discrete, highly localized regions such as at the ends of flying buttresses.)

21 For the calculation of thermal stress, we have assumed physical properties that would generally be associated with the concrete described in n. 19 and that the surface of the dome is 10°C cooler than the mass of the concrete below the surface. Theory is given by Timoshenko and Goodier, as in n. 17, 433-37. Differential settlement (see n. 16) and earthquake loadings (which could produce differential settlement) can also induce additional tensile stresses. But without full records, their effect is difficult to predict, and it is highly unlikely that a uniform pattern of cracks would have resulted in the vault.

22 The section illustrated in Figure 9 is actually from a large-diameter, annular barrel vault framing Hadrian's "Teatro Marittimo." Even though the axis of the barrel is curved slightly, the overall structure behaves essentially as a linear barrel vault.
— to protect the cracked, outer regions of the dome from the elements. Our modeling, then, has led to a new view of the influence of the actual structural behavior on the final design of the Pantheon, and also, for that matter, to a reinterpretation of the Roman architectural revolution.

**Roman Structural Design**

There is no question that during the zenith of Imperial Rome’s power and wealth, Roman architecture acquired new aspirations and techniques of construction. The periods of exceptional commercial and political activity of any civilization are usually symbolized by large-scale building. And the architecture of the Hadrianic era, for which the Pantheon is probably the prime example, was no exception. Yet our study of the structure of the Pantheon leads us to question the generally held belief that the success of this new architecture was dependent upon the development of a unique Roman building technology.

Rome’s contribution to monumental architecture derives mainly from the widespread use of the circular arch, which allowed large wall openings for light and access, and the spatial development of the arch form in concrete: in barrel vaulting (generated by a lateral translation of the arch), groined vaulting (formed by intersecting barrel vaults), and hemispherical domes (the circular arch, rotated). The three-dimensional form of many of the concrete structures of, for example, Hadrian’s Villa is striking indeed (Fig. 10), as is their apparent plasticity (because one sees only the final rendering, and not the intricate timber form work needed to create the complex shapes). Yet, the basic constructional idea generating the domes and vaulting of this architecture remains that of the planar arch with its characteristically deep voussoirs, surcharge over the springing, and substantial buttressing to resist outward thrusts.

Roman structural development was nowhere near so radical as that of the late nineteenth century, when the introduction of the new industrial materials brought forth a true revolution in building design. A far better analogy is provided by the late twelfth-century development of the High Gothic cathedral, for which the stage was first set with the significant improvement of medieval building technique during the century preceding. A second major factor leading to the technical success of the Gothic was that new buildings, even though they often took what appeared to be unexplored paths, retained many elements from earlier designs. In effect, an earlier building acted as an approximate model confirming the stability of new, larger construction. And perhaps most important of all, the Gothic building organization allowed apprentices to rise through the ranks, even to become master builders, which served to ensure continuity with earlier design and construction techniques.

In this light, there is special significance in the fact that the circular arch and pozzolana cement both found major use in Roman substructure and other utilitarian construction long before being adapted for “high” architecture. Significant masonry-arch bridges had been built for crossing the Tiber as early as 109 B.C. (the Pons Mulvius with spans as great as eighteen meters) and 62-21 B.C. (the Pons Fabricius with twin, twenty-four-meter spans). Furthermore, Vitruvius, writing a century before the Hadrianic era, discusses in some detail the composition and application of concrete made from pozzolana.

The decision to begin to employ concrete for large vaults and domes, such as the Temple of Mercury, of which Vitruvius made no mention, was constructional, we believe, rather than structural. It was based primarily on extensive building experience. We do not doubt that vault construction using cut stone or brick would have been more costly, given the availability of sources of Roman building materials, the organization of construction labor, and the evident speed of the work. But one must bear in mind that the skilled labor, and hence the great expense of erecting the timber centering needed for both types of construction, probably would have been much the same.

Concrete does afford one important structural advantage over common stone vault construction, however. It allows the type of gradation, without special effort, in the weight of materials that was found to be so advantageous in the Pantheon analysis. Nevertheless, this did not make concrete the only method of choice. Stone and brick continued to be used extensively for monumental construction in the

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23 The tensile strength of metals, for example, allowed tall structures, such as the Eiffel Tower, to be anchored into foundations instead of requiring, as was necessary for all past monumental construction, great masses of masonry to ensure stability. Another consequence was the relatively sudden achievement of a new reach in building spans (see n. 1).

24 Mark, 10-11.


provinces. And although no other domed building of the Imperial era approached the span of the Pantheon, a number of masonry-domed buildings of very large span were constructed much later on. Among these were the similarly scaled domes of the Cathedral of Florence and St. Peter's in Rome, which were erected over tall crossing piers that made them subject to still another crucial set of structural problems. Indeed, the brick, 0.46-meter-thick hemispherical dome used by Christopher Wren to enclose the 30.8-meter-span interior crossing of St. Paul's Cathedral is a structure that is valid to compare with the Pantheon dome. The ratio of thickness to span of Wren's dome, 1:67, if applied to the 43.3-meter-span of the Pantheon, gives an equivalent thickness of 0.65 meters instead of the actual 1.5 meters. The outward thrust of the thinner brick dome would thus be similar to that of the actual lightweight concrete dome, and although compressive stresses in the brick dome itself would be somewhat greater, they would still be well within an acceptable range.

None of this depreciates the achievement of the Pantheon in a pre-scientific age. But the technical underpinning of that achievement has been largely misunderstood. Rather than representing any break with earlier tradition, the basic form and support of the dome came directly from long Roman experience with masonry circular-arch construction and from using concrete as a substitute for masonry in a wide variety of structures, including even rather large domes. The coincidence of the observed cracking within the Pantheon dome with the model predictions for dome behavior based on concrete having nil tensile strength should put to rest the idea that Roman pozzolana somehow accomplishes feats that no modern designer would expect of unreinforced concrete. Roman structural development was facilitated by the use of pozzolana concrete. But the fact that it was not caused by it gives a new vantage point from which to reexamine the whole issue of structure and style in later Roman large-scale building design.

Earlier studies by Robert Mark often have focused on Gothic architecture (Experiments in Gothic Structure, 1982, and a related article in Scientific American, November, 1984), though his research has ranged from Christopher Wren (Scientific American, July, 1981) to this recent investigation of Roman architecture. [School of Architecture, Princeton University, Princeton, NJ 08544]


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