

THE PANTHEON: CROWN JEWEL OF ROMAN CONCRETE

EXPLORE THE "ETERNAL TEMPLE," THE BEST PRESERVED OF ALL CLASSICAL MONUMENTS, WITH DAVID MOORE, P.E.

Editor's note: The cover story, which begins on page 13, is based upon the research of David Moore, P.E., and addresses the broad sweep of Roman concrete and engineering. This article, written by Moore at CONSTRUCTOR's request, goes from general to specific, taking an up-close look at the Pantheon, which is the finest example of Roman engineering and concrete extant in the modern world.

My wife and I were just passing time before the airport bus left our hotel in Rome and we returned home. When the friendly hotel clerk that I was chatting with discovered I was a retired engineer, he insisted that we visit the Pantheon to see the marvels of the great Roman engineers and architects. We acquiesced to his insistence, but skeptically. How sophisticated could these builders have been two thousand years ago?

After a brief walk, we turned a corner, and there, at the end of a beautiful piazza was a strange, very large, round building covered with thin red bricks, holding a massive dome, fronted by a beautiful portico. We were drawn to it instantly. It had the mark of genius.

We stepped up into the gabled porch, lined with granite columns, and then into the building through bronze doors, 21 feet high. I was startled as my eyes swept across the colorful mosaic patterns in the polished stone floor, across the complex series of indentations in the wall and up into a vaulted dome, 10 stories high. In the center of the dome, the sky shone through an opening that filled the interior with daylight. Amazingly, the floor had a slightly convex curve to it. Was this building really made in ancient Rome? It was so modern-looking, beautiful, and well preserved. The walls had large niches that had held famous statuary. A tour guide told us the Pantheon had originally been a Roman temple

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dedicated to all gods and only later became a Christian church.

I was amazed. I felt intuitively that any building this large with such a complex structure and interior could only have been made with modern methods, using complex calculations, blueprints, Portland cement, and heavy construction equipment. I questioned the tour guide on its true age. He smiled and said it was built in 123 A.D. by the Roman Emperor Hadrian, and constructed largely of concrete. I was shocked. Was it really concrete, true concrete, in the age of the Romans?

The entire building was a mystery. As we left, I remarked to my wife, "If we gave the task of designing this building to today's engineers, they couldn't do it. There is no steel reinforcing in the dome. It violates our building codes." But there it was, still standing after almost 2,000 years. With this mystery tucked away in my mind, and with plenty of time in retirement, I returned to the United States, determined to find out more about this marvelous building and its construction. My search led me to realize this building is a window into the past, a near perfect example of the brilliant architectural achievement of the builders of ancient Rome.

In my research on this magnificent structure, I quickly discovered that it is unique in many ways. The architect designed the structure so that it would fully enclose an imaginary sphere, 143 feet (43.3 m) in diameter. It is amazing to think of the mathematics required to locate the construction points on the inside of this ball-like structure. As for size, the clear span of the dome of St. Peter's Basilica in Vatican City, built some 1,500 years later, fell five feet short



Photo by Lakisha Campbell.

Like a bright cycloptic eye, the oculus sends a shower of light over the ornately painted walls of the Pantheon. The structure inspired the artist Michelangelo to describe it as being of "angelic and not human design." It is a physical articulation of the creativity and ingenuity of Roman builders. Built mostly by the emperor Hadrian—also known for his wall separating modern-day Scotland from England—the Pantheon has survived for 1,879 years. The unique structure was built using the Romans' ancient concrete, which contained no rebar or other reinforcing elements. —Stephani Miller

of the Pantheon's. In fact, the clear span of the dome was not substantially surpassed until the adoption of steel and reinforced concrete in the modern era.

Let me lead you through the parts of this building, in the hope that you, too, will appreciate its ingenious technology and the people that made it.

HOW TO BUILD A LOAD-BEARING WALL WITHOUT REINFORCING RODS

The foundation of the Pantheon, like the wall and the dome, is made with Roman concrete. The Romans developed the mortar for their concrete by combining three components: fine volcanic ash (known as pozzolan), lime (from burnt limestone), and water (part of the slaking process during lime production). To build a load-bearing wall, the Romans created a form using wood, stacked rock, or brick. They laid down a layer of aggregate, consisting of hand-sized rock or broken brick, inside the form and then tightly tamped pozzolan mortar into the aggregate with a special tool. They then repeated this process, layer by layer upward. The mortar was made with carefully controlled ratios of pozzolan, lime, and water. Each batch of mortar was hand-carried in baskets to the placement.

SECRETS OF ROMAN CONCRETE



The exterior pediment of the Pantheon, the temple dedicated to all gods. Translated, the carved script across the pediment reads: “Marcus Agrippa, son of Lucius, in his third consulate, made this.” The Pantheon was built by Agrippa in 27 B.C., destroyed, and rebuilt in the second century A.D. by Hadrian. Remarkably well preserved, it is constructed mainly of a pozzolan-based concrete with a brick veneer.

— Stephani Miller

It was a slow process, with strict quality control.

The Roman builders were very conscious of their materials, and reduced the weight of the concrete by using aggregate of different weights for different zones. The foundation had an aggregate of travertine, a heavy rock. In the highest parts of the dome, the aggregate was light tufa and pumice. This took careful planning, to place different rocks, and to stockpile rocks during the construction to make a graded wall. Interestingly enough, the foundation for the Pantheon rests on blue clay. To make matters worse, the clay swells and shrinks with the water levels in the nearby Tiber River. In 1833, when the body of the painter Raphael was removed from a crypt beneath the Pantheon floor, it was discovered that the crypt had filled with clay, indicating unstable and moving soil around the foundation.

A UNIQUE STRUCTURAL SUPPORT: THE BRICK-RELIEVING ARCH

From the outside, the cylindrical wall that holds up the dome seems somewhat plain and austere, consisting of a simple red brick facing with the hint of brick arches embedded in it. The wall is 104 feet high and presents an awesome sight from the ground. The wall is not merely a uniform cylinder but one that contains many cavities and chambers on different levels. Structurally, the wall becomes a set of eight structural piers with niches in between. The concrete wall is about twenty feet thick at the piers, which is necessary in order to support the downward and outward forces of the 5000-ton concrete dome. There is no evidence that a staircase ever existed between the

BIRTH OF THE PANTHEON

Bloodshed founded Rome, and bloodshed founded the Roman Pantheon. Admiral Marcus Vipsanius Agrippa had the original Pantheon erected in 27 B.C. after he crushed Anthony and Cleopatra at Actium.

The Pantheon, which confounds engineers and stupefies archeologists, had a humble beginning as a small, rectangular building. Admiral Agrippa dedicated it to the Romans’ septet of planetary gods out of gratitude for his conquest. After two fires (one caused by lightning) severely damaged the original structure, Emperor Hadrian rebuilt the temple from A.D. 117 to 125, using a radically different design with the single dome supported by a cylindrical wall.

Hadrian added a more conventional looking portico on the front, but retained the inscription from the original building, which basically states that “Agrippa built it.” In fact, it was Hadrian who built it!

The Pantheon has continued to stand as a Catholic church—Santa Maria ad Martyres—since its consecration in the 7th century.

— Stephani Miller

upper and lower chambers, so we may assume their primary function was to reduce both weight and construction materials, and they also might have helped speed the curing process of the Roman concrete.

The Romans employed a unique structural support in their walls: the brick relieving arch. An outside view of the building only hints at the complex series of arches and vaults that are embedded in the wall. The arches were built with two-

foot square bricks placed on end around an arched form. On the inside of the building, they were used to distribute overhead loads over wall openings, like the niches, to the side piers. If a stronger support was needed, the Romans simply added another series of bricks over the first. In addition, there are arches embedded inside the walls. There the space beneath the arch was filled with concrete and brick to integrate the arch into the wall.

Photo by Lakisha Campbell.

Why did they use brick arches when they had concrete already? Their pozzolan-based concrete took considerably longer to come to full strength than modern concrete, so embedded arches were used to support the wall while the concrete was curing. This shows that Roman architects knew about the structural weakness of their concrete during the early stages of curing and used a time-tested system to counteract it. How the Romans positioned these arches with their mathematical and surveying instruments is not clearly known.

AN ETERNAL MYSTERY: THE PANTHEON DOME

The dome is an unconventional structure at best, with many unresolved questions concerning its design and construction. It looks modern, but, despite some myths about the building, it contains no iron or other reinforcing. From the inside, the dome can be examined in three sections: the lower section with its coffers; a smooth section towards the top; and the oculus or opening in the center. The 140 coffers in the lower part of the dome are both decorative and structural. These are a zenith in ancient construction practices. Each coffer is a semi-rectangular inset with four inside steps. There are five bands of coffers on the inside of the dome, with the coffers aligned longitudinally in a beautiful fan-like geometry. How did the Romans acquire the advanced technology to position these coffers on a spherical surface?

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The smooth section towards the top leads to the open skylight, or oculus. The oculus in the center is about 30 feet in diameter, completely open to the elements. It provides beautiful natural daylight in this large windowless building built in an age of oil lamps. The architect recognized that there were high compressive forces in this area that could cause failure, and thus a cast bronze ring was riveted together and installed on the thick lip of the oculus. In addition, there is a collar of bricks, set on edge like the arches, to support the ring. What about rain falling into the building? The slightly convex floor moves water to floor drains, which, in turn, remove it from the building.

The sophistication of the design and placement of this structure is considerable when we remember that the Romans had only a crude surveying instrument, a bench-like device with an open water channel, for sighting to establish elevations for their work at these great heights. The calculations undoubtedly involved both trigonometry and solid geometry.

UNANSWERED QUESTIONS

Originally, the entire dome was covered with glistening bronze plates, which were removed in 663 A.D. Later, in 1454, lead plates were installed to serve as the roofing material, which have remained ever since.

A look at the dome's cross-section reveals that it is thinner at the top than near the base to reduce weight and improve the strength of the dome. The cross-section, however, also reveals seven external step rings molded into the dome near the base. Each is made of concrete, just like the rest of the structure, and built like a low Roman wall with a brick face. We do not know the Roman rationale for molding these step rings into the dome. One argument is that this was for convenience during construction: a vertical wall would have been easier to construct, using their methods, than one having a steep slope on that part of the dome. Another suggestion is that the Romans added thickness to this part of the dome to counteract hoop stress. But the most surprising answer comes from Robert Mark of the Princeton University Architecture Department and Paul Hutchinson, an engineer, in their March 1986 article, "On the Structure of the Roman Pantheon" in *Art Bulletin*.

ABOUT THE AUTHOR

This article was written by David Moore, P.E., and is drawn from his book *The Roman Pantheon—The Triumph of Concrete*. (To order, log onto www.romanconcrete.com).

A registered professional engineer, Moore has more than 45 years of wide-ranging civilian and military assignments to his credit, including Project Engineer, U.S. Corps of Engineers, Saudi Arabia; Construction Manager, U.S. Marine Corps, Okinawa; and Manager for Planning, Programming, and Construction, U.S. Navy, Guam.

Moore holds both an M.A. and a B.S. in civil engineering from Utah State University, and the Degree of Engineer from Stanford. He is a retired commander in the U.S. Navy Reserve (Seabees) who served in combat on Saipan in World War II and in the Vietnam War. Moore has also served as adjunct professor of engineering at the Central Texas College Pacific Far East campus.

But first, let us back up to 1930, when A. Terenzio, the Italian Superintendent of Monuments, mapped 14 noticeable cracks on the interior of the dome. These cracks are all longitudinal, running from the base of the dome towards the oculus. Because lead plates covered the exterior of the dome, the depth of the cracks was unknown. Terenzio viewed the cracking as the result of a differential settlement caused by uneven loads on the wall.

In 1985, Mark and Hutchinson analyzed the structural properties of the dome using a three-dimensional structural analysis computer program. They determined that the length of the cracks (from the base of the dome upwards to about 54 degrees) corresponded quite well with natural range of hoop tension in the dome. In addition to the dead weight of the structure, it also is likely that the wet-dry cycling of the blue clay, and its movement under the foundation, in addition to sizeable swings in temperature along with earthquakes, contributed to the cracking as well.

Mark and Hutchinson postulated that the cracking removed the ability of the dome to resist the forces of hoop tension near the base. The structure that was left did not act like a dome, but instead acted as if it were a series of arch segments

that extended from the top of the wall to a common compression keystone at the oculus. Their analysis showed that if the dome was structurally one unit, the step rings would be slightly detrimental to its strength and they would have provided no structural benefit to the designer—regardless of their aesthetic value. If the dome, however, was treated as a series of arch segments, then the weight of the step rings near the base had a beneficial structural effect, acting somewhat like a buttress. This suggests that the Romans knew that their concrete could not withstand much tensile stress, and instead solved the problem by taking advantage of their extensive practical experience with the arch.

We must, nevertheless, recognize that the concrete dome of the Pantheon has cracked. At the risk of conflict, we might consider this question: Would it be proper to place a steel band around a step-ring to nullify tensile forces for safety purposes? The Pantheon is a complete building from the Roman Imperial Age that provides a unique window into the past. Built almost entirely of a unique construction material, Roman concrete, the Pantheon remains an important legacy for our profession.

—By **David Moore, P.E.**, author of the book *The Roman Pantheon—The Triumph of Concrete*. Copies may be ordered at www.romanconcrete.com.

ABOUT THE PHOTOGRAPHER

Lakisha Campbell, Director of E-Business and STP Marketing at AGC of America, took the pictures of Roman concrete used in this issue of *CONSTRUCTOR*. The photographs were taken with a Nikon 775 digital camera, on her recent vacation in Rome, Italy. Digital cameras are more prevalent in daily use, for work and pleasure. The speed of delivery and immediate access to these electronic files is useful on construction jobsites. To learn more about other technology tools that make the business of construction more efficient, visit: www.agc.org/technology.

SPECIAL THANKS

Special thanks also go to Stephani Miller, *CONSTRUCTOR*'s former editorial assistant, who played a key role in molding and shaping the Roman Concrete series and bringing it to fruition.