Archaeo-Engineering: Learning from and Preserving the Structures of the Ancient World

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Overview

Awe-inspiring structures enduring from ancient times pervade the earth today. Structures from Europe and the Americas alike, such as Roman aqueducts and theaters and towering Maya pyramids, are mighty displays of structural engineering prowess from a seemingly premature time. The unsurpassed longevity of these structures makes them susceptible to structural failure, and therefore, engineers have a paramount task in preserving them with modern structural engineering. In addition, several examples of ancient engineering prove to be ingenious and designed with pioneering skill allowing them to endure significant tests of time. The responsibility of the archaeo-engineer is to analyze these structures not only to preserve them for generations to come, but to glean information about the people who built them, their structural engineering knowledge and understanding, and even the culture in which they lived. This paper reviews two remarkable works of ancient structural engineering: the Maya arch and consequent suspension bridge at Yaxchilan and Roman concrete vaulting in the Great Hall of Trajan's Market, showcasing the work of ancient as well as modern archaeo-engineers.

The Maya Arch and the Suspension Bridge at Yaxchilan

The engineering accomplishments of early Americans are seldom publicized compared to their European counterparts, but the accomplishments of these peoples such as the Maya are remarkable and worth studying. In the Yucatan rainforest of southern Mexico lies the ancient ruins of the Maya, including high-rise palaces and pyramids and long span suspension bridges. The dense vegetation of this area hid these engineering gems from the outside world for more than a millennium, but they have now been discovered and studied in depth by both archaeologists and engineers.

Of particular interest is the city of Yaxchilan, a city thriving in the period of 250 to 900 AD. This city was originally studied by nontechnical explorers and archaeologists beginning in the late 1800s. Recently, archaeo-engineers have studied the city and its associated engineering marvels from a technical perspective and the results have been extraordinary. Structures spanning large spaces with the use of arches are visible around the dwellings of the Maya. These arches are a considerable structural engineering feat for their time leading to in depth discussion in several archaeo-engineering publications.

To build structures such as the arch, the Maya developed a method for producing hydraulic cement 1500 years ago. Common masonry structures would not withstand the great amount of damage caused by unruly vegetation such as tree roots and jungle vines entering masonry joints. The Maya produced cement using wood-fired blast furnaces to superheat limestone into cement clinker[1]. This cement was subsequently mixed with coarse aggregate, water, and a polymer from the sap of indigenous trees to make cast-in-place concrete. Concrete was used as a durable construction material in the Maya's greatest structures, not the least of which being the Maya arch. These arches can be analyzed and understood structurally through Figure 1, showing the construction and forces involved with the structural design of the arch.

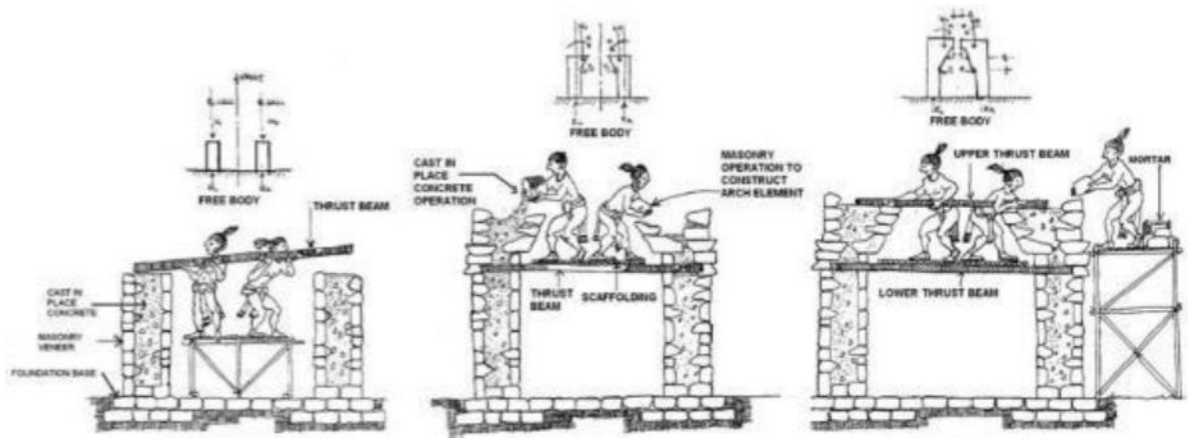

Figure 1: Construction of the Maya Arch[1]

The left depiction shows masonry walls extending to the intended springline of the arch. These masonry walls acted as the form for the cast-in-place concrete which was poured into the cavity between the wall faces. At the springline, a timber thrust beam was inserted into either end of the wall. This thrust beam acted as both a base for scaffolding for the construction of the upper portions of the arch, and a compression member resisting the tendency of the overhanging partial arches to collapse inward. The middle depiction shows the concrete and masonry construction on the upper portion of the arch. When the construction reached a certain height, a second thrust beam was added as shown in the right depiction. This arch also worked in compression to resist the added bending moment and inward forces produced by the unfinished arch. Finally, the arch was closed at the top which then converted the thrust beams from compression to tension members due to the added weight of the top of the arch pushing the supporting walls outward. Most surviving Maya arches no longer have the timber thrust beams due to rotting, but the cavity where they once laid is visible.

This arch allowed for structural spanning capabilities with an important example being the suspension bridge at Yaxchilan across the Usumacinta River, the longest suspension bridge of the ancient world with a main span of 63 meters[2].

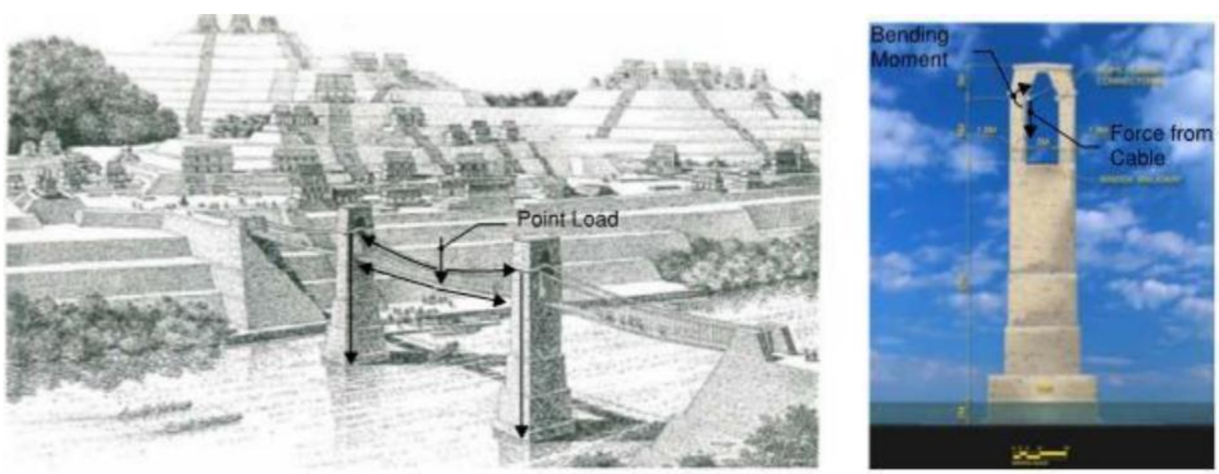

Figure 2: The Maya suspension bridge at Yaxchilan with load paths added and an elevation of the bridge pier[2]

The ruins of this bridge were discovered by archaeo-engineers and subsequent analysis of the ruins and surrounding area resulted in the structural understanding of the bridge. Figure 2 shows a depiction of what the bridge may have looked like in ancient times. Two large cut stone and cast-in-place concrete piers held a hemp rope suspension bridge across the river, which would raise up to 15 meters in the rainy season, hence, making the bridge a necessity to the survival of the city. Maya arches adorn the top of the piers and are integrally important to the structural design. It should be noted that the design of portions of the bridge are speculative, as the bridge is in ruins, but the analysis is done with the understanding of other surviving Maya structures and still offers legitimate insight into the structural design capabilities of the Maya.

Following the load path of a point load in the middle of the main span offers the opportunity to learn the design of the bridge. The point load is transferred directly to timber boards along the walking path which are supported by hemp rope on either end running in the span between piers. A suspension cable made of hemp rope hangs above the board level tied to the boards by ropes in tension. The load is transferred from the cables up to either main pier. The pier utilizes a Maya arch with a protruding stone on the interior of the arch to carry the suspension cable load and is cast in the concrete and masonry arch. The rope bearing on this stone, visible in the pier elevation of Figure 2, induces a bending moment which is absorbed by the concrete and the previously addressed design of the arch. The loads then travel vertically down through the walls into the pier and finally into the foundation of the bridge pier at the bottom of the river.

The Vaulted Concrete Ceiling of Trajan's Great Hall – Rome

The ceiling of Trajan's Great Hall, shown in Figure 3 consists of originally unreinforced concrete and is a remarkable engineering achievement of ancient Rome. Unlike the Maya suspension bridge, this structure is still standing in its entirety and therefore offers the opportunity for the archaeo-engineer to study its structure and be instrumental in its preservation.

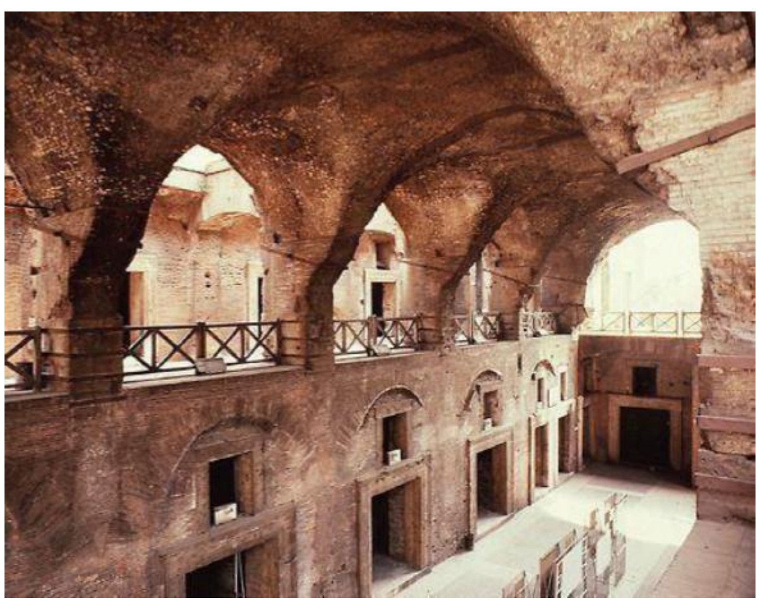

Figure 3: Trajan's Great Hall[3]

Figure 4 shows a solid model of Trajan's Great Hall with the main concrete vault spanning more than 8 meters from its supports on the shear walls. Modern archaeo-engineers have analyzed the structure to determine a great deal about the Roman engineer's knowledge, the areas of the structure most susceptible to failure, and to produce methods to preserve the structure.

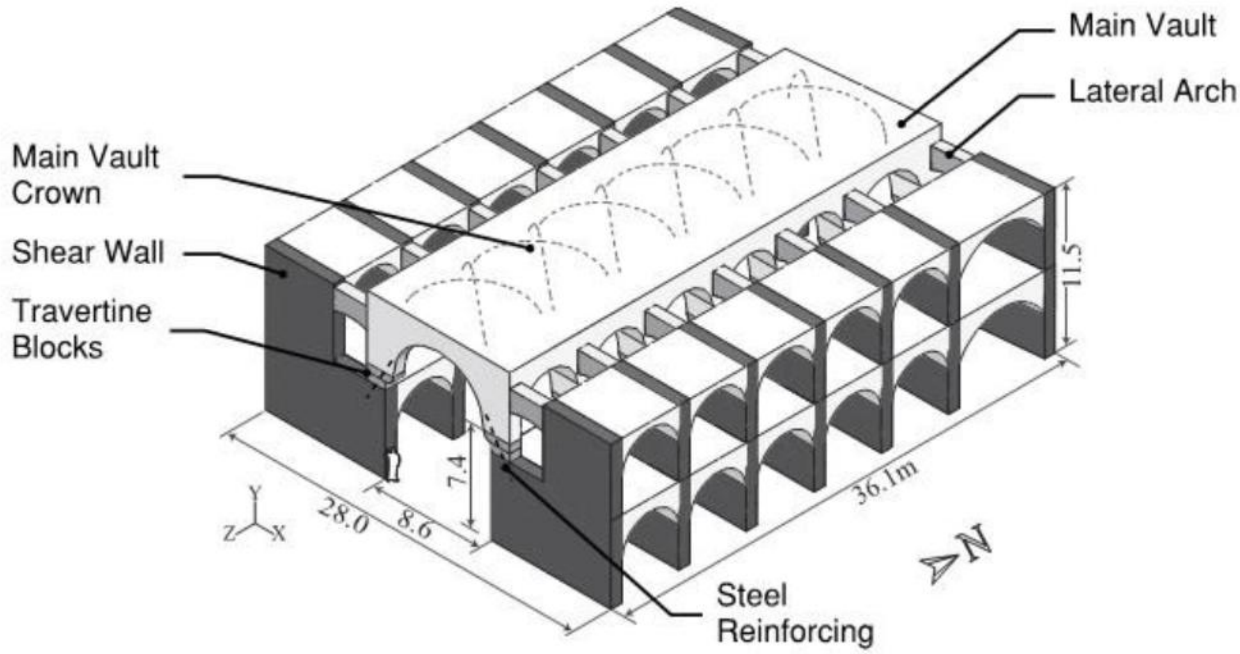

Figure 4: Solid model of the Great Hall (Main Vault) and surrounding structures#. Annotations by author[4]

The main vault was constructed using concrete made of pozzolanic volcanic ash and ~10 cm volcanic rock and brick coarse aggregate[4]. Amazingly, the concrete has mechanical behaviors qualitatively similar to those of modern concrete: the compressive strength (~750 psi) is on the order of tenfold the flexural tensile strength (~75 psi), though only a fraction of the strength of modern concrete. Since the concrete is both analogous to modern concrete and a continuum, finite element analysis was utilized by archaeo-engineer Philip Brune to analyze the structure. Unlike previous analysts, Brune found that the lateral arches minimally support the thrust of the main vault. In addition, the maximum compressive stresses were at the interface of the main vault and the travertine blocks while maximum tensile stresses were at the main vault crown where bending moment is greatest[4]. The maximum compressive stress developed (~100 psi) is well below the experimental strength of the Roman concrete but the tensile stress is not as satisfactory as it reaches more than 30 psi offering a factor of safety of only about two for a nearly 2000-year life cycle. Tensile cracking developed at the crown of the intrados on the entire length of the main vault. In addition, the interface between the travertine blocks and the vault concrete has minimal frictional resistance and is therefore susceptible to translation by sliding.

These structural problems offered the perfect opportunity for archaeo- engineers to develop a solution. Figure 5 shows the area prone to tensile cracking. The concrete in this area (shown by black dashed lines) was replaced as part of a restoration program at the Great Hall. Rome was officially classified as seismic prone in 2003[5]. This classification led to structural fortifications at several places prone to failure by seismic activity. Due to the potential for sliding at the travertine-concrete interface, inclined steel reinforcing bars were installed at each of the main pillars as noted in Figure 4. To increase the tensile strength of the concrete at the crown of the main vault ceiling, horizontal steel reinforcing bars were inserted across the vault just above the crown (shown by dashed white lines in Figure 5)[5]. The importance of archaeo-engineers to this project cannot be understated as this structure holds great cultural value and had strong potential for structural failure without modification.

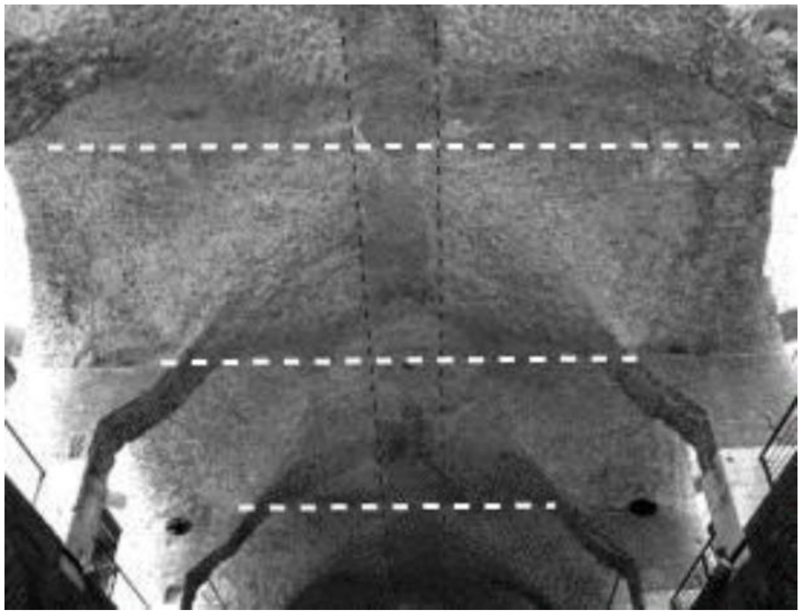

Figure 5: The crown of the main vault showing replaced concrete between black dotted lines and approximate location of steel reinforcing inside ceiling[5]

Other Accomplishments by Archaeo-Engineers

Professor Steven Ellis at the University of Cincinnati, is a leading Roman archaeologist who is currently leading excavations at the Pompeii Archaeological Research Project: Porta Stabia in Pompeii, Italy among other projects. Professor Ellis is very familiar with the Great Hall and many other ancient Roman structures. Professor Ellis believes archaeo-engineers are important to archaeological sites as they use their technical expertise to observe the foundations and short walls of ancient ruins and anticipate the upper portions of structures that no longer stand. Archaeo-engineers also realize the ancient drainage patterns for entire cities such as Pompeii which offers a great deal to the study of the ancient people who lived there[6].

Conclusion

Numerous ancient structures still exist around the world and the practice of archaeo-engineering allows for the analysis and preservation of these impressive structures. The study of these structures not only produces a vast amount of structural engineering information about the ancient people's technical knowledge, the materials they used, and the design methods they employed; but it also gives information about the ancient cultures as a whole, much of which cannot be realized by the nontechnical archaeologist alone. Structural engineers acting as archaeo-engineers are therefore vitally important to the study of archaeological and ancient structures, people, and cultures and the preservation of remarkable engineering accomplishments.

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Bibliography

1. O'Kon, James A. "Forensic Engineering Research Uncovers Lost Maya Engineering Landmarks." *ASCE Forensic Engineering* (2007): 14. Print.
2. O'Kon, James A. "Computer Modeling of the Seventh Century Maya Suspension Bridge at Yaxchilan." *ASCE Computing in Civil Engineering* (2005): 14. Print.
3. "Interior of the great hall, Markets of Trajan, Rome, Italy, ca. 100–112 CE." *The Ancient World,* Tumblr, 11 Jun 2010. https://s-media-cache-ak0.pinimg.com/736x/d3/0a/93/d30a937ccb9294e94af0670afc687560.jpg.
4. Brune, Philip and Renato Perucchio. "Roman Concrete Vaulting in the Great Hall of Trajan's Market: Structural Evaluation." *ASCE Journal of Architectural Engineering:* 18(4) (2012): 332-340. Print.
5. Ungaro, L., M. Vitti, and E. Speranza. "The Great Hall of the Trajan Markets Throughout the Centuries." *Structural Analysis of Historic Construction* (2008): 1509-1517. Print.
6. Ellis, Steven, University of Cincinnati. Personal Interview. 13 Apr. 2017.
7. Gargari, Mousa T., University of Cincinnati. Personal Interview. 9 Apr. 2017.

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