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Research

The Arch: Born in the Sewer, Raised to the Heavens

Abstract. The great ancient civilizations all knew about the arch yet the Greeks relegated its use to underground sewers and never raised an arch above ground: Why? The Egyptians, the Babylonians, the Assyrians and of course the Romans all exploited the arch as a means of spanning and enclosing space. Yet, curiously, Greece, one of the most cultured of the ancient civilizations and the builder of magnificent temples used stone in a most unnatural way, as a beam. The arch as a construction technique is intimately connected to the material of which it is constructed, namely masonry. Stone, when used as a beam is limited by size, scale and proportion. The Greeks certainly understood this as they closely spaced columns to support stone lintels. They also meekly tried to use stone in an A-frame configuration using a corbelled arch in Mycenea (1325 BC) but they never made the transition to the true arch using stone voussoirs. WHY? Perhaps the answer lies in a lack of understanding of the mechanics of the materials and the nature of compression and tension.

Early development of the arch

The great ancient civilizations all knew about the arch yet the Greeks relegated its use to underground sewers and never raised an arch above ground except in a minor or ornamental manner: Why? Examples abound in nature of arches such as the stone arch off Milos. Yet, curiously, Greece, one of the most cultured of the ancient civilizations and the builder of four of the seven wonders of the ancient world – the statue of Zeus at Olympia, the Temple of Artemis at Ephesus, the Colossus of Rhodes and the Lighthouse at Alexandria – and the builder of magnificent temples, used stone in a most unnatural way, as a beam. Even the architect of the Parthenon, Ictinos, thought that arches were not stable.[1]

The Egyptians, the Babylonians, the Assyrians and, of course, the Romans all exploited the arch as a means of spanning and enclosing space. The third-century B.C. Porta di Giove in the city wall of Falerii Novi (Etruria) and the first-century B.C. Pons Fabricus, a circular arch spanning less than 25m over the Tiber River in Rome, are typical examples. The Ponte Molle (Pons Mulvius) built by Marcus Aemilius Scaurus in 109 B.C. in Rome, with seven arched spans of 15-24m, is still standing.

The arch as a construction technique is intimately connected to the material of which it is constructed, namely masonry. Stone is limited by its size, scale and proportion when used as a beam. The Greeks certainly understood this, as they

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spaced columns closely to support stone lintels in temples such as the Parthenon. That structure used white pentelic marble from Mt Pentelicus in Attica, the same marble used for statues such as the Venus de Medici (sculpted by a Greek in the first-second century A.D.). One problem with marble is that, as a metamorphic rock derived from limestone, it is easily corroded by water and acid fumes. The disastrous deterioration of both statuary and temples witnessed in Athens is a direct result of this weakness.

Perhaps as a result of the observation of natural stone arches, Eupalinus of Megara led the excavation for a 1000m long water tunnel on the Greek island of Samos in 520 BC through a limestone mountain.[2] It was a magnificent engineering achievement. Eupalinus, the engineer for the venture, organized two crews working from either end. After working for ten years and without modern surveying apparatus, the tunnel deviated at the meeting point by less than 5m horizontally and 1m vertically. But for the purpose of our study, the interesting fact is the shape of the cross section that was about 1.8m in width and height with a curved soffit. Although not a true arch, it is clear that the arching concept of stone was understood by Eupalinus.

The Greeks also meekly tried to use stone using a (false) corbelled arch in the Lion Gate (1250 BC), an entrance to the Citadel, and in the Treasury of Atreus, the entrance to the Princes' tombs, both in Mycenea.[3] There are a number of other examples of stone arches used more in an ornamental fashion using stone voussoirs or true arches. The gateway to the Agora in Priene, built on a terrace above the harbor in 150 B.C., incorporated a 6m span arch. On the Acropolis, but below the Parthenon, arches can be seen. At Asclepion, built in 400 B.C. on the Greek island of Kos, off the Turkish coast where Hippocrates taught, a multiple-arched façade defines the Propylea, the baths and guest rooms of what was the oldest hospital in the world. South of Troy, the Gate of Asso is in the form of an arch and may actually predate the Gate at Volterra. Miletus had a similar arch. At Ephesus, the Library of Celcus has a number of decorative marble arches that date from a time after the classical Greek Era (700-400 B.C.). Further back in time, about 1360 B.C., the Hittite capital in Boghazkoy in Anatolia, east of Ankara, includes an elliptical arch as the King's Gate. Although not truly Greek, it was clearly an antecedent.

The masonry arch first appeared between the fifth and the fourth centuries B.C. in Greece, Etruria and Rome. Sometime in this period, the Etruscans most likely introduced the Romans to the arch. The Etruscan Gate at Volterra from the fourth century B.C. is considered the first example of a true arch. In Europe, the oldest known arch is the Cloaca Maxima, a huge drain built in 578 B.C. by Lucius Taquinius Priscus. The Romans adopted and developed the structural arch to an art form, such as at the forum of Thessalonica built in the second century A.D. along a Roman Road, but in Hellenistic architecture the arch was recognized as no more than a self-conscious tour de force.

What then were the reasons for the hesitant use of the arch by the Greeks in a more structural manner? One reason may have been a lack of understanding of the mechanics of the materials and the nature of compression and tension. Construction, in the days before the development of structural mechanics, always evolved as a trial-and-error process. It is quite likely that the arch as a structural element represented too much of a leap for the Greeks from simple post and lintel construction, perhaps because the thrust from an arch needs a lateral support and such support is easily provided below ground but needs special provision above ground.

Perhaps the material played a part! Consider the fact that the Romans built arches primarily of igneous granite or sedimentary limestones in such structures as the aqueduct in Segovia built during Emperor Trajan's time (ca. 100 A.D.) with 128 arches of white granite, and the 275m long Pont du Gard in Provence (14 A.D.), a three-tiered aqueduct 49m high constructed of limestone. They also used metamorphic rock such as tufa (a light volcanic igneous rock) and travertine marble in the Mulvian Bridge in Rome, which consists of 18m arches.

Strength of stone

Having learned from the Etruscans, the Romans acted confidently in their use of these different qualities of stone, from the strongest granites to the weaker marbles and limestones, and also took advantage of smaller stones which were adequate for an arch as compared to the larger stones needed for a lintel. The Greeks, on the other hand, built primarily of limestone or marble. Dense limestone and marble are both of about equal strength although less than half the strength of granite (see Table 1). However, limestone is a much more workable stone that can be cut or sawn more easily as well as splitting easily, having been deposited in layers. It is therefore well-suited for use in fluted columns and large lintels.

Stone	Compressive Strength	Flexural Strength
Granite	131 MPa	8.3 MPa
Marble	52 MPa	6.9 MPa
Limestone	12-55 MPa	n/a
Sandstone	28 MPa	n/a

Table 1.

Another possible reason against the construction of arches stems from the need for wood centering. In the Greek lands, the absence of forests made good quality timber a somewhat scarce commodity. Also, the skill needed to construct centering for the voussoirs may never have developed. This issue is not dissimilar to one faced in the recent past by designers wanting to build concrete shell structures. Such structures were very popular in the middle of the last century but are no longer being built. The reason is that centering and formwork is needed for this construction to define the shape and support the wet concrete. Rather than a question of scarcity of wood, the problem is the cost of the custom hand labor required to build the forms. For this reason shell structures are no longer being built, even though such structures are very efficient. It is really the same problem faced by the Greek builders wanting to erect arches that are in their own way much more efficient than the alternative post and lintel.

It is only in later years that the arch appeared in Greek construction such as the archway to the Kato Paphos in Cyprus built in the twelfth century and destroyed in the earthquake of 1222.

We may never know the true reason why structural arches did not appear in Hellenistic architecture but as argued above, the answer may be a combination of lack of structural experimentation, constraints presented by available stone and limitations on availability or cost of wood centering.

Notes

1. In *Math and the Mona Lisa* (Smithsonian Books, 2005), Bülent Atalay states: "Although the Greeks could make arches by fitting together wedge-shaped stones, they had not extended the idea into spanning large spaces by making domes of such stones."
2. Cited by Herodotus and the home of Agamemnon.
3. Examples of corbelled arches existed in many diverse civilizations such as the Maya and the Khmer.

About the author

Matthys P. Levy is a founding Principal and Chairman Emeritus of Weidlinger Associates, Consulting Engineers. Born in Switzerland and a graduate of the City College of New York, Mr. Levy received his MS and CE degrees from Columbia University. He has been an adjunct professor at Columbia University and a Distinguished Professor at Pratt Institute and a lecturer at universities throughout the world.

Mr. Levy is the recipient of many awards including the ASCE Innovation in Civil Engineering Award, the IASS Tsuboi Award, the ENR Medal of Excellence, three Lincoln Arc Welding awards, three PCI awards, the Founder's Award of the Salvadori Center and an AIA Institute Award. He was named a Structural Engineering Legend in Design by Structural Engineering Magazine in 2003. He has published numerous papers in the field of structures, computer analysis, aesthetics and building systems design, has illustrated two books and is the co-author of the best-selling book *Why Buildings Fall Dow* as well as *Structural Design in Architecture, Why the Earth Quakes, Earthquake Games and Engineering the City.* His latest book, *Adventures in Weather*, is looking for a publisher!

Mr. Levy is a member of the National Academy of Engineering, a Fellow of the Institution of Civil Engineers and the American Society of Civil Engineers, a member of the International Association of Shell & Spatial Structures, the International Association of Bridge and Structural Engineers and other professional societies. He is a registered Professional Engineer in the US and Eur Ing in Europe; he is also a founding director of the Salvadori Center that serves youngsters by teaching mathematics and science through motivating hands-on learning about the built environment.

Projects for which he was the principal designer include the Rose Center for Earth and Space at the American Museum of Natural History, the Javits Convention Center and the Marriott Marquis Hotel in New York, the Georgia Dome in Atlanta, the La Plata Stadium in Argentina, the One Financial Center tower in Boston, Banque Bruxelles Lambert in Belgium, the World Bank Headquarters in Washington, DC, and a cable-stayed pedestrian bridge at Rockefeller University. He is the inventor of the patented Tenstar Dome structure, a unique tensegrity cable dome used to cover large spaces with minimal obstruction.

Mr Levy was represented in the exhibit, 'The Engineer's Art' at the Centre Pompidou in Paris. He has appeared on numerous television shows including NOVA, Modern Marvels, the History Channel, ABC News, PBS series on Domes and others.

Mr. Levy has served as an expert in forensic investigations including the World Trade Center Collapses in New York, the Versailles Ballroom Collapse in Jerusalem, the failure of the UNI Dome in Iowa, the Fire Damage to the Meridian Building in Philadelphia, the collapse of Precast Concrete Stands in Atlanta, the quality of Aquarium Construction in Duluth, the adequacy of documents for construction of a Multi-Screen Movie theatre in San Francisco, the cause of fabric roof failure in Montreal.