
The Pantheon (A.D. 118-128)

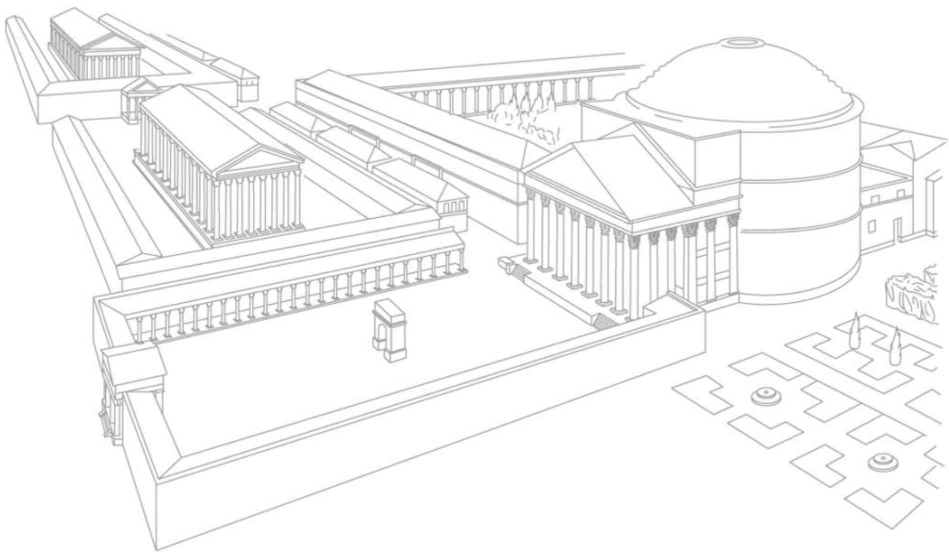
THE PANTHEON (A.D. 118-128)

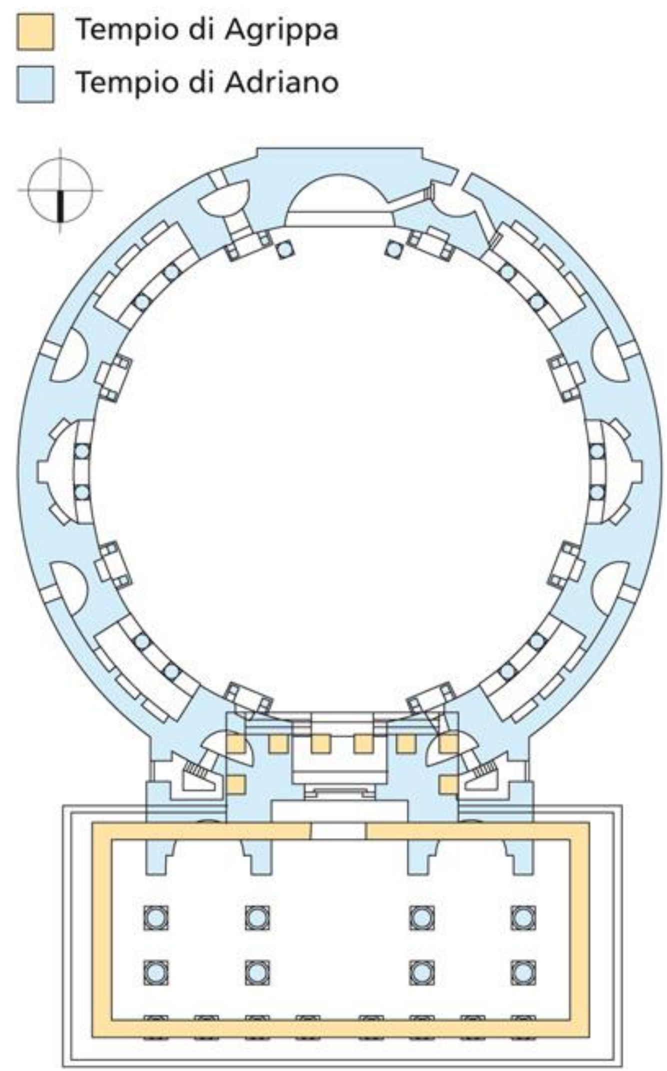
- «Avevo ritoccato di persona i progetti troppo cauti dell'architetto Apollodoro. Delle arti della Grecia volli servirmi per le decorazioni, come per un lusso supplementare, ma per la struttura dell'edificio ero risalito ai tempi primitivi e favolosi di Roma, ai templi rotondi dell'Etruria antica. Avevo voluto che quel santuario di tutti gli dei riproducesse la forma della terra e della sfera stellare, della Terra dove si racchiudono le sementi del fuoco eterno, della sfera cava che tutto contiene.
- Era quella, inoltre, la forma di quelle capanne ancestrali nelle quali il fumo dei più antichi focolari umani usciva da un orifizio aperto alla sommità. La cupola, costruita d'una lava dura e leggera che pareva partecipe ancora del movimento ascensionale delle fiamme, comunicava col cielo attraverso un largo foro, alternativamente nero e azzurro. Quel tempio aperto e segreto era concepito come un quadrante solare. Le ore avrebbero percorso in circolo i suoi riquadri, accuratamente levigati da artigiani greci: il disco del giorno vi sarebbe rimasto sospeso come uno scudo d'oro. la pioggia avrebbe formato una pozzanghera pura sul pavimento; la preghiera sarebbe volata simile al fumo verso quel vuoto nel quale collochiamo gli dei. Quella festa fu per me una di quelle ore nelle quali tutto confluisce. In piedi, nel fondo di quel pozzo di luce, avevo al mio fianco le gerarchie del mio principato, e la sostanza di cui si materiava il mio destino, ormai edificato più che a metà.»
- *Memorie di Adriano* di Marguerite Yourcenar

THE PANTHEON

- «Concrete vaulted construction represent one of the ancient Romans most original and enduring contributions to the artistic and architectural patrimony of the Mediterranean world.» (Lynne Lancaster, 2005).
- Concrete and vaulted structures are among the main key words of the course, whose goal is to highlight the history of building techniques and materials, beginning from the ancient Romans to trace the following developments until the invention of 19° century reinforced concrete.
- The use of materials and technical innovations are placed into the social, economic and political context, and studying these topics a cross-cultural competence is required, embracing both scientific and humanistic fields.

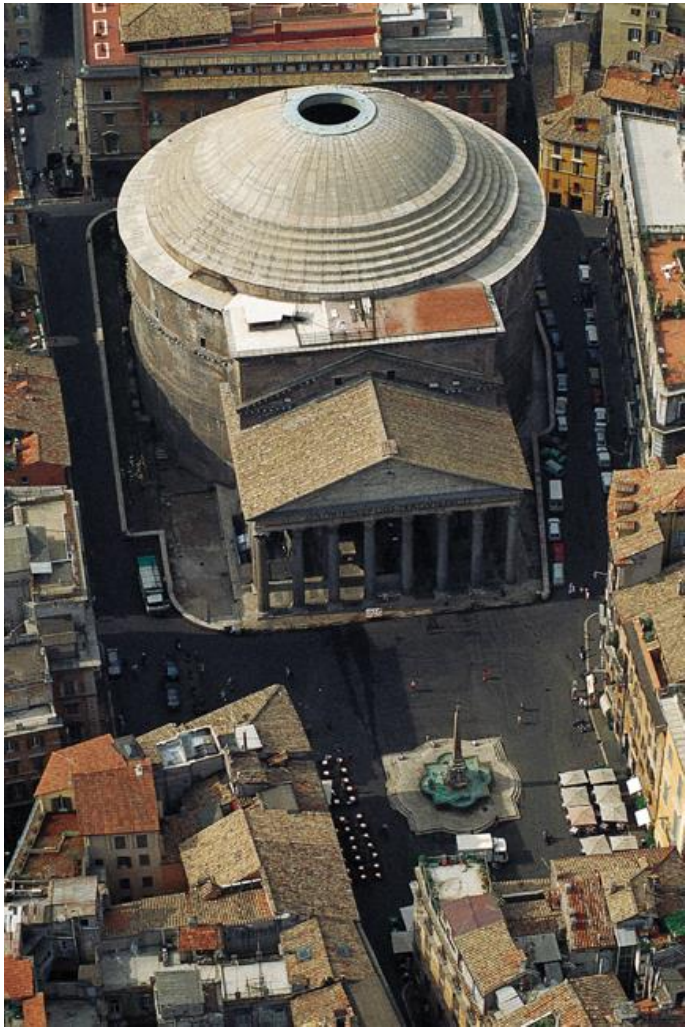
THE PANTHEON FROM AGRIPPA TO HADRIAN





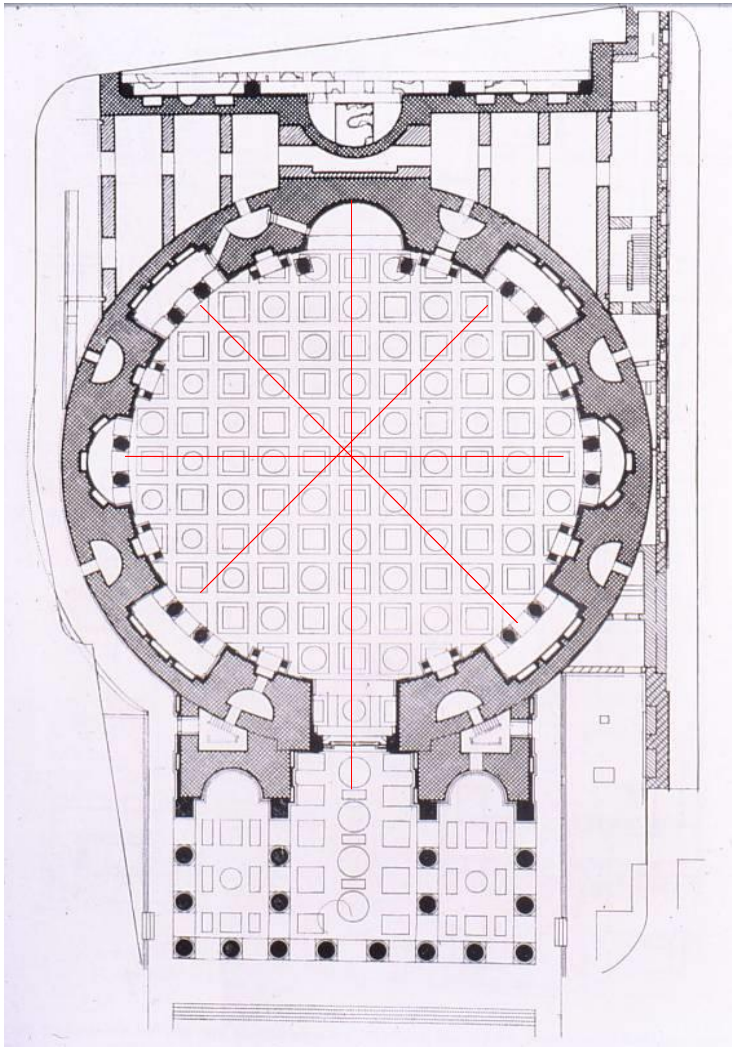
The Pantheon was originally built by Agrippa in 27 B.C. , but it burned down in the fire that destroyed much of the Campus Martius in A.D. 80 and was rebuilt by Domitian. It was damaged by lightening under Trajan and then rebuilt in its present form under Hadrian from A.D. 118-128.

THE PANTHEON



The main structure consists of a large dome (43,30 m. diameter) supported by a 6 m. cylindrical wall into which are built niches such that the weight of the dome is concentrated onto the eight piers between them.
The porch and its intermediate block on the north side of the building are bonded to the rotunda wall in the lower wall at all, but brick stamps show that is roughly contemporary.

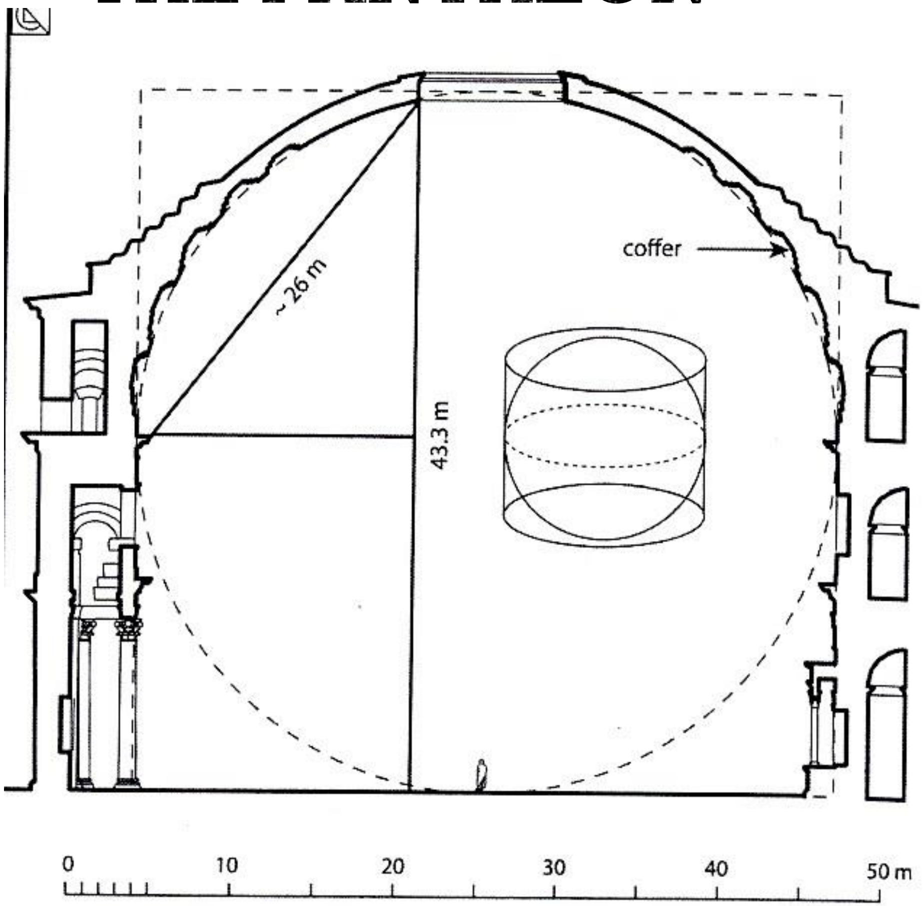
THE PANTHEON



The governing order of the Pantheon's structural system was based on a sixteen-part geometry, which was very easy to lay out for a circular form by simply using a compass and a straightedge to divide the circle first into quarters, then eights, and finally sixteenths.

The lay out of the Pantheon is related to circles and squares, from the floor covered by marble till to the coffered dome.

THE PANTHEON

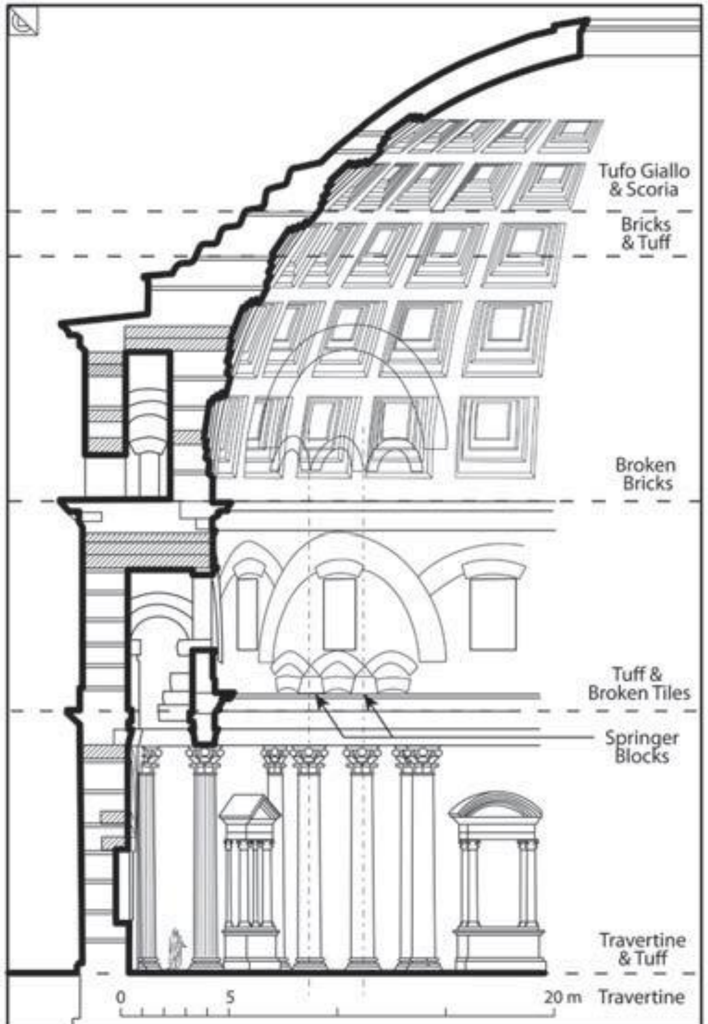


;6. Pantheon (A.D. 118–128). Geometry of dome based o
phere within a cylinder.

The design is modeled on a sphere within a cylinder, which was also the device that Archimeds had carved on his tomb representing one of his greatets mathematical discoveries, as to say the theorem determining the 2:3 relationship between the volume of the sphere and the cylinder.

THE PANTHEON

THE PANTHEON



The use of concrete provided the builders a means of controlling the mass of a structure by using stones of different weights as caementa in different parts of
the building.

The section of the Pantheon shows the distribution of the different types of caementa used: from the heaviest (travertine) at the bottom to the lightest (volcanic scoria and yellow tuff) at the top.

Notice, however, that the whole dome is not made as light as possible. Only the crown has the lightweight scoria and yellow tuff.

THE PANTHEON: MATERIALS AND TECHNIQUES

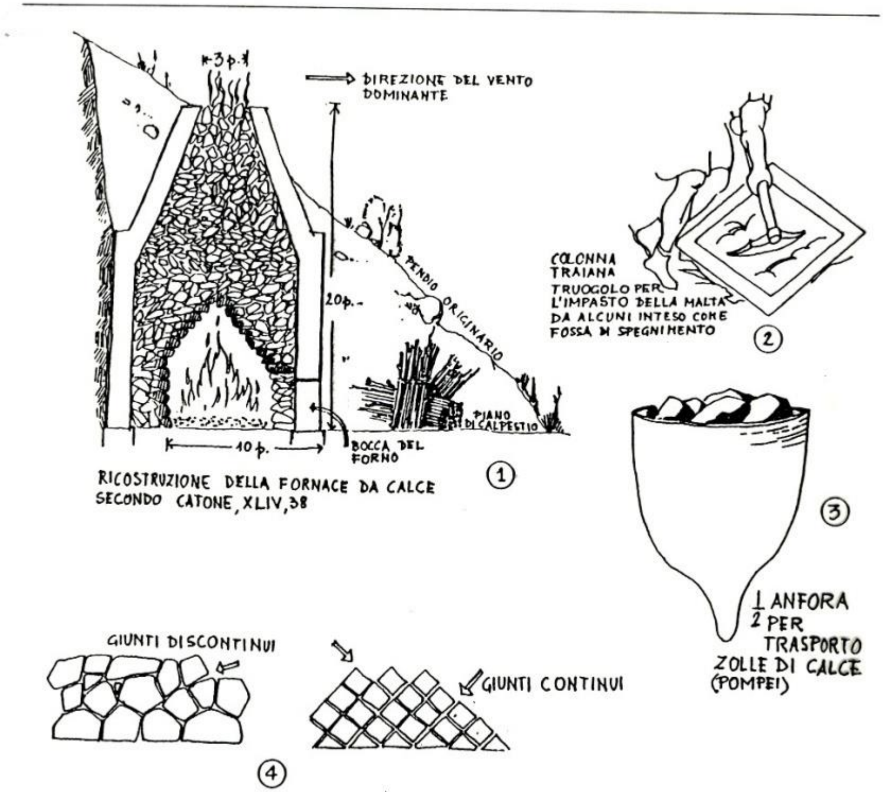
Materials for the Pantheon's structure:

- mortar,
- bricks,
- opus caementicium,
- pozzolana

- Building techniques: the arch and the vaulted structures such as the domes.

LIME AND MORTAR

FIGURA 7.6
Calce e muratura



The production of lime for mortar is a two step process: firing and slaking.
First the limestone or another calcium rich stone, such as marble or travertine, is fired in a kiln to produce quicklime, which comes out of the kiln as a very lightweight version of the original stone. Before the quicklime can be used for mortar, it has to be put through a slaking process in which the fired stones are combined with water.

LIME AND MORTAR

- Use rock containing $CaCO_3$ (limestone)
- Heat to ~1000°C (1850°F) to burn off CO_2

  $CaCO_3 + \text{heat} \rightarrow CaO + CO_2$ (CaO = "quicklime")

- Slake quicklime (mix with water) 3-4 times initial volume

  $CaO + H_2O \rightarrow \text{heat} + Ca(OH)_2$

  (disintegrates into powder – hydrated lime, which has an affinity for CO_2)

- Harden the hydrated lime (mix with aggregate = mortar)

  $Ca(OH)_2 \rightarrow CaO + H_2O$

  $CaO + CO_2 \rightarrow CaCO_3$

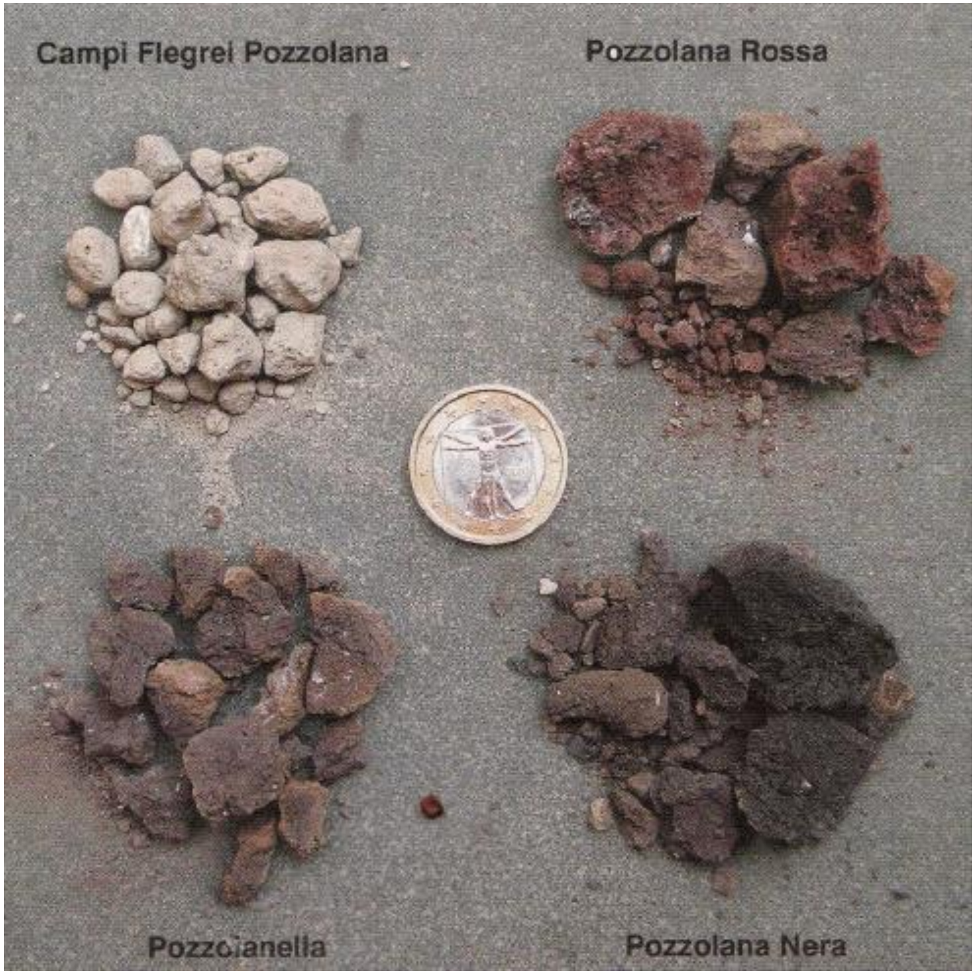
MORTAR AND POZZOLANA

- The mortar used by the Romans employed pozzolana, a volcanic ash that imparted added strength and hydraulic qualities that were lacking in the simple lime mortar used by the Greeks. Recent studies show that the resistance to compression of pozzolana- lime mortar is five to eight times stronger than that of lime mortar.
- A simple lime mortar made of siliceous quartz sand (SiO_2), slaked lime ($Ca(OH)_2$) and water (H_2O) hardens and gain strength trough the contact with carbon dioxide (CO_2) in the air as the water evaporates. Unlike the quarts sand which is inert, the pozzolana plays an active role in the chemical transformation of the mortar during the hardening process.
- Pozzolana contains both silica (silicon dioxide, SiO_2) and alumina (aluminum oxide Al_2O_2) which trough the eruptive process are converted into soluble forms allowing a chemical reaction to take place when mixed with water and slaked lime.

"POZZOLANA"

Pozzolana is a modern generic term for volcanic ash used in the building trade to make mortar and it applies to a type of material produced by volcanoes throughout the world. The ancient writers called it pulvis puteolanus or dust from Pozzuoli.

"POZZOLANA"



Four types of "pozzolana" showing the difference in colour among them. The Campi Flegrei pozzolana (pulvis puteolanus) at upper left is easily distinguishable from the other pozzolanas quarried near Rome.

"POZZOLANA"

Pozzolan

A siliceous and aluminous material (contains silica and aluminum), which possesses little to no cementing ability by itself, but when divided finely in the presence of water reacts chemically with calcium hydroxide (lime) to form compounds with cementitious properties.

Originally named after "dust from Puteoli" (modern Pozzuoli), commonly called "pit sand" by Romans.

Natural Pozzolans

- Volcanic ash, glass, and pumice
- Diatomaceous earths (contain siliceous diatom microskeletons)

Man-Made Pozzolans

- Industrial byproducts (fly ash – coal burning, silica fume – silicon smelting)
- Burned organic matter rich in silica (e.g., brick, ceramics, rice husks)

COCCIOPESTO

Cocciopesto is the name applied to a mortar with crushed terracotta, although it often contains pozzolana as well. The addition of crushed brick or terracotta creates a hydraulic mortar similar to pozzolana-lime mortar. The firing of the clay, which like pozzolana, is rich in silica, also produces a soluble silica component.

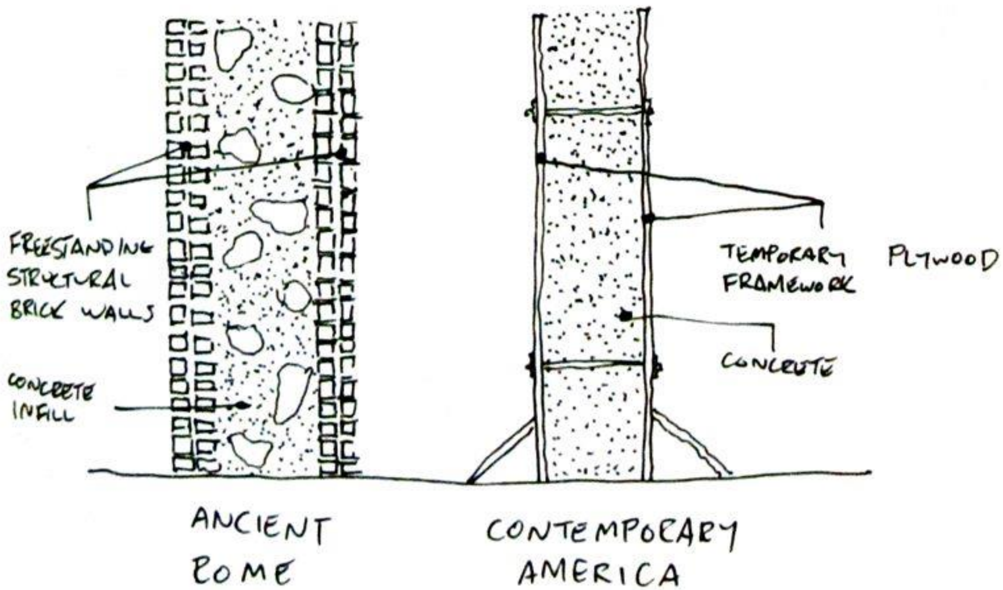
THE ROMAN CONCRETE, OPUS CAEMENTICIUM

Roman concrete is different from what we think of today as a concrete.
The word caementa means rough, unhewn quarried stones and refers to the rubble of fist-sized pieces of stone or broken bricks that were used in the mortar as aggregate.

THE ROMAN CONCRETE, OPUS CAEMENTICIUM

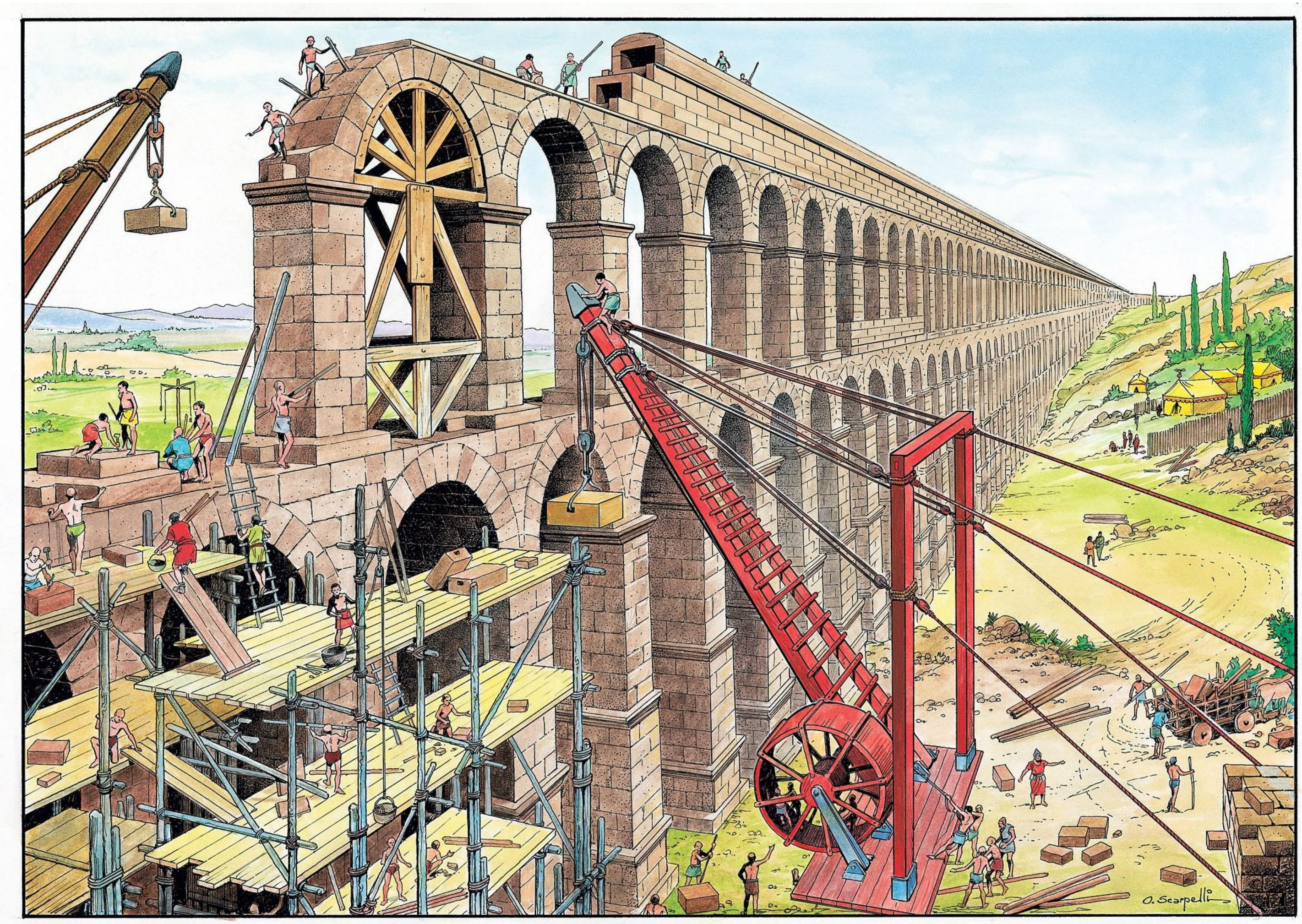
The way that ancient and modern concrete is put in place is also different. Modern concrete is poured into place over a network of steel reinforcing bars, whereas the caementa and mortar of Roman concrete were laid separately, by hand and trowel.

THE ROMAN CONCRETE, OPUS CAEMENTICIUM



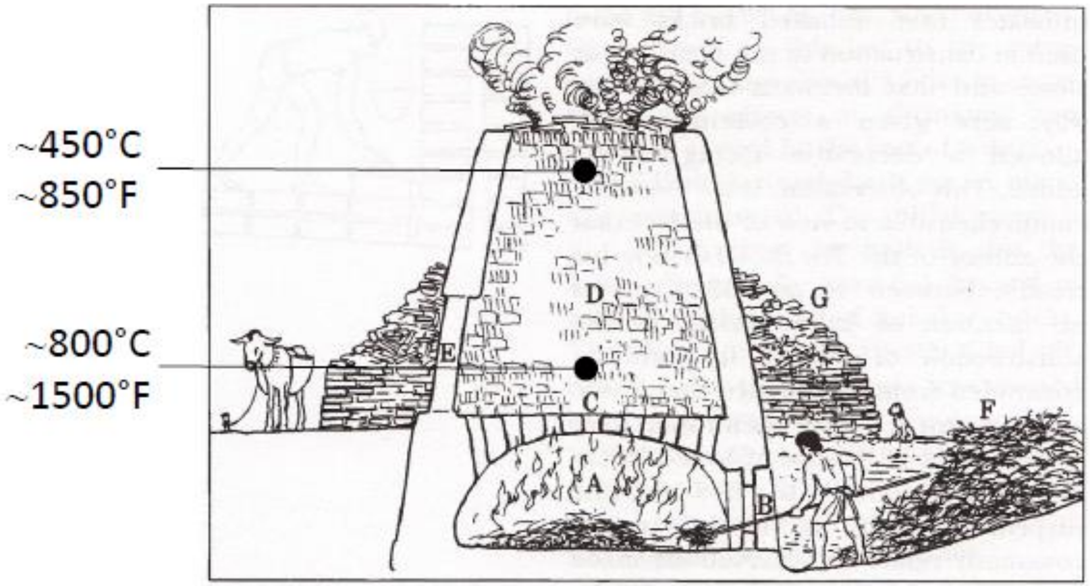
In both ancient and modern concrete construction, some type of structure or centering, is necessary to contain and model the wet mortar until it sets and gains strength.

THE ROMAN CONCRETE, OPUS CAEMENTICIUM



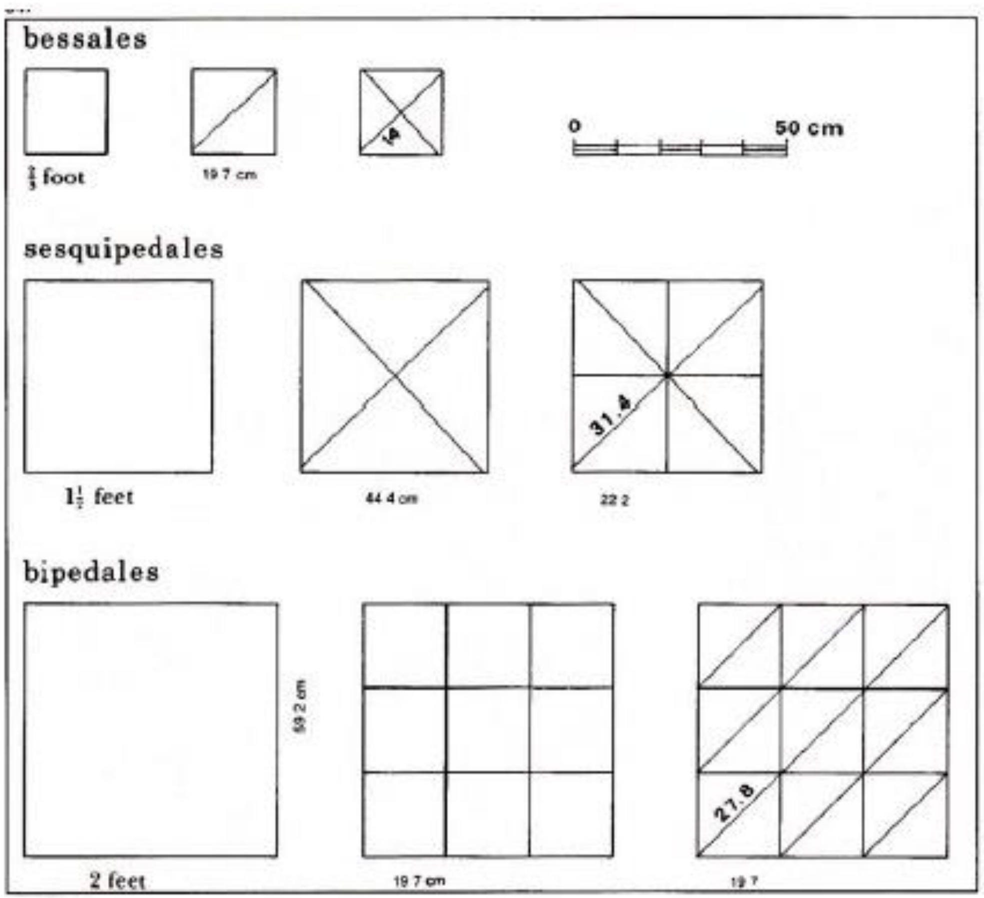
THE BRICKS

A Brick kiln



A = Hearth (combustion chamber)
B = Door for fuel and ventilation (partially blocked during firing)
C = Shelf pierced by holes
D = Bricks to be baked in the charge chamber
E = Loading door (blocked during firing)
F = Fuel supply
G = Bricks/stones/clay piled on side as insulation

THE BRICKS

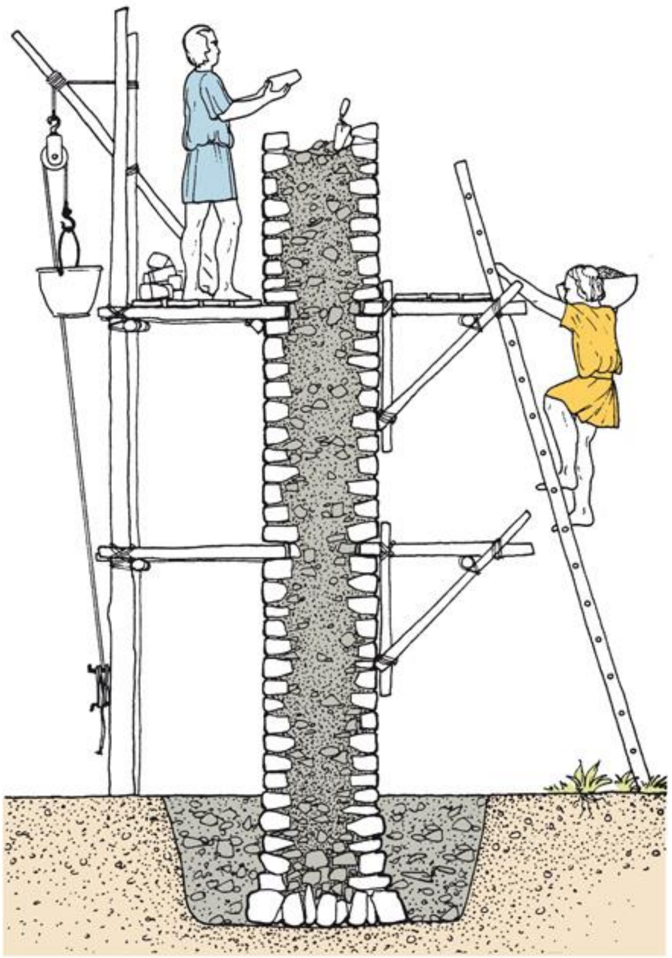


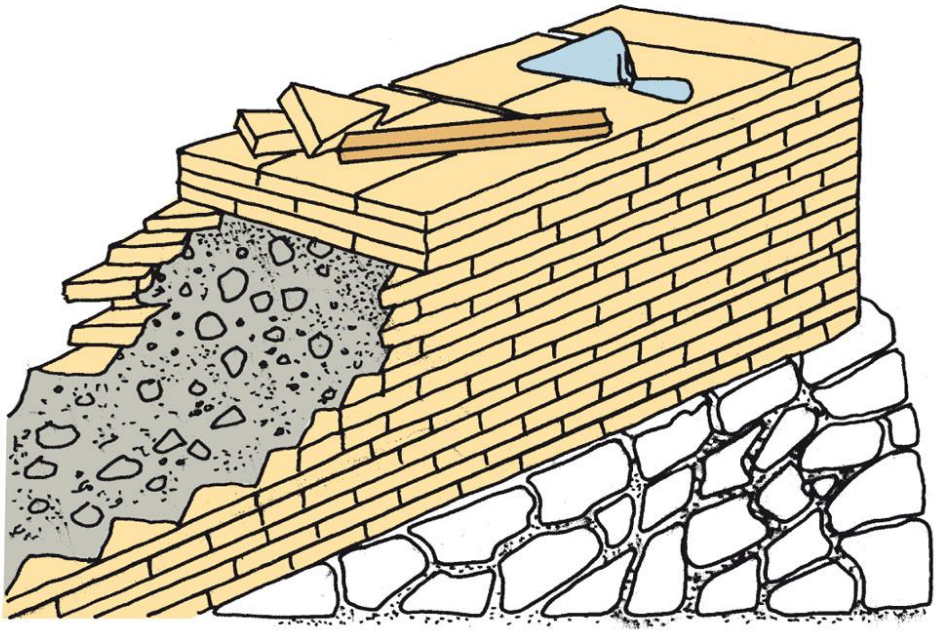
Brick became an important material for vaulting by the end of the first century A.D. and the development of brick industry had a great effect on the vaulting techniques in Rome. The bricks were made in four basic sizes: Bessalis (⅔ Roman Foot), Pedalis (1 Roman Foot) Sesquipedalis (1½ Roman Foot) and Bipedalis (2 Roman Feet).

THE BRICKS

Stamps on the bricks provide information both on the general locations of the clay beds and on people involved in the industry.

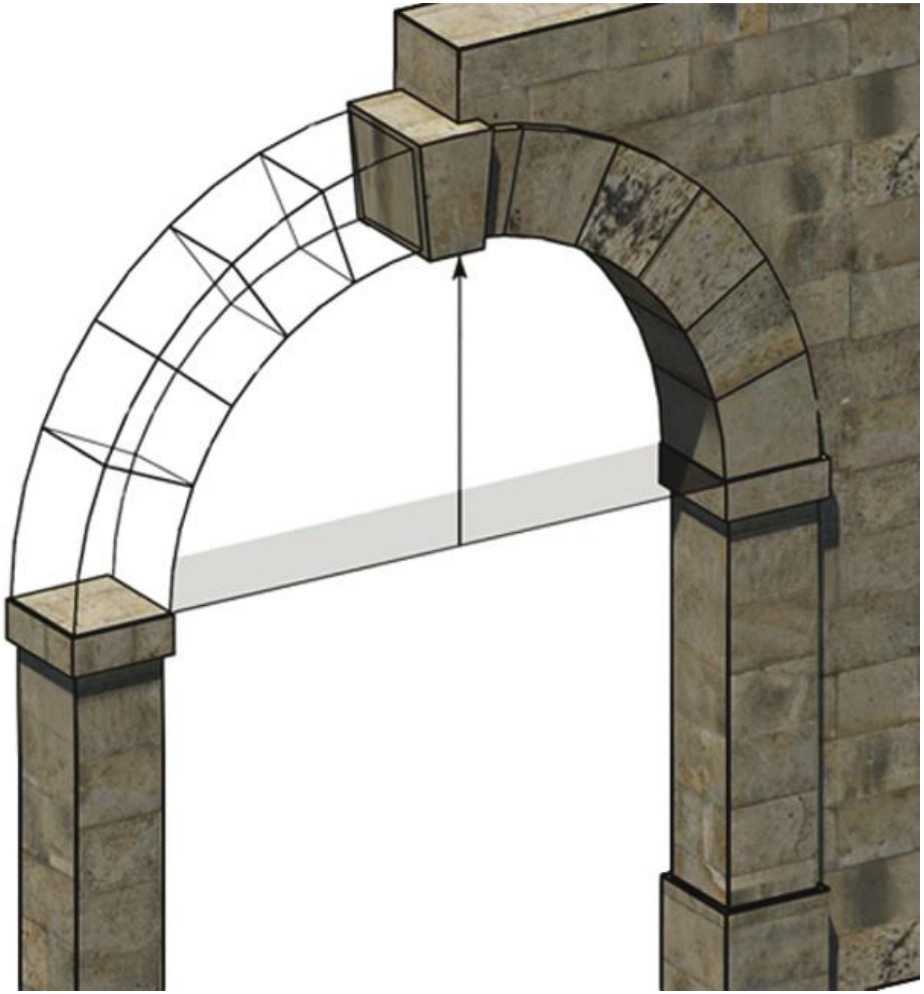
MASONRY





"L'opera a sacco" or faced concrete is made by two standing walls, either stone or bricks, and the hollow space between fullfilled with opus caementicium.

THE ARCH

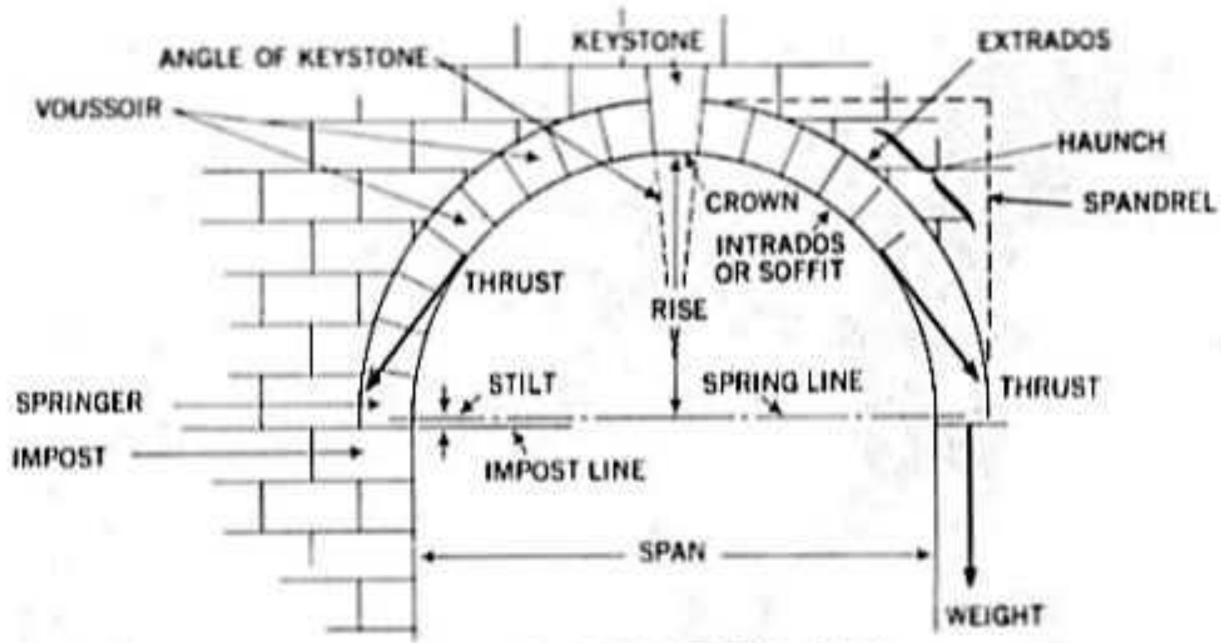


Structural form was a critical factor in the success of Roman buildings.

The interplay between forms and material was ultimately the key to longevity.

The arch which was originally developed for stone construction became the basis for the development of concrete vaulting.

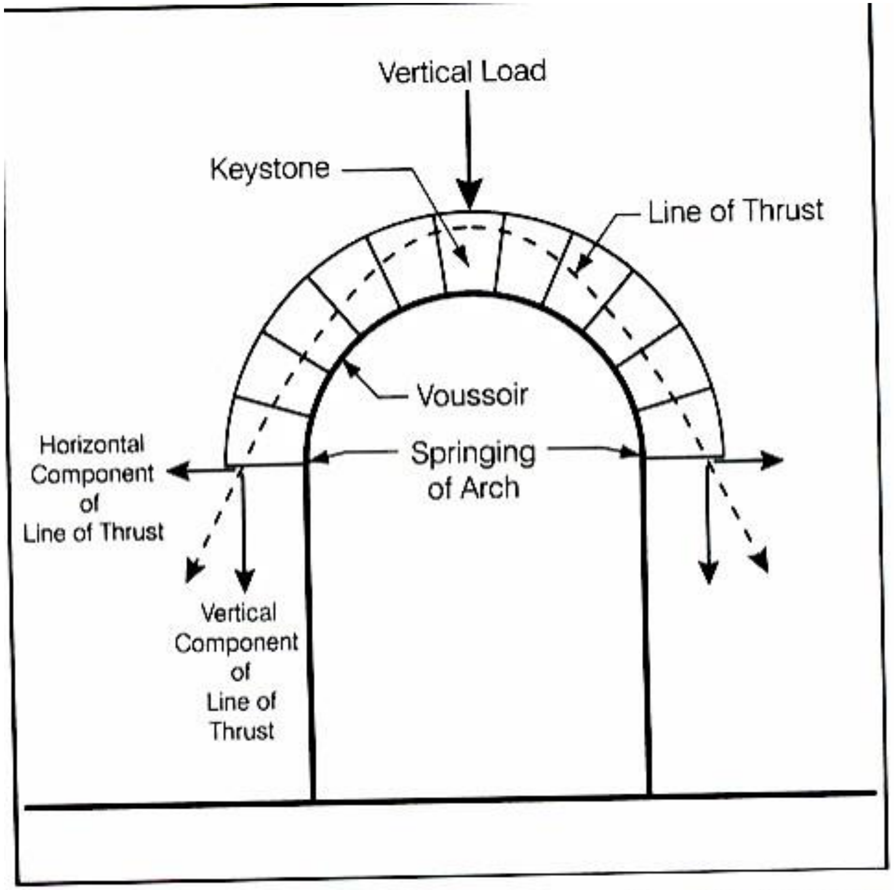
THE ARCH



ELEMENTS OF THE ARCH

Voussoirs are wedge-shaped stones that make up an arch. The radiating joints between the voussoirs serve to direct the weight of an arch and anything it supports towards the sides and away from the opening under the arch.

THE ARCH

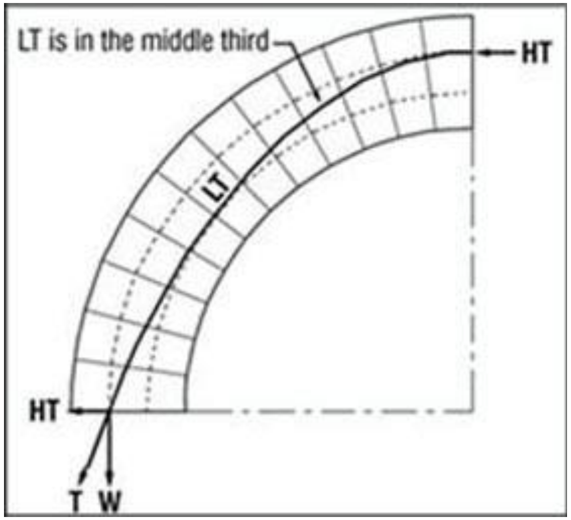


2. Diagram showing principle parts of an arch and its behavior.

- The result is that the arch pushes out at its springing, and this outwdar thrust must be countered or controlled in some way.

  If the arch is built into a wall, the surrounding masonry acts as a buttress to contain the horizontal thrust.

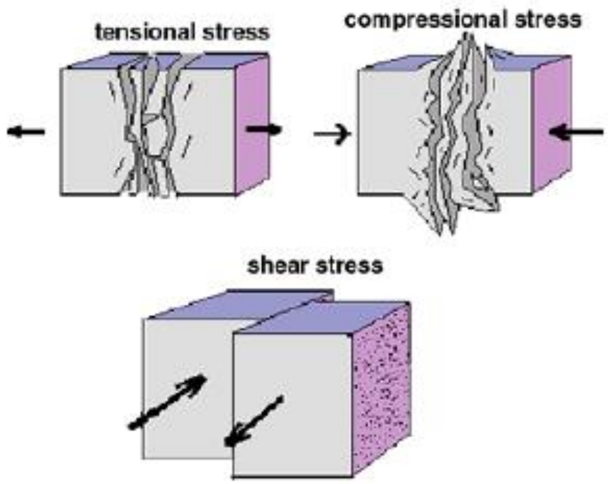
THE ARCH

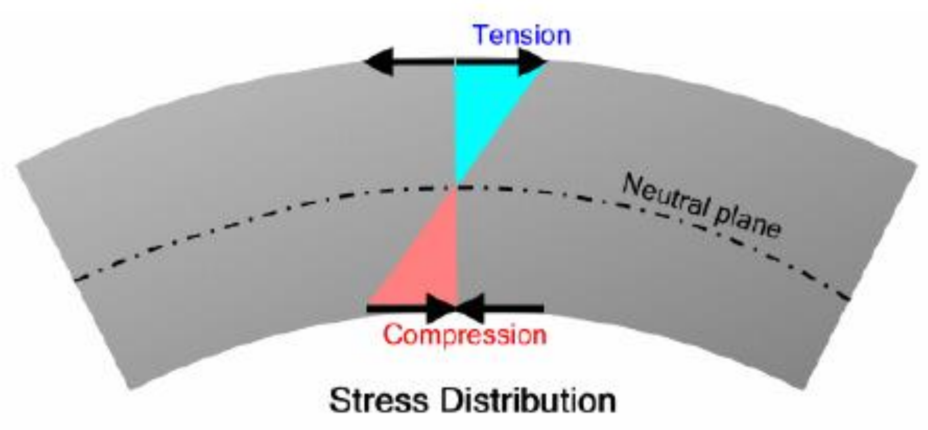


Middle Third Rule

- Middle Third Rule
  - – The forces in a object, e.g. a bearing wall, must remain in the middle third of the object for it to remain in compression only
- The same rule applies to arches; the line of thrust must remain in the middle third of the arch for it to remain in compression only.

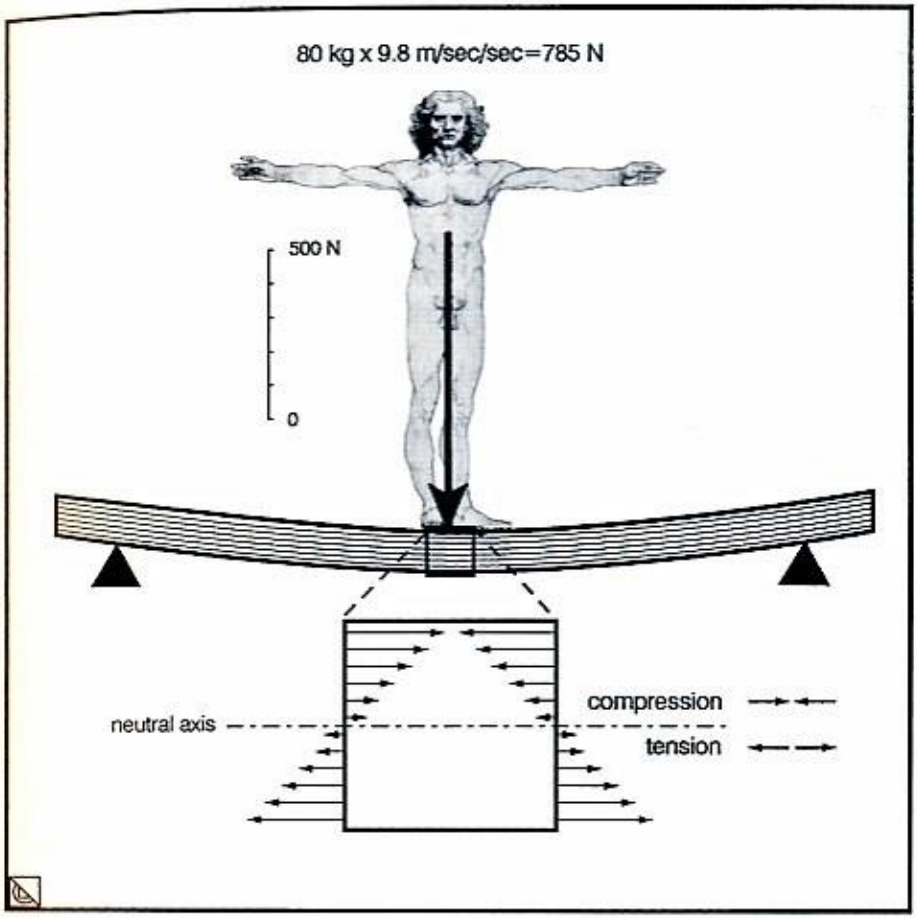
THE ARCH





The strength of any material is measured in terms of stress, which can occur as compression (compressive stress) or tension (tensile stress).

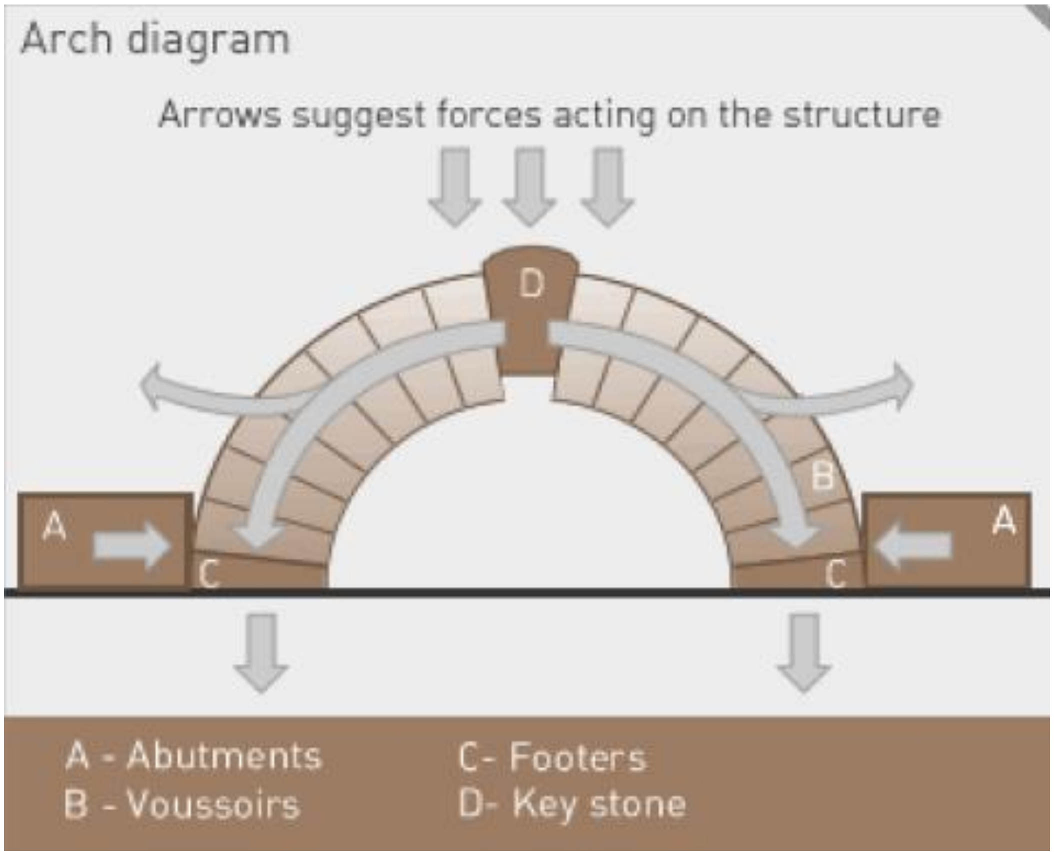
THE ARCH



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

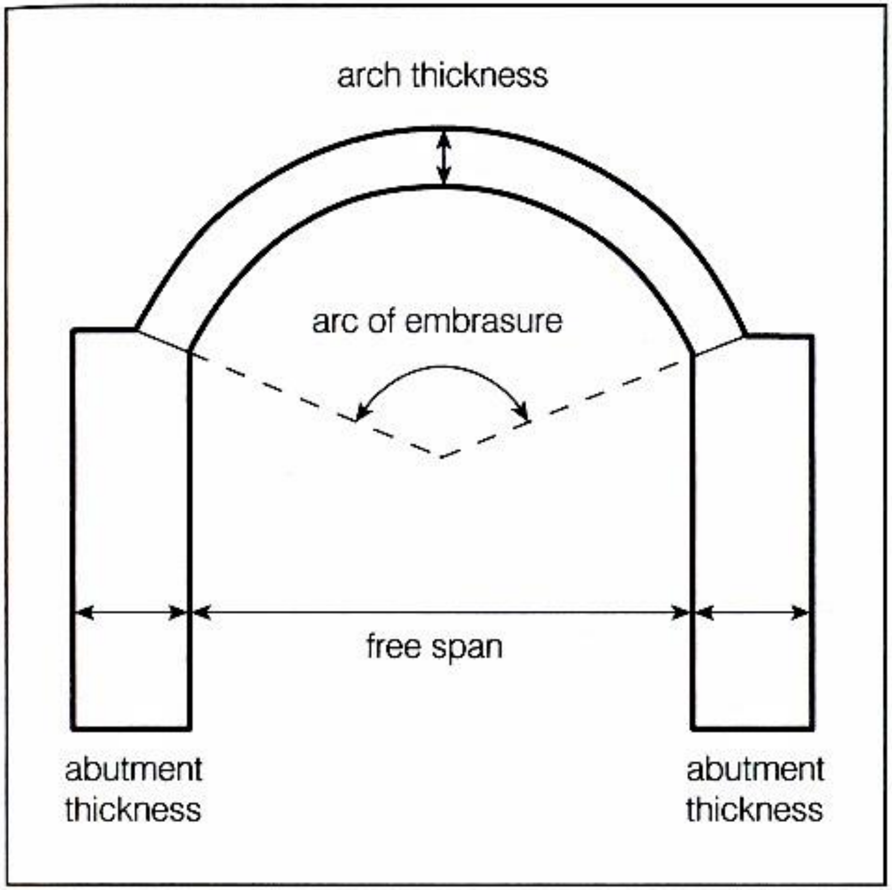
The example of a man on a beam shows both types of stresses within the beam.
As the beam bends downward under the man's weight, the upper half is in compression because the top surface is squeezed together and becomes shorter, and the lower half is in tension because the lower surface is stretched.
At a point in the middle of the beam there is a neutral axis that is not undergoing tension or compression.

THE ARCH



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.

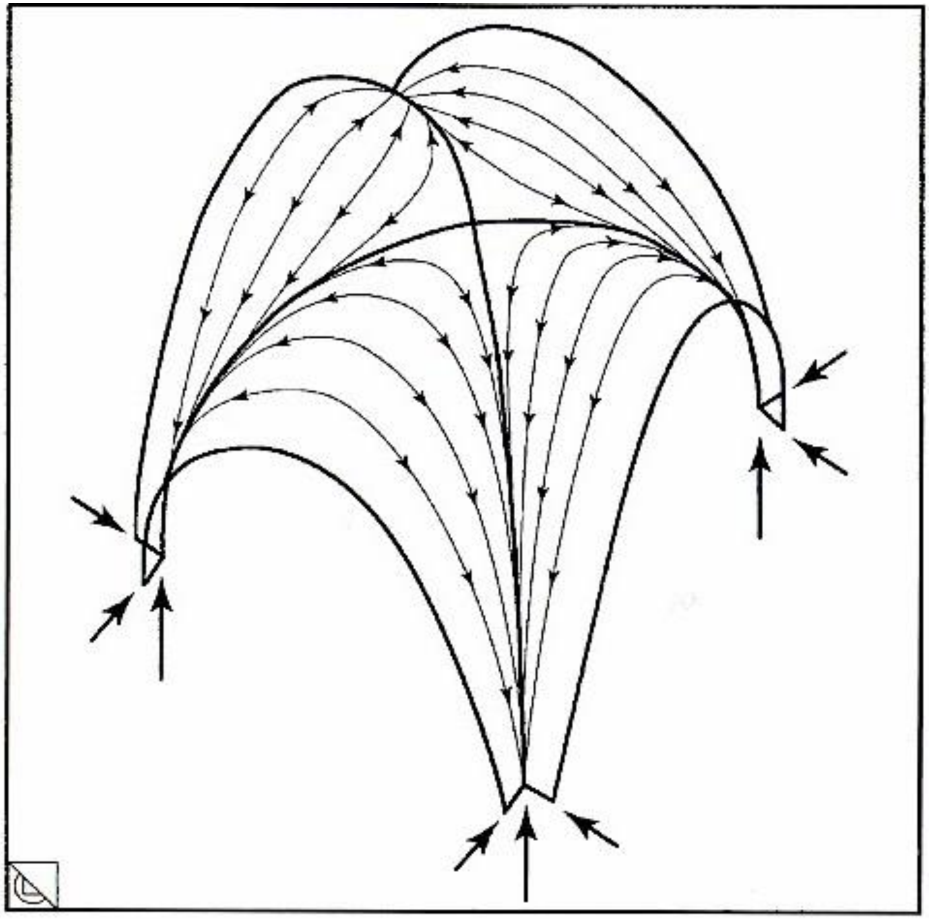
THE ARCH



115. Diagram showing four factors that affect the stability of an arched structure.

The structural behavior of an arch or barrel vault is dependent on four variables: the arc of embrasure, the thickness of the arch, the free span and the abutment thickness.

THE CROSS VAULT



117. Diagram showing the lines of compressive force in a cross vault. Based on Alexander et al. 1977: fig. 8.

The behavior of the cross vault differs from that of the barrel vault: it is a load concentration system that directs both vertical load and the horizontal thrusts to the corner supports.

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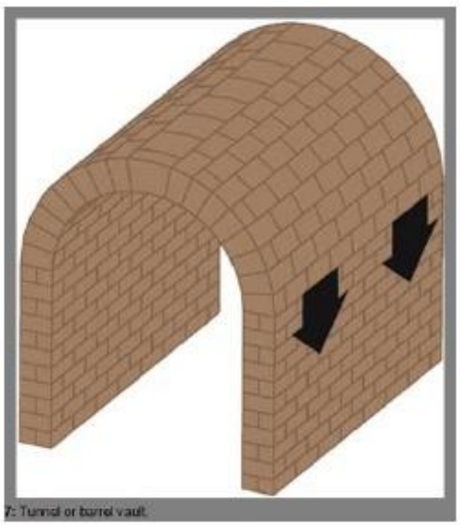
One of the greatest advantages provided by cross vaults was the ability to let more light into a space than it was possible with a barrel vault.

BARREL AND CROSS VAULTS

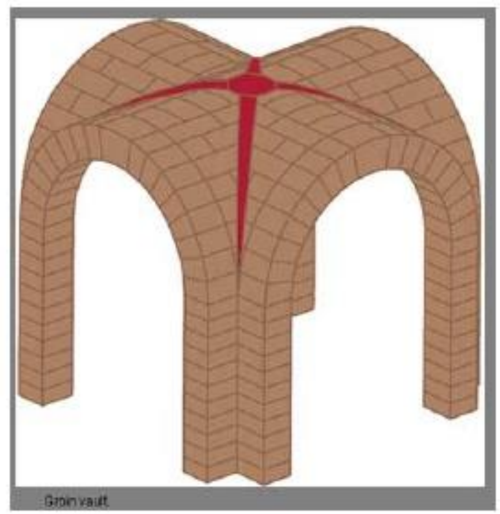
Barrel and Groin Vaults

If the arch is extended, a barrel or tunnel vault is formed. If two barrel vaults intersect perpendicularly, a groin or cross vault is formed.



7: Tunnel or barrel vault.

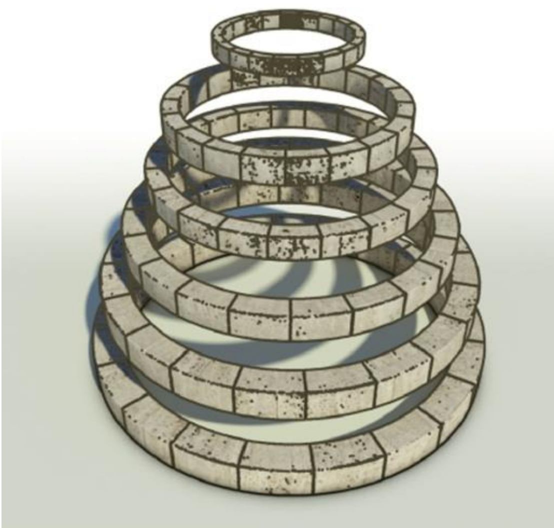
Barrel vault – is a round arch extended to create a tunnel like structure

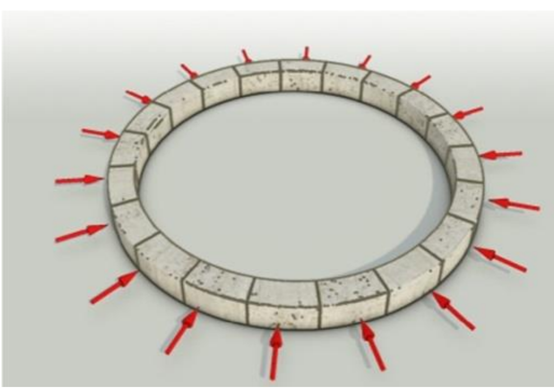


Groin vault

Groin vault – formed by two intersecting barrel vaults creating 4 openings

DOMES AND SEMIDOMES

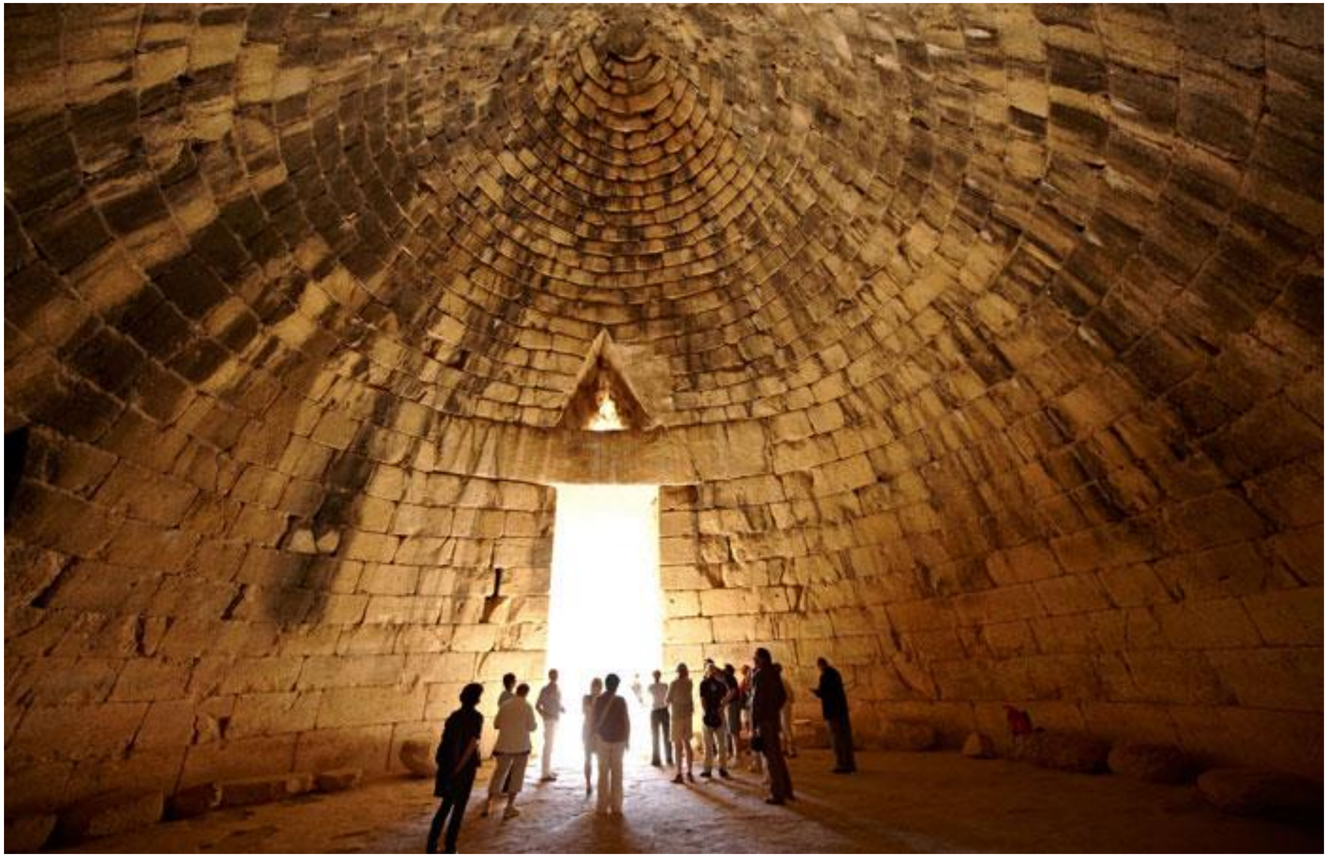




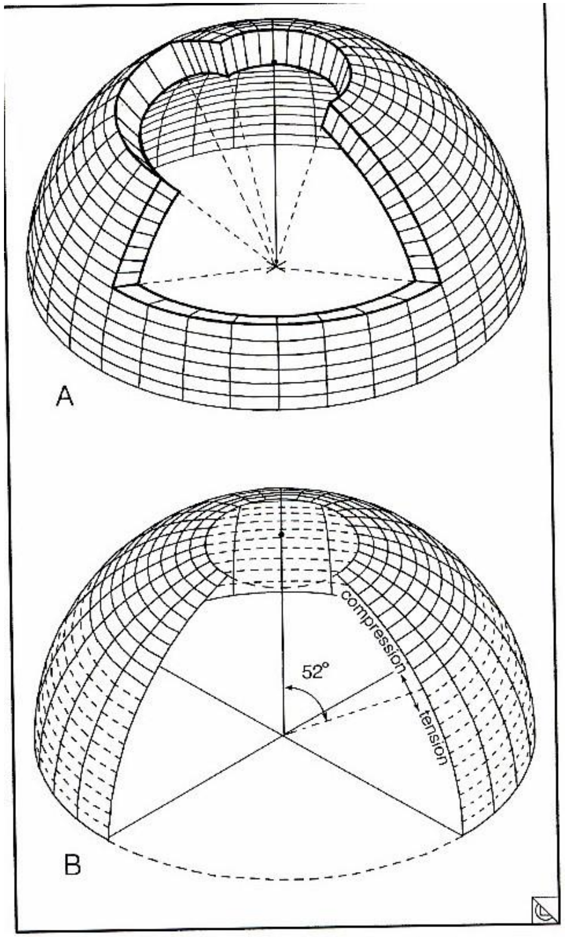
A dome of cut stone construction is essentially like a series of self-supporting horizontal rings stacked one on top of the other. If the domes were sliced vertically, the converging joints of the voussoirs would allow each slice to stand on its own , and if were sliced horizontally the converging joints form horizontal rings in compression, each of which could support itself.

Hence, the cut stone dome is like a three-dimensional arch where each successive ring acts like a keystone to lock the blocks into a place.

DOMES AND SEMIDOMES



DOMES AND SEMIDOMES

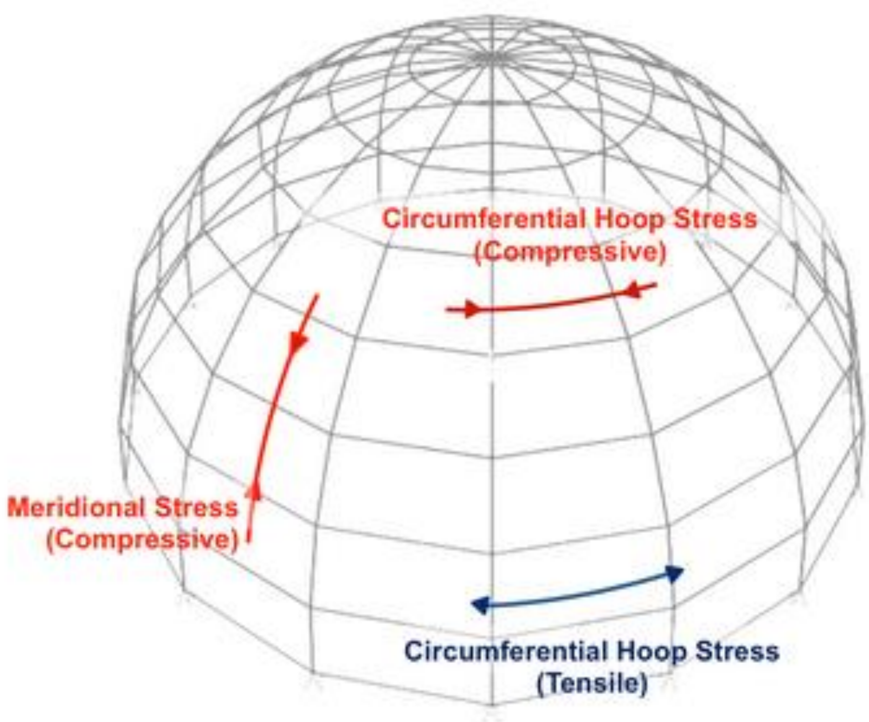


123. A: Diagram of construction of dome built of stone voussoirs. B: Diagram showing stress patterns in an uncracked concrete dome.

Roman domes of concrete, however, are usually built in horizontal layers of unshaped caementa laid in an abundance of mortar, so there are no converging voussoirs edges to perform the same function as in the cut stone dome.

Unlike a simple barrel vault, a dome also has stresses occurring in both direction of curvature: meridional stresses (along the longitudinal lines) and circumferential hoop stresses (along the latitude lines).

DOMES AND SEMIDOMES



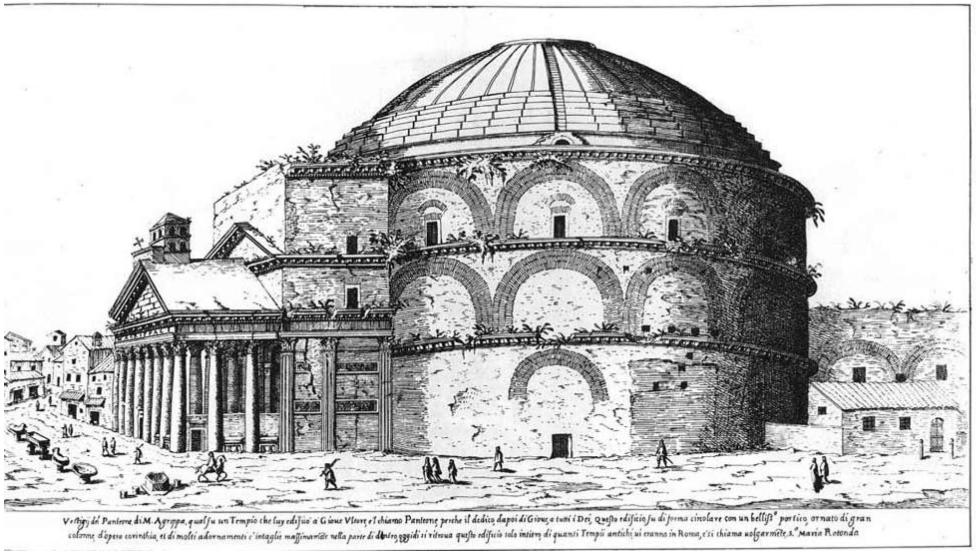
Structural analyses of the domes show that both the meridional and hoop stresses are in compression at the crown but that tensile hoop stresses develop in the haunches.

In a hemispherical dome the point of change from compression to tension is about 52^{0} from the crown of the vault with the tension increasing towards the base.

RELIEVING ARCHES

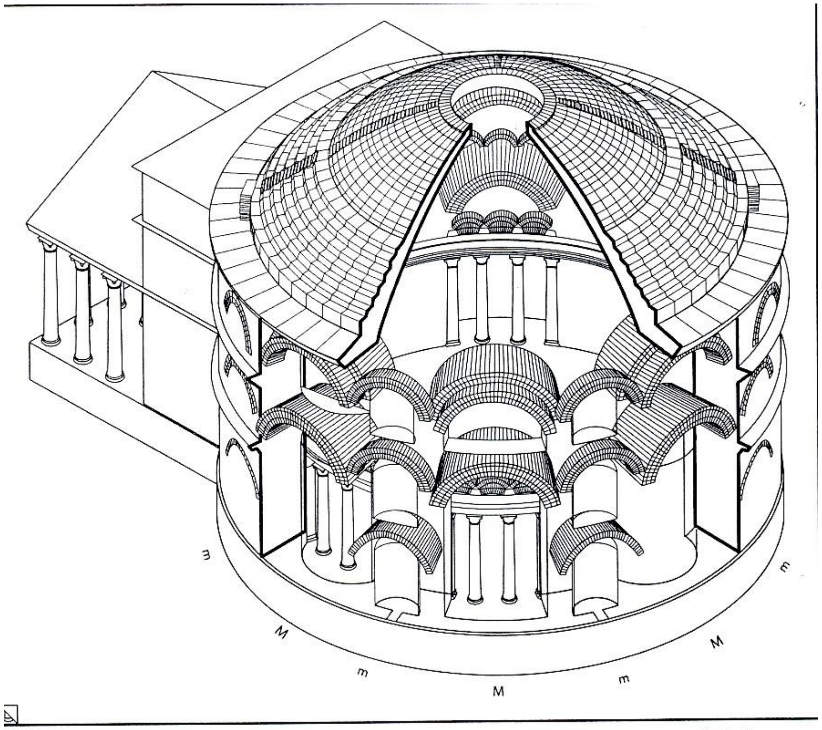
Roman concrete vaults have sometimes been attributed monolithic properties because of the use of pozzolanic mortar, but most large Roman domes and semidomes, including the Pantheon, have vertical cracks in their lower zones, indicating that the concrete was not able to resist the tensile stresses that developed in the haunches.

RELIEVING ARCHES



The key to the structural integrity of the rotunda is the series of vaulting ribs into the rotunda wall. The wall of the rotunda contains series of relieving arches at three levels.

RELIEVING ARCHES AND MORE

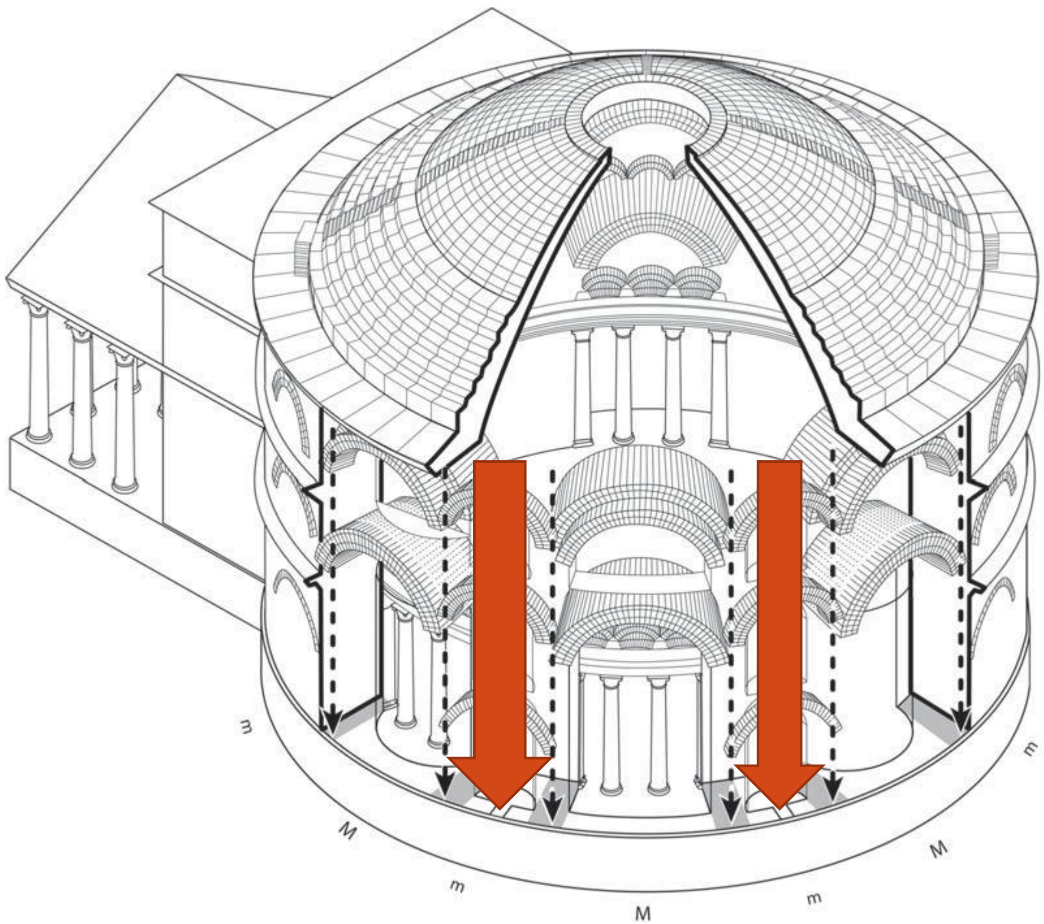


80. Pantheon (A.D. 118–128). Drawing showing the system of ribs built into the rotunda wall. “M” indicates the major system of ribs connecting the piers, and “m” indicates the minor system within the piers

The rotunda wall is 6 m. thick, but it’s pierced with voids so that structurally it acts more like eight large piers than a solid wall as it appears from the exterior.

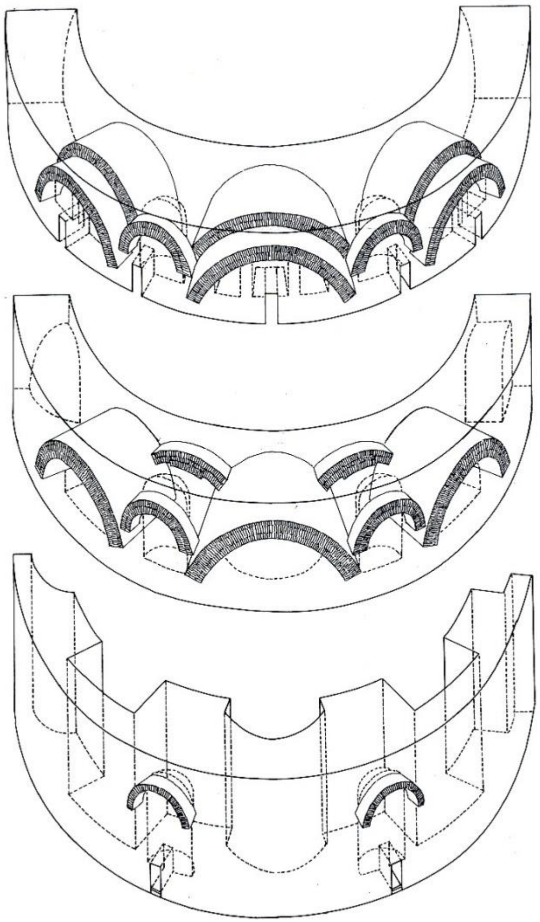
The key to the structural integrity of the rotunda is the series of vaulting ribs into the rotunda wall. The relieving arches visible in the wall are actually the ends of vaults built of radially laid bipedales that extend all the way through the wall in most cases.

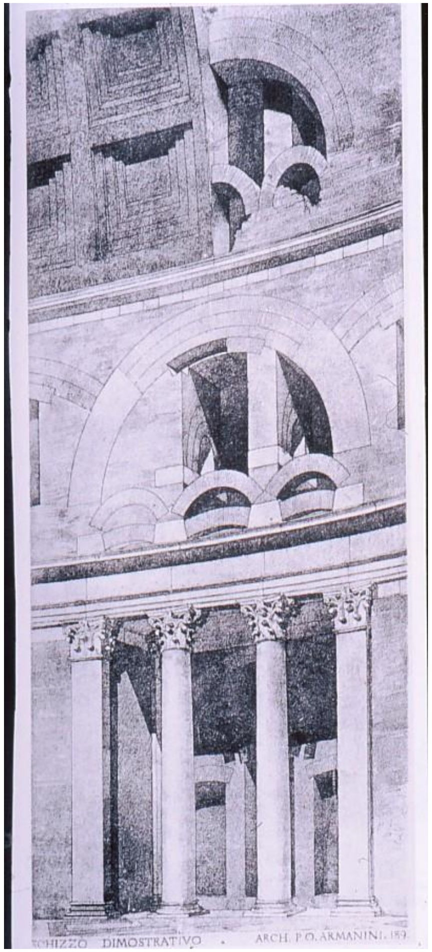
THE HADRIAN'S PANTHEON



The wall of the rotunda contains series of relieving arches at three levels. The lowest arches consist of only a single ring of bipedales whereas the upper ones are more substantial and consist of two or three rings of brick (either bipedales or sequipedales). These arches were intended to direct the loads from the massive dome to the sides of the eight piers between the large interior niches.

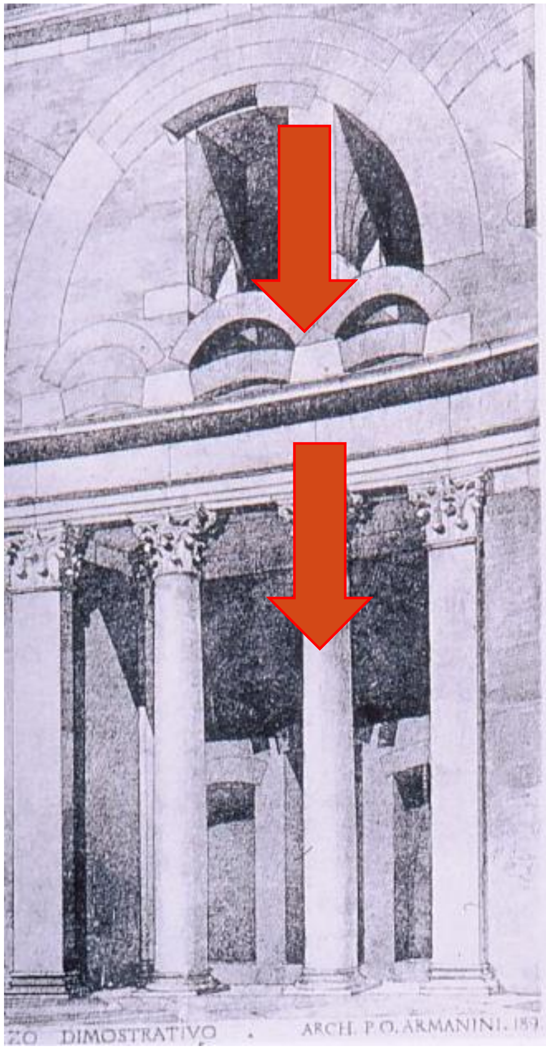
RELIEVING ARCHES AND MORE

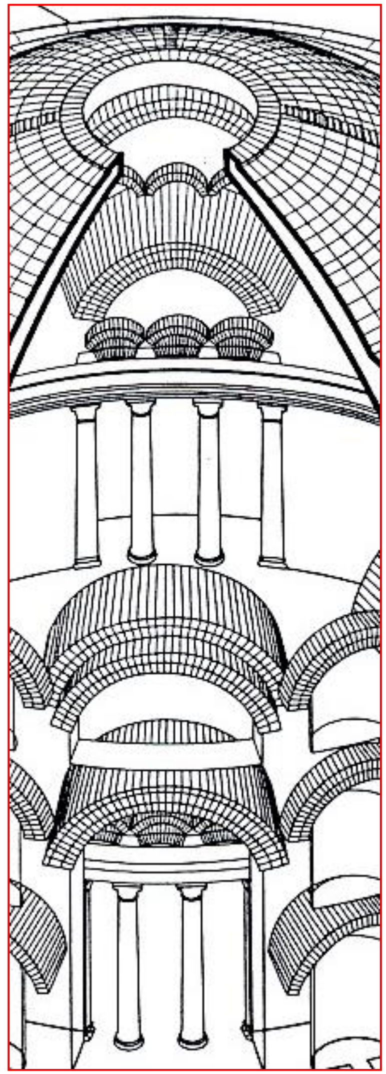




There are two system of arches at work in the rotunda wall: the major arches (11,8 m. span) which span between the eight piers and cover the niches visible on the interior, and the minor arches (5,35 m. span) which are contained within the hollow piers themselves.

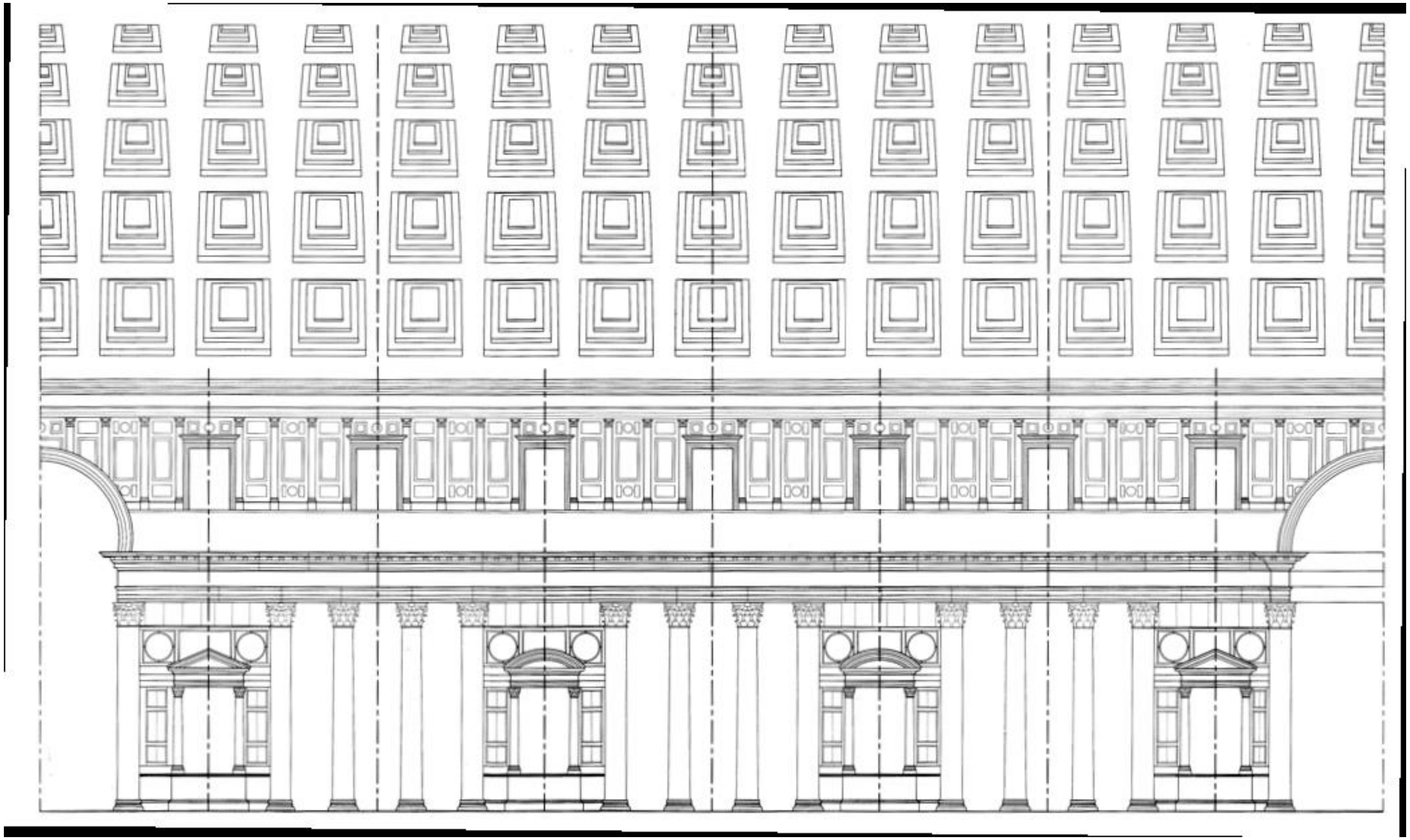
THE PANTHEON





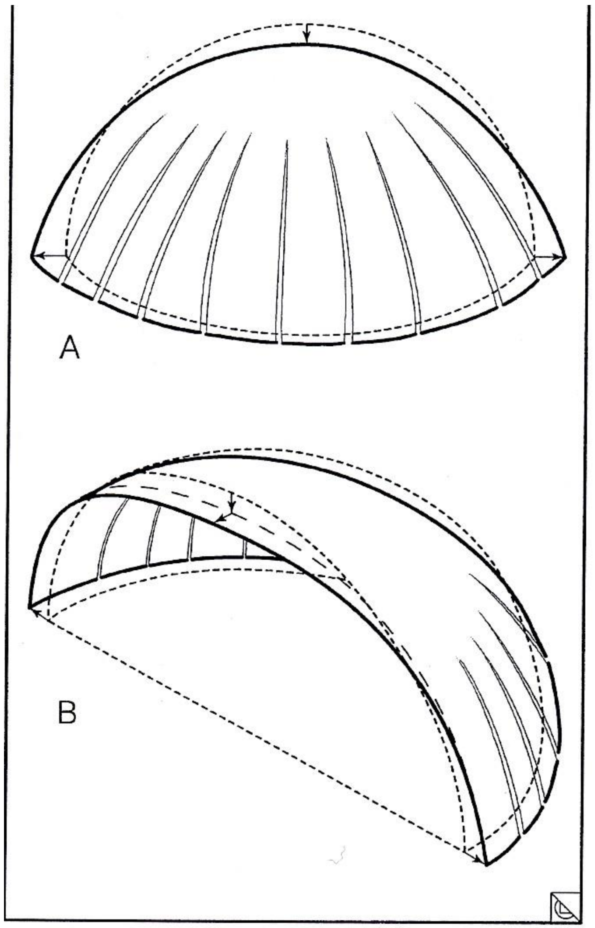
On the interior walls there are some series of smaller relieving arches supported on travertine impost blocks that are intended to transfer the load away from the architraves and onto the columns of the niches.

THE PANTHEON



Pantheon, interior elevation of the rotunda projected flat. The only instances in which there is concordance between different levels of the composition are indicated by dotted lines.

DOMES AND SEMIDOMES



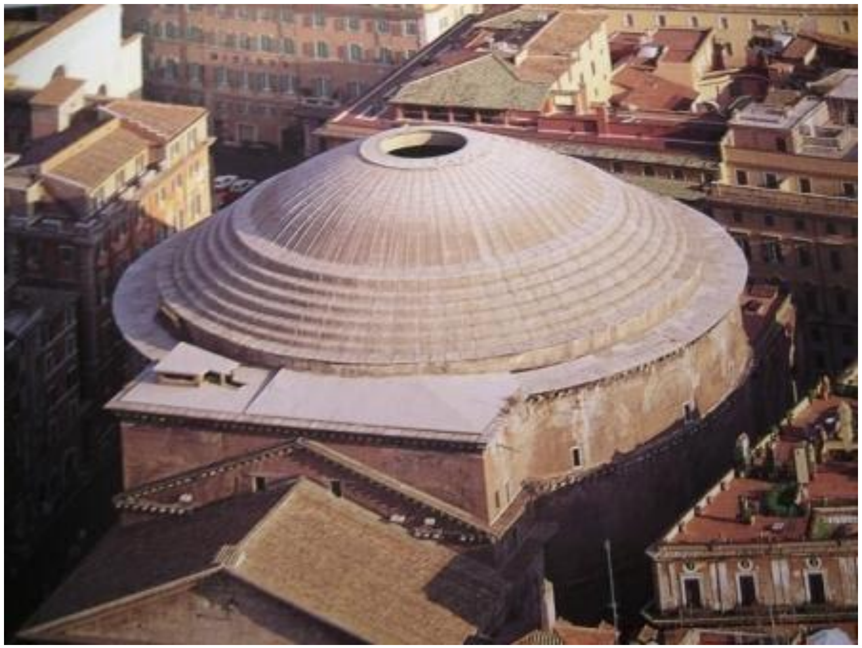
124. A: Deformation pattern of cracked dome. B: Deformation pattern of cracked semidome.

Some repairs of the cracks in the Pantheon dome can be dated to brick stamps and reveal that the cracks occurred soon after construction, so the builders clearly would have been aware of the phenomenon and by this period would not have assumed monolithic properties for their large spanned domes.

Once a dome develops cracks, it results in a series of wedge-shaped arches propped up against each other at the crown.

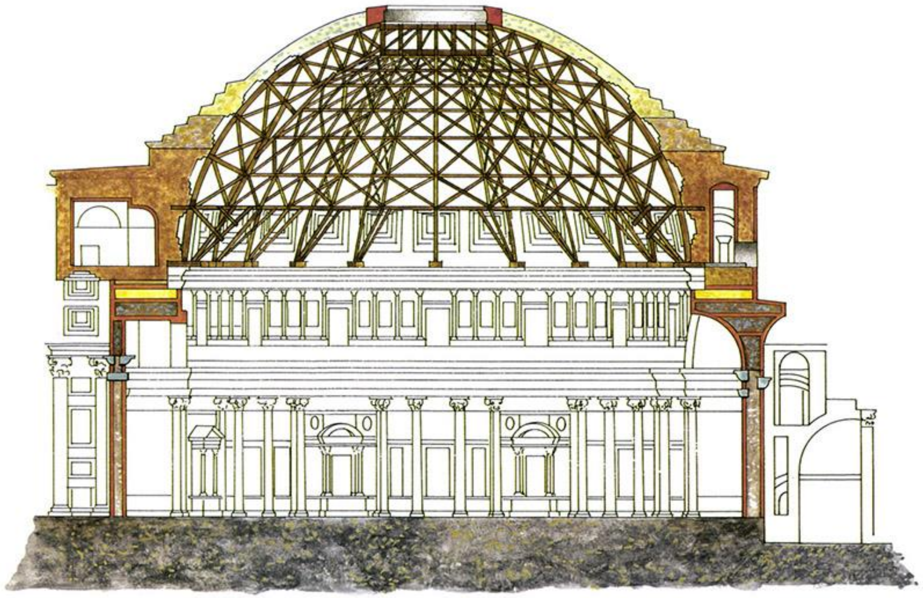
As long as the abutments do not give way, the dome with radial cracks will remain stable.

DOMES AND SEMIDOMES



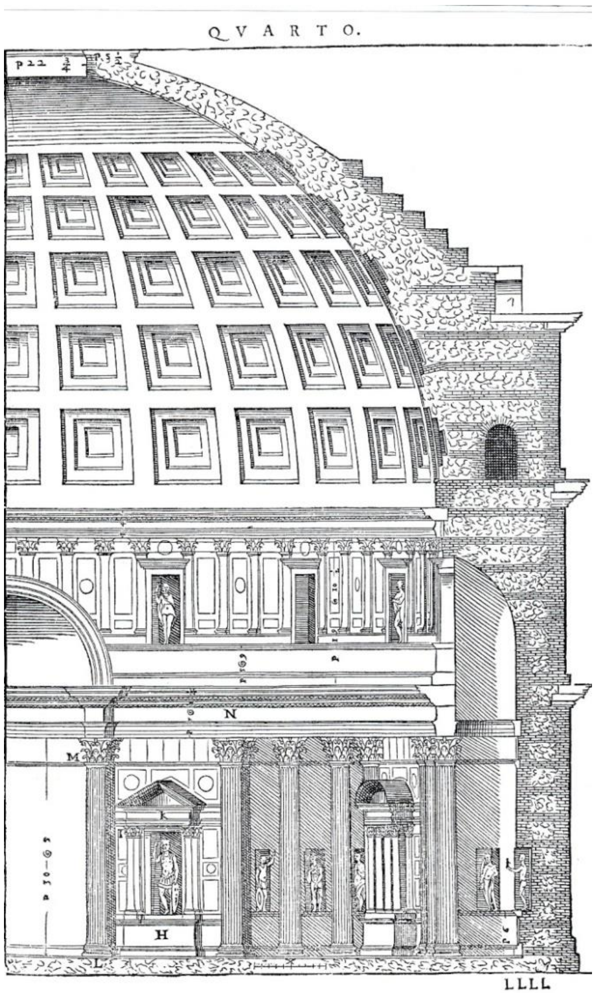
A method for regulating the outward thrusts both in domes and semidomes was the use of a series of step-rings built above the haunches of the extrados. The most famous example is on the exterior of the Pantheon dome. Two main explanation have been proposed for their purpose. One is that they were intended to act structurally by increasing the load on the haunch in order to reduce the horizontal thrust of the vault by countering it with additional vertical load.

DOMES AND SEMIDOMES



The other was that they were added to make the construction of the dome easier to build, so that the exterior could be built in steps, thus avoiding forming the curved extrados in the lower parts of the dome.

DOMES AND SEMIDOMES

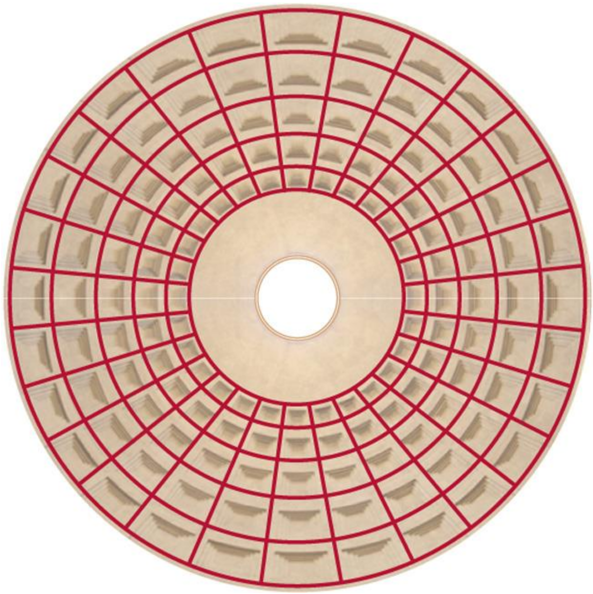


Another is that they were intended to act as devices to facilitate the construction by allowing the workers to build in vertical increments rather than to have to shape the steep lower portions of the dome.

An examination of the development of domes and semidomes suggests that the first explanation (structural) was the original intention and that the second explanation (constructional) was an advantage only exploited later..

The cross section drawing was designed by Andrea Palladio.

THE PANTHEON'S DOME COFFERS



The unusual number of 28 coffers in each of the five concentric rows present an added difficulty in order to the geometry of the Rotunda, infact it's impossible to divide a circle into twenty-eight spaced parts with compass and straightedge.
Twenty-eight is a special number in the antiquity , being one of only four numbers known for which the sum of the factors equals the numbers.

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