BUILDING CONSTRUCTION 2, PROJECT 2

THE PANTHEON

ROME, ITALY

BY: CHAN PIN QI, LEE JO EE, MAHI ABDUL MUHSIN, TAN SHING YOEU, TAN ZI JIAN, DANAR JOVIAN

CONTENT

GROUP MEMBERS:

CHAN PIN QI (0314676)
LEE JO YEE (0314880)
MAHI ABDUL MUHSIN (0314421)
DANAR JOVIAN (0314575)
TAN SHING YOEU (0314850)
TAN ZI JIAN (0318291)

HISTORY

The Pantheon is the best preserved building from ancient Rome and was completed in c.125 CE in the reign of Hadrian. Its magnificent **dome** is a lasting testimony to the genuis of **Roman** architects and as the building stands virtually intact, it offers a unique opportunity for the modern visitors to step back 2000 years and experience the glory that was Rome.

Until, the 20th century, the Pantheon was the largest **concrete structure** in the world. The Pantheon was dedicated to pan theos, "**all the gods**." When it became a church, it was dedicated to the Virgin Mary and all the martyrs.

The Pantheon was originally built in 27-25 BC by the magistrate **Marcus Agrippa** (his name appears on the inscription outside), to commemorate the victory of Actium over Antony and Cleopatra. This original temple burned down in 80 AD. The second temple was dedicated to every known god, from which the Pantheon gets its name. Hadrian himself is credited with the basic plan, an architectural design that was unique for the time.

THE EXTERIOR & INTERIOR

AN OVERVIEW OF THE EXTERIOR

The building consists of two principal parts - the porch, which is very classical Greek and the circular main building which is more roman in style. The circular building is built with brick and concrete but was originally faced with white marble stucco to match the porch in appearance. The dome is concrete with the external surface originally covered in bronze. the whole building stands on a 1.3 m high base which originally extended a further 7 metres in front of the colonnade, steps in numidian yellow marble extended from the outer ends of this base.

INTERIOR

The Pantheon may well be the first building from Classical architecture where the interior is deliberately made to outshine the exterior. The circular part of the building or rotunda was entranced via two bronze doors measuring 12 x 7.5. The rotunda measures 43.2 m in diameter which is exactly the maximum height of the dome, itself a perfect hemisphere. At the very top of the dome is an opening to the sky (oculus) which is 8.8 m in diameter and has a decorative bronze sheet frieze. The dome is made from a light tufa and scoria (a type of pumice) mix of concrete (*caementa*) and its interior is further lightened by five rings of 28 coffers which reduce in size as they rise towards the centre of the dome. These may have been originally covered in bronze sheets. The wall of the rotunda is 6 metres thick and has seven alcoves which are alternatively semi-circular and rectangular.

The Pantheon was originally built by **(1)**Marcus Agrippa in 27 BC in the Campus Martius. Agrippa's Pantheon was destroyed in the 80 AD fire, was rebuilt by Domitian, and burned again in 110 AD. A recent re-examination of brick stamps has determined that reconstruction began soon after the second fire of 110 AD and was completed by Hadrian (123-126 AD). Design of the structure we see today was thus begun under Trajan's reign, and was very likely designed by Trajan's favorite architect, **(2)**Apollodorus of Damascus, although a few of the decorative features must have been designed under Hadrian (The 14th Emperor of Rome). The original inscription was reused by **(3)**Hadrian, contributing to the confusion which existed over when the current structure was built and by whom.

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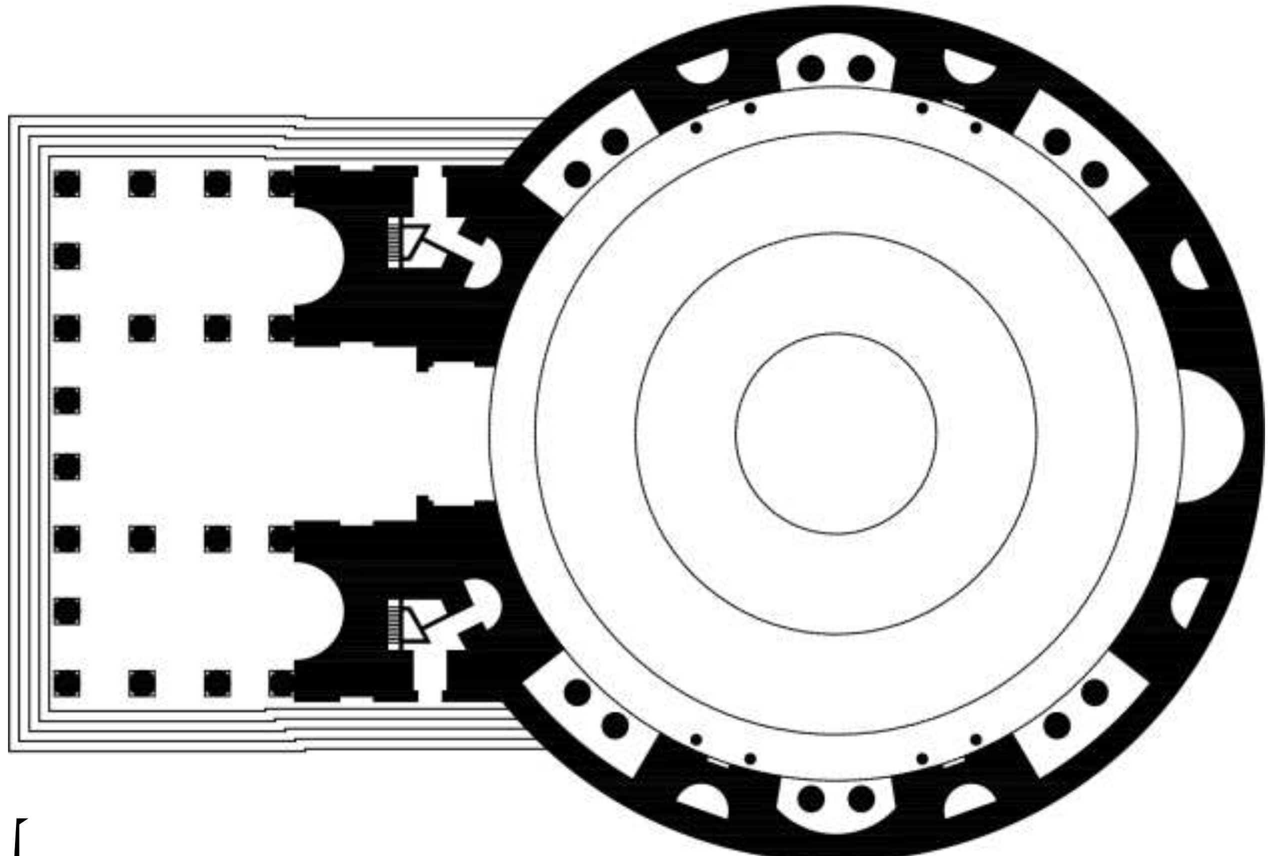
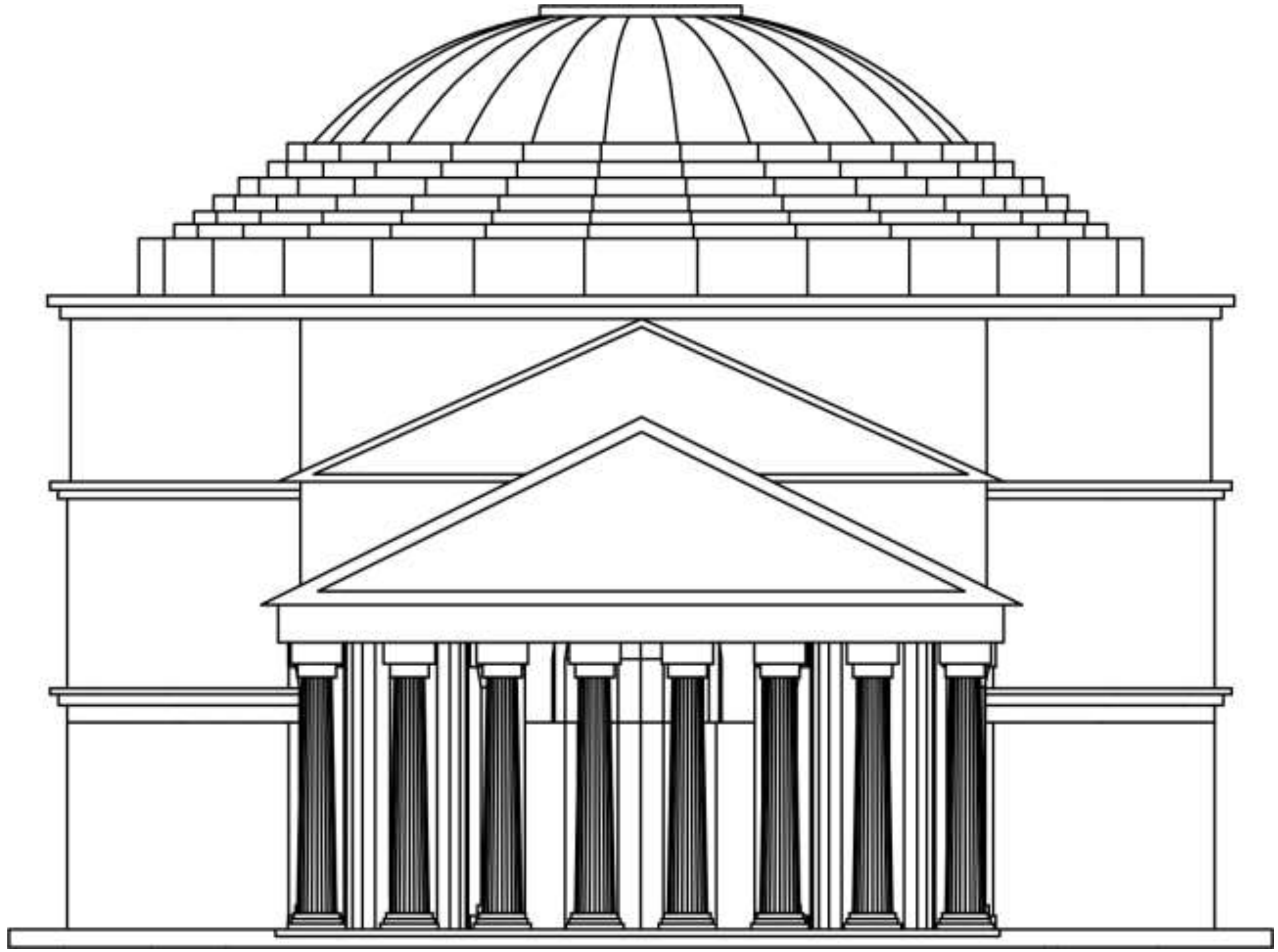


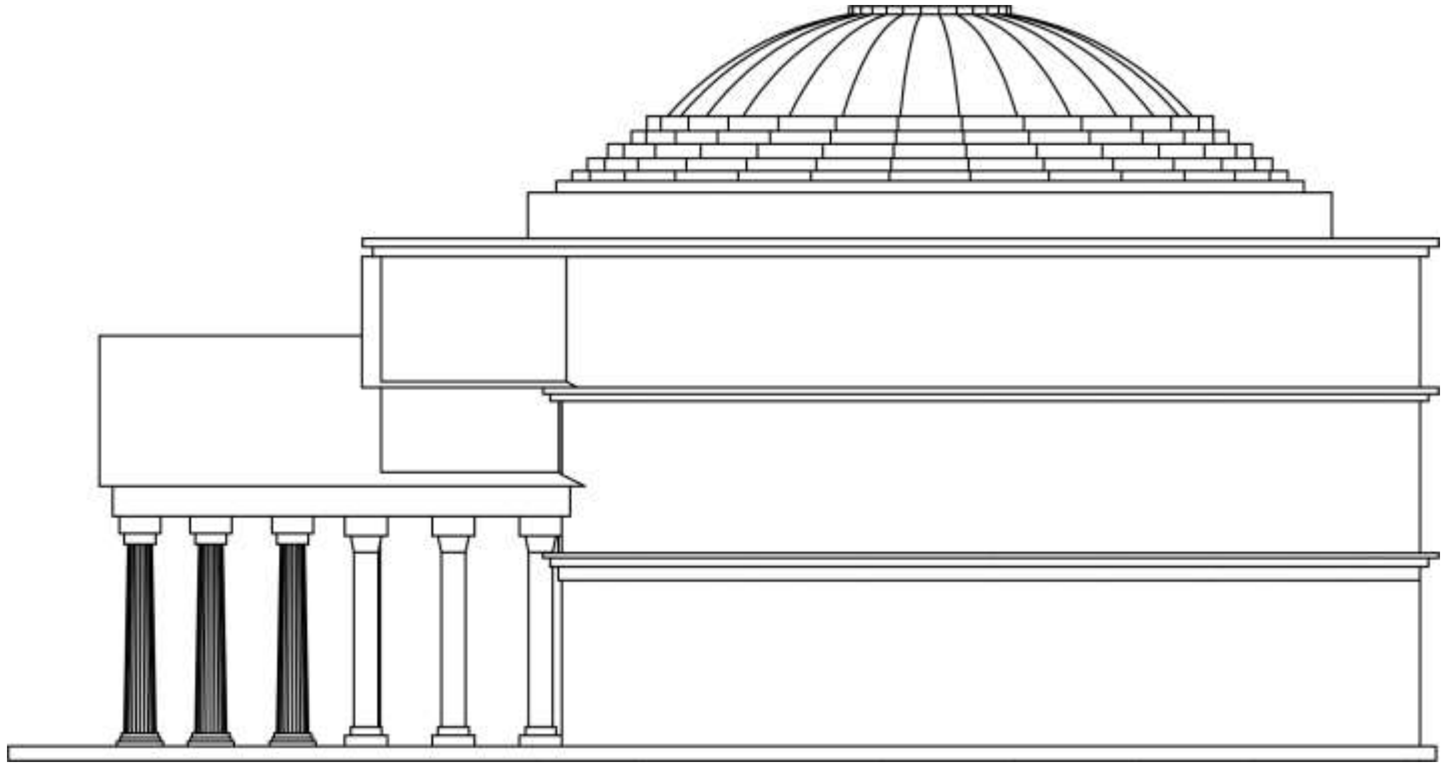
PLAN

SCALE 1 : 500

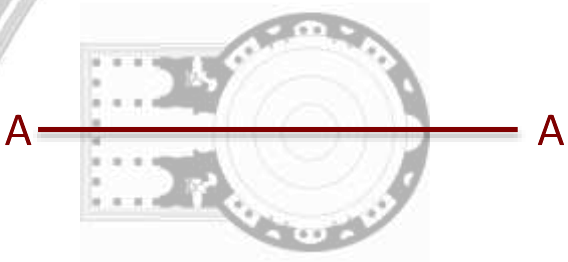


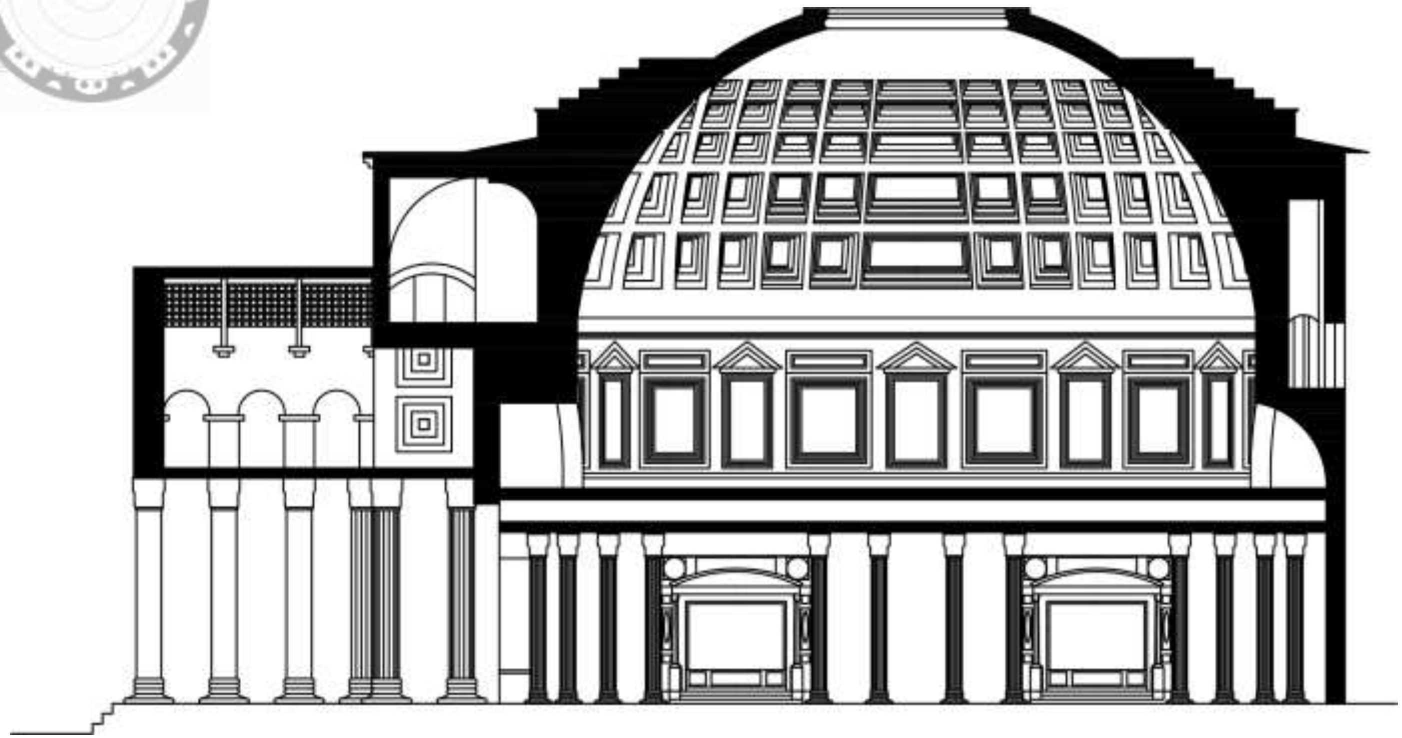
FRONT ELEVATION

SCALE 1 : 500



SIDE ELEVATION
SCALE 1 : 500





SECTION A-A

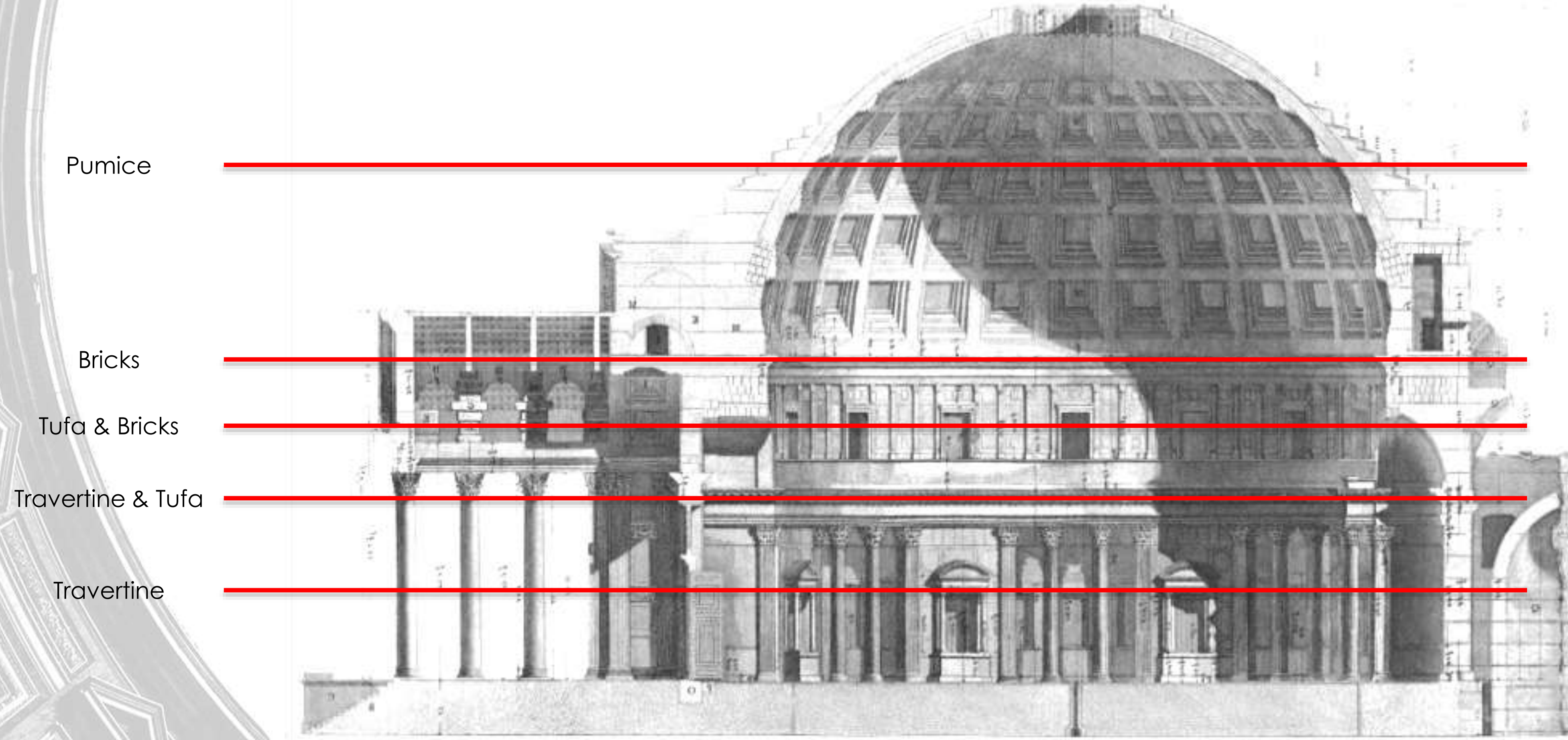
SCALE 1 : 500

MATERIALS

The materials used to built the Pantheon was mainly of brick and concrete. This concrete is a mixture of mortar with small stones that is mixed with limestone (travertine), bricks and other materials.

The Romans were aware of the heavy nature of their buildings. So as they build the Pantheon, lighter materials were used as the building rises higher and higher. This use of lighter materials on top alleviated the immense weight of the dome. The series of arches mainly built by using bricks.

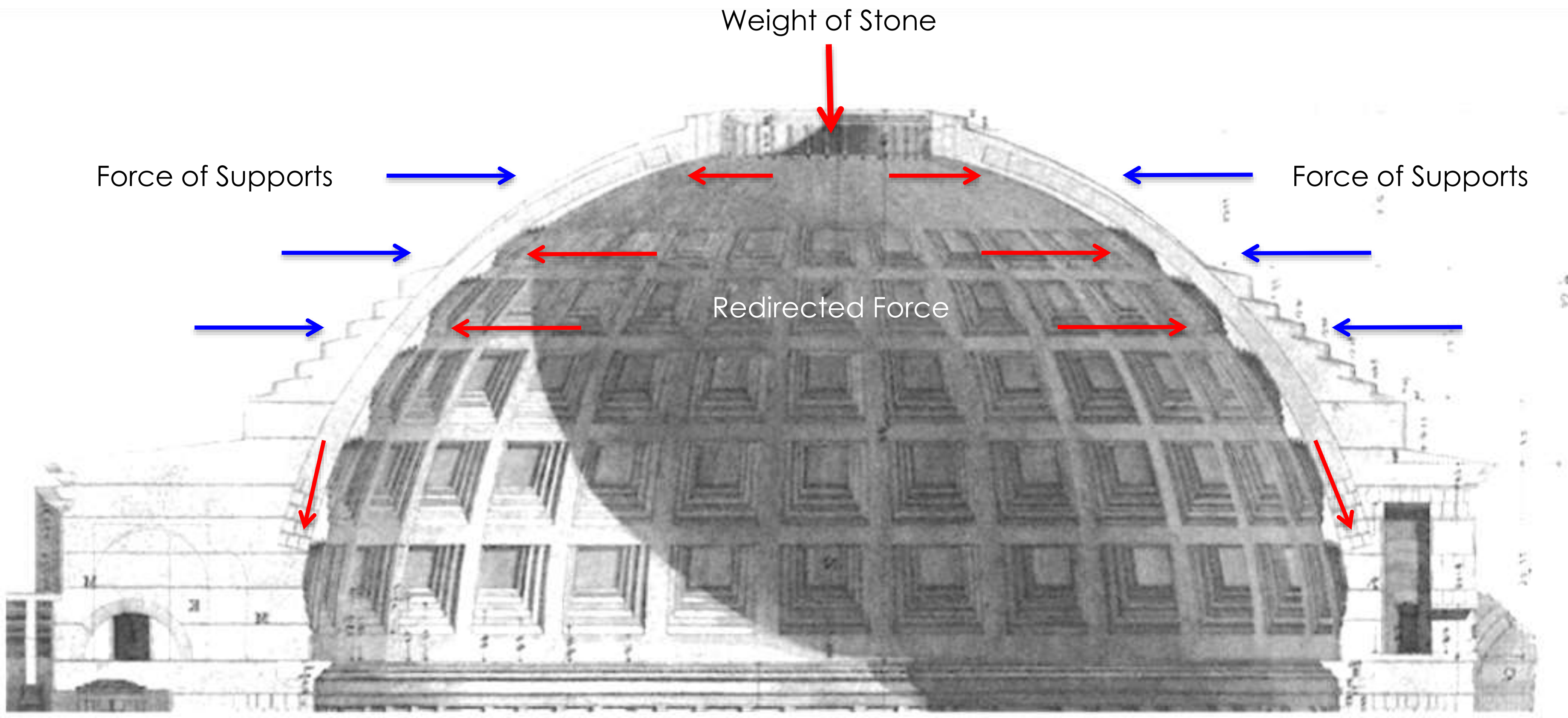
On the lowest level is the travertine, then a mixture of travertine and tufa, then tufa and brick, then all brick was used around the drum section of the dome. The dome is made from a light tufa and scoria (a type of pumice) mix of concrete (caementa) and its interior is further lightened by five rings of 28 coffers which reduce in size as they rise towards the center of the dome.



LOAD DISTRIBUTION

The massive size of the Pantheon is accompanied by a tremendous weight. Roman architects used ingenious design to create a stable structure without the use of internal supports.

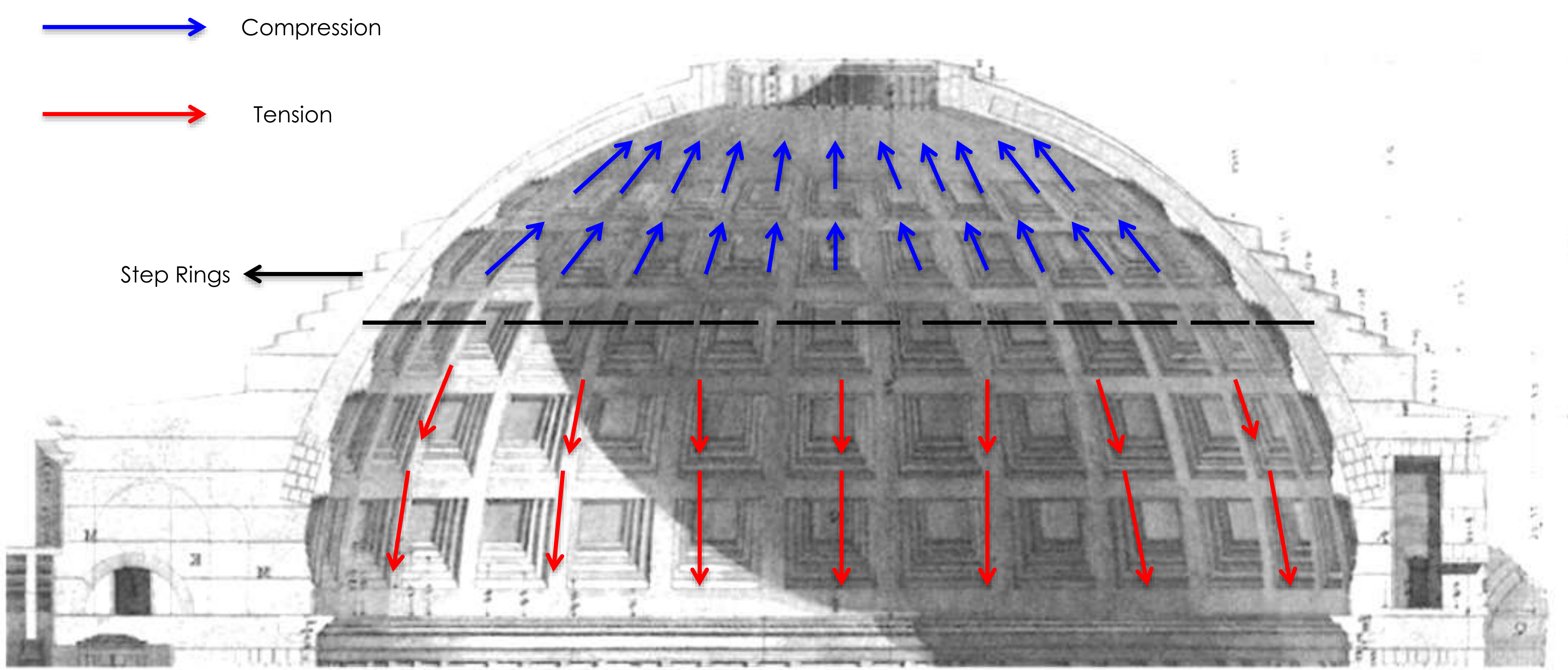
The tremendous weight of the stone on top of the entryways, windows, and passages would cause them to collapse. The architects solved this problem with the use of arches. Arches take the tremendous force of the stone above it and redirect this force through its sides to the Pantheon's support walls and piers. These support walls and pillars provide a horizontal normal force to counteract the force of the stone above the arches. The structure's weight is channeled through the piers to its foundation.



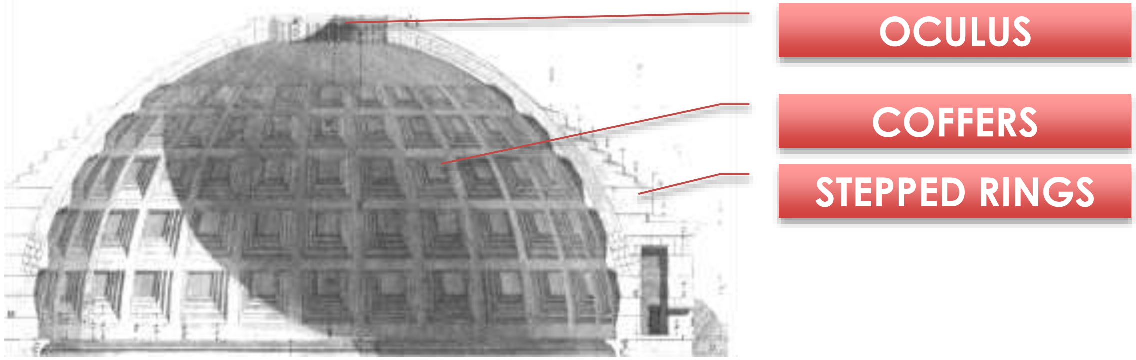
LOAD DISTRIBUTION

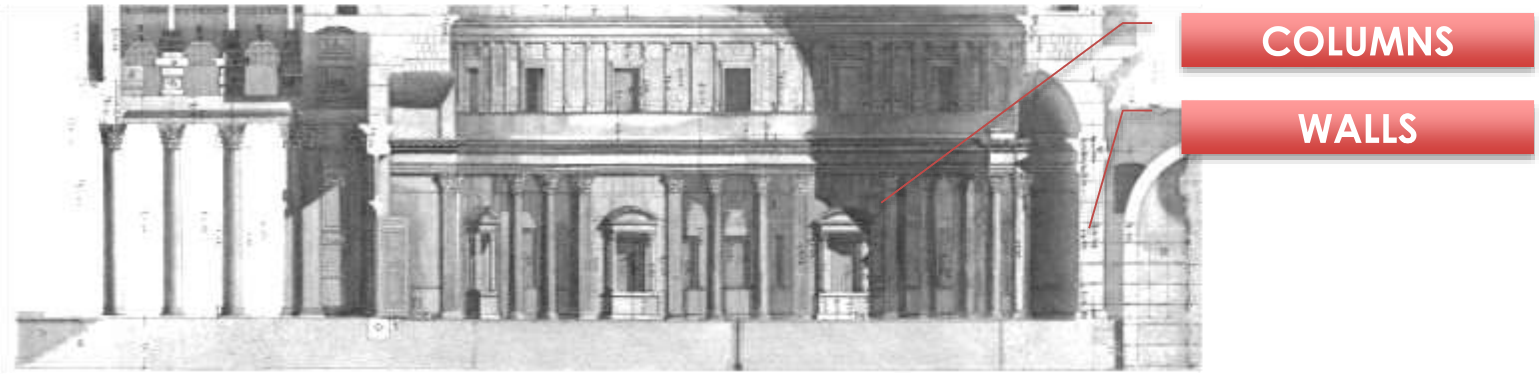
Domes maintain their shape through a balance of tension and compression forces. The figure shows a better understanding on how domes work. The vertical lines of the dome are called meridians. At the top of the dome, the meridians push together under the domes weight, creating compression forces. Towards the bottom of the dome, the meridians are pushing outwards, stretching the dome apart with horizontal tension forces.

At a certain level on all domes (indicated in the figure below by the dotted line), there is an area that is neither in tension or compression. The tension and compression forces must both be dealt with to enable the dome to stand. To deal with the massive tension forces, the Roman architects poured several layers of concrete around the base of the dome. These layers are called step rings, and they provide a normal force to push inward against the tension forces that push out. The rings also help to redirect the tension forces down into the walls below.



SURFACE STRUCTURE, is defined as "members are united as one homogeneous entity to form the structure and spaces." Hence, Pantheon upper structure, known as the oldest concrete shell, supports on it own with these elements stated below. It acts a roof and has created a more spacious and monumentally spacial quality.



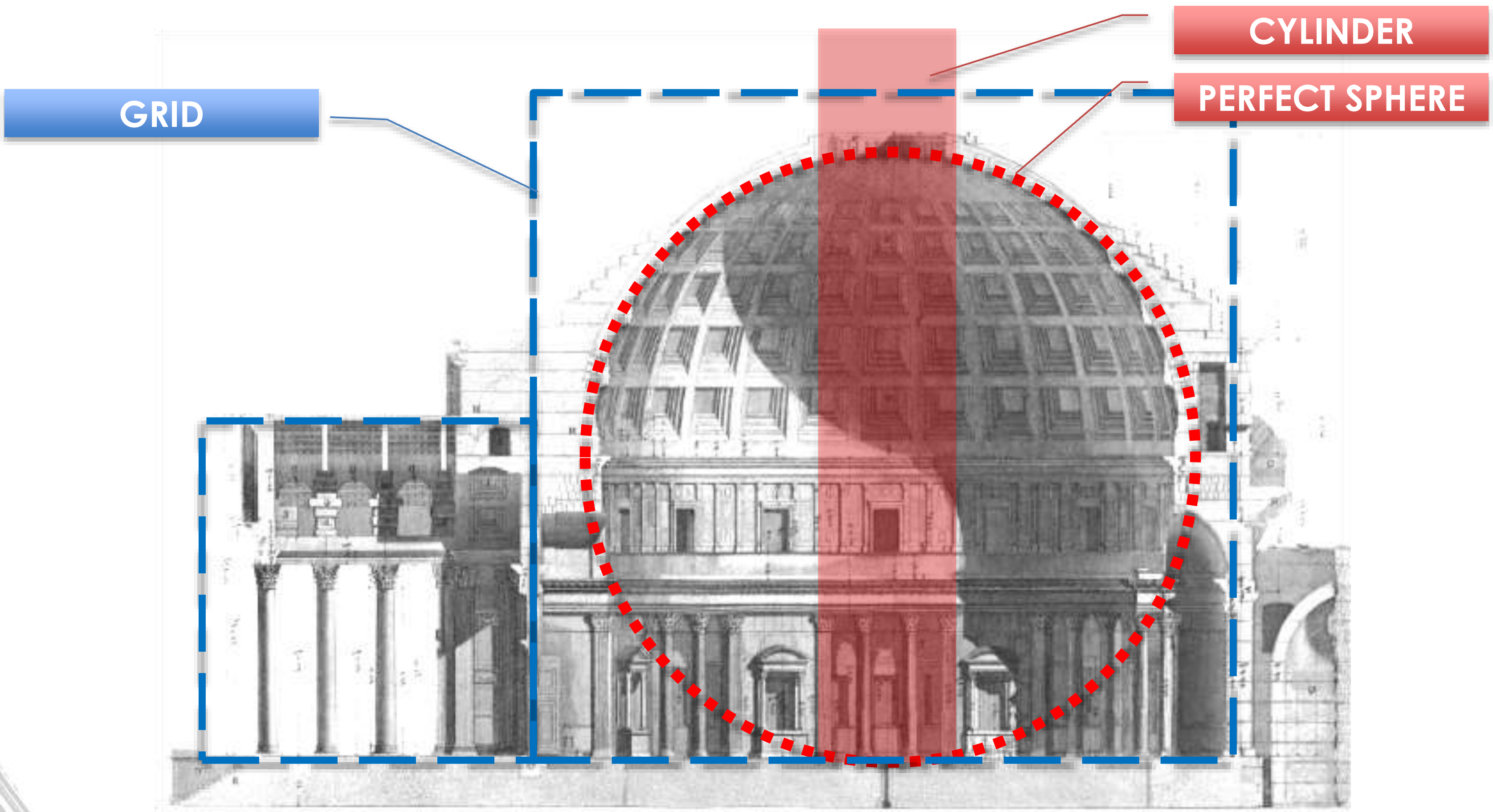


SOLID CONSTRUCTION, which "relies on homogeneous mass" are referring to the lower part of Pantheon which has used heavy construction materials (limestone, bricks) as supports and the elements stated here.

Further explanation and justifications will be provided in the following pages.

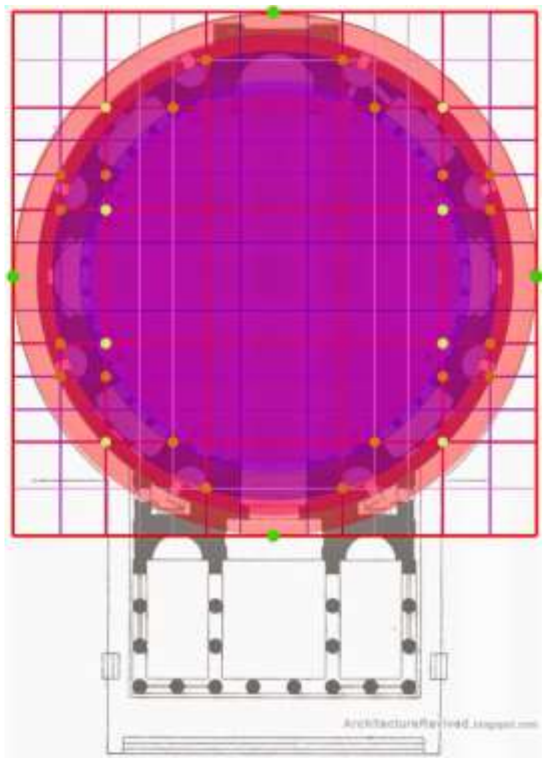
The Pantheon consists of a **rectangular portico** with three lanes of columns fronting a circular building which designed as a **huge hemispherical dome**, that is 43.3 meters in diameter.
The dome is modelled on a sphere within a cylinder, of a same diameter and of a height that has the dimension of the dome's radius at 21.65 meters.

An interesting observation to make is that the dome internal geometry **creates a perfect sphere**. The height of the rotunda to the top of its dome matches its diameter.



IN FACT, the form of the Pantheon is derived from the circle and SQUARE in plan and section view.
The Pantheon's design begins with a square subdivided into a grid. Certain points of the grid intersects circles. Refer to the plan view

On the section view, the Pantheon likewise starts out with a subdivided grid. A rectangular form derives from fairly simple geometric subdivisions.



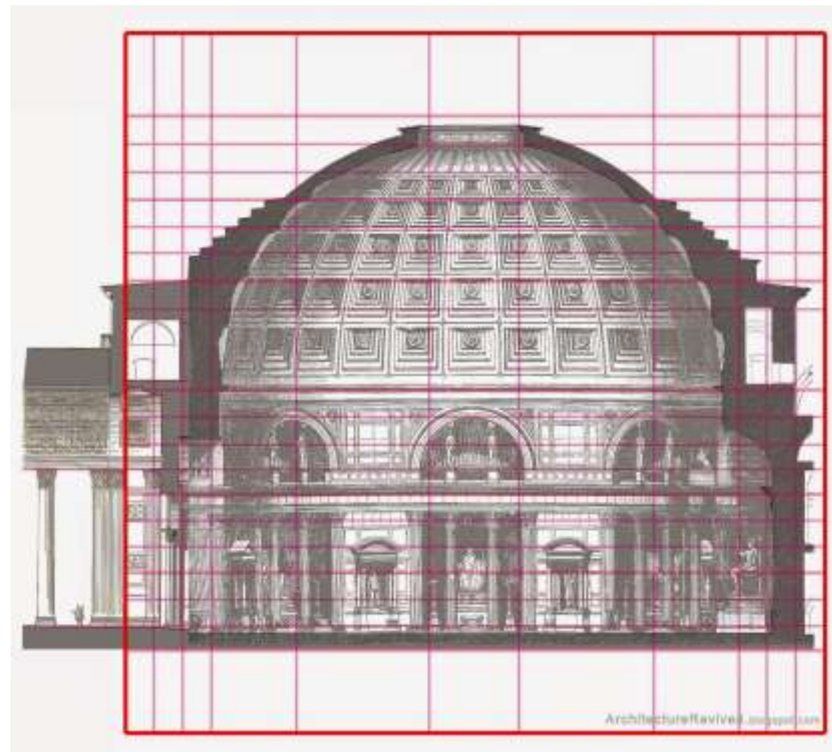
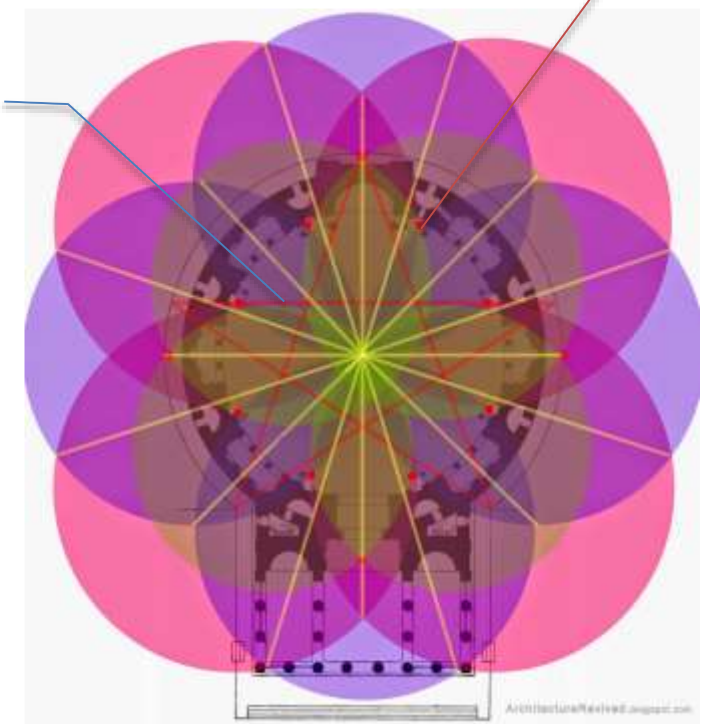


Image resource: http://architecturerevived.blogspot.com/2014/05/the-pantheon-romes-architecture-of.html

GEOMETRY AND FORM

Circles are arranged into overlapping quadrants, to render out a complex star pattern. The intersection of circle form an 18 pointed star, which divided the Pantheon into 18 part quadrants and a five pointed star.

Apply the same circle and stars in section view, the **intersection points** bring out the **rectilinear form** together with **curves**. Overlap the circle at the top to find the sacred dimensions of the coffers around the oculus and the dome.



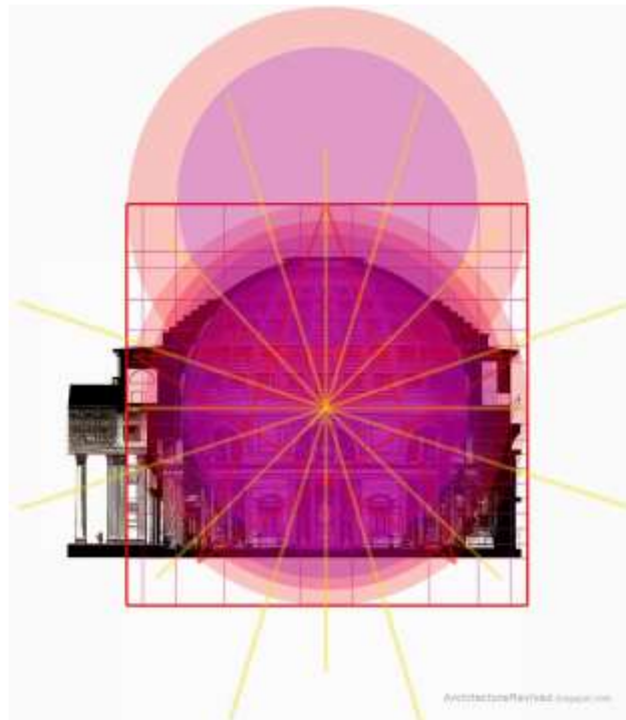
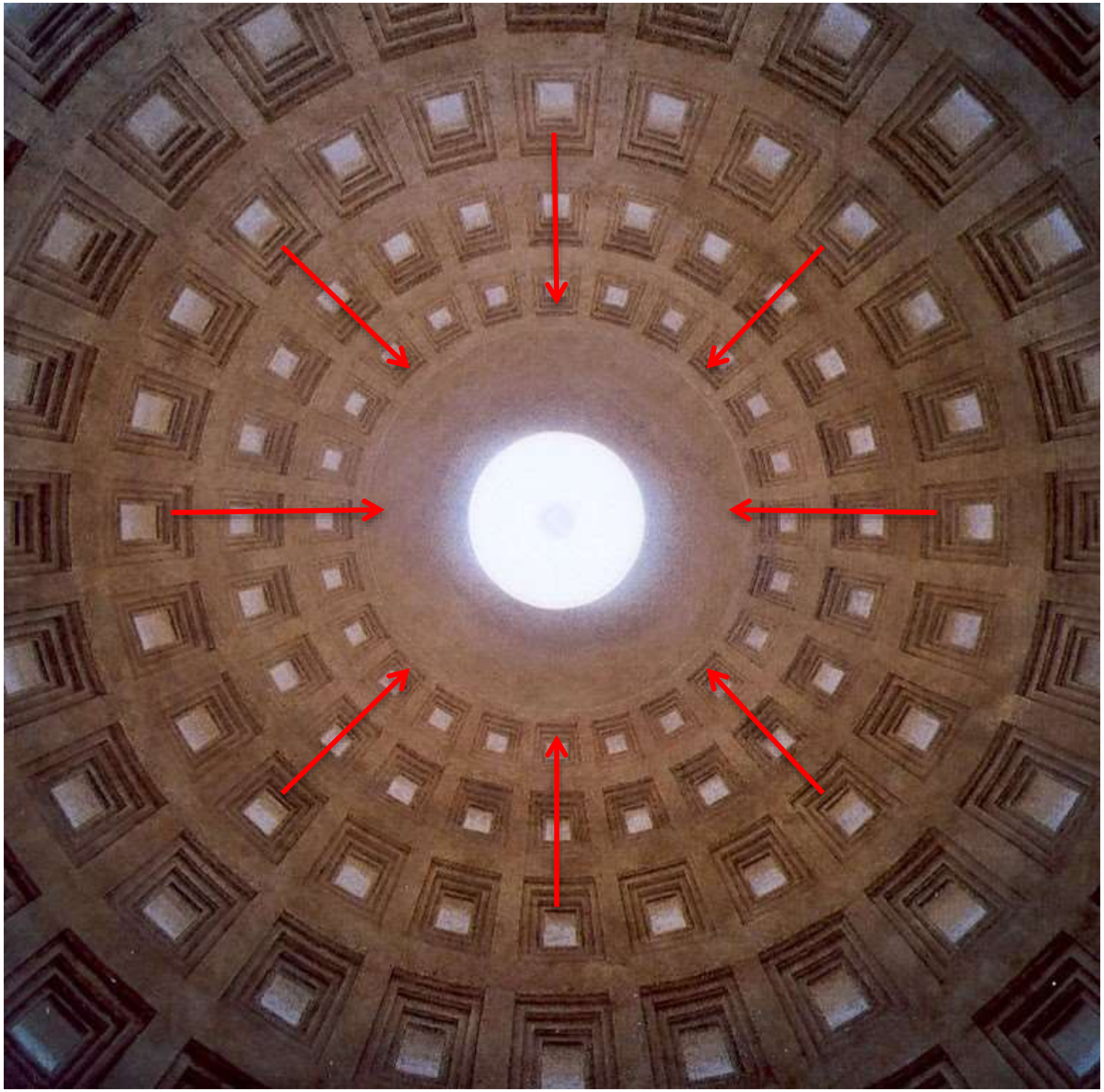


Image resource: http://architecturerevived.blogspot.com/2014/05/the-pantheon-romes-architecture-of.html

The dome maps a relationship of earth and man to heaven. With the touch of culture and belief, the structure and form become more sophisticated behind.

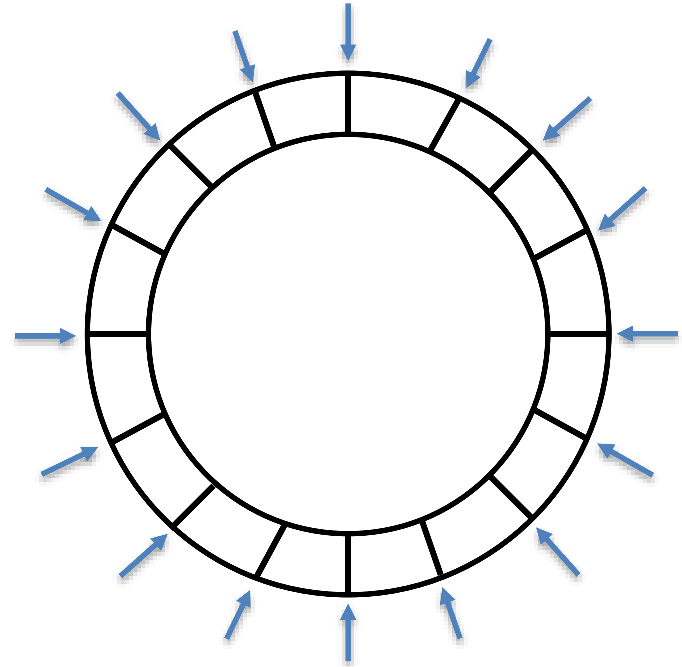
LOAD DISTRIBUTION

The oculus, or eyehole, is 27 feet in diameter, and made up of 4.5 foot thick ring of bricks. The ring acts exactly like an arch, except that its ends are joined together. Compressive forces are redirected along the ring's body. The only difference between the ring and the arch is that the compression forces come from all directions. These forces wedge the ring stones tightly together. The compression forces cancel each other out and the top of the dome is left in a state of horizontal equilibrium. This oculus ring is nothing but a hole due to the fact that as the structure goes up, the materials that was used becomes lighter to a certain extent that no material, in this case bricks, can be cut into a thin layer thus the hole.



Net Compression Force = 0

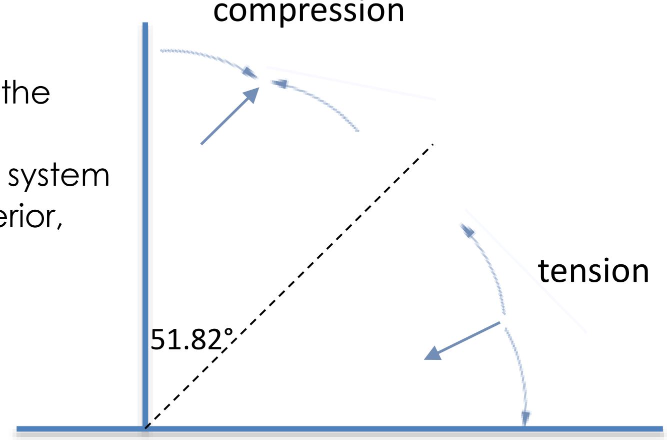
THE OCULUS



Surprisingly, right where the compression forces are the greatest on the dome (the top), the Roman architects chose to have nothing but air. The oculus, or eyehole, is 27 feet in diameter, and made up of 4.5 foot thick ring of bricks. The ring acts exactly like an arch, except that its ends are joined together. Compressive forces are redirected along the ring's body. The only difference between the ring and the arch is that the compression forces come from all directions. These forces wedge the ring stones tightly together. The compression forces cancel each other out and the top of the dome is left in a state of horizontal equilibrium.

The oculus was only reinforced by a row of bricks and bronze-framed

Centering was not required for the lower third of the dome, so the Romans used a lighter centring system supported from the dome's interior, second cornice line.



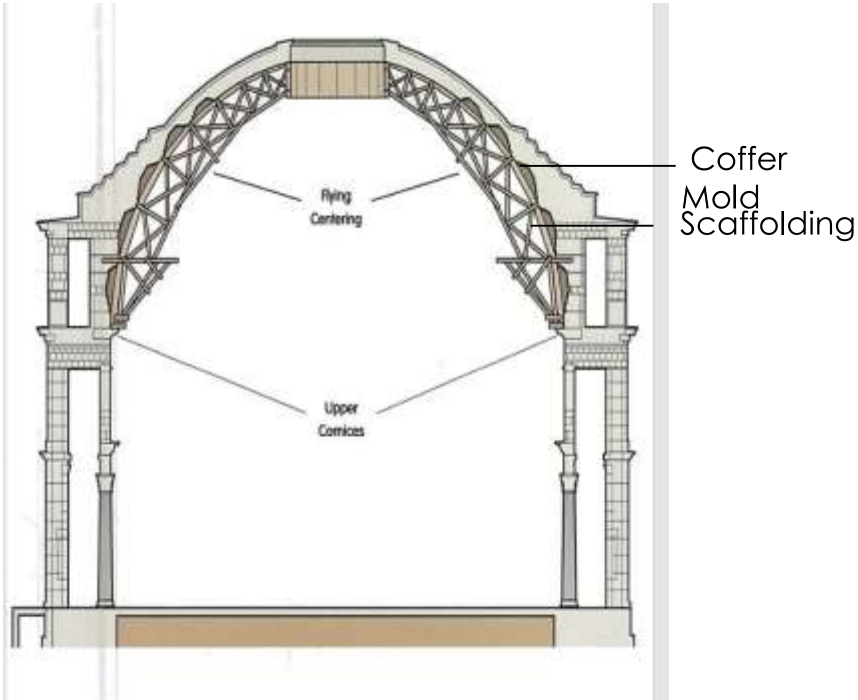
COFFERS

INNER DOME – **COFFERING**

Coffer molds were installed and the concrete was poured in section.

There are five rows of coffer and each ring is smaller than the one beneath it.

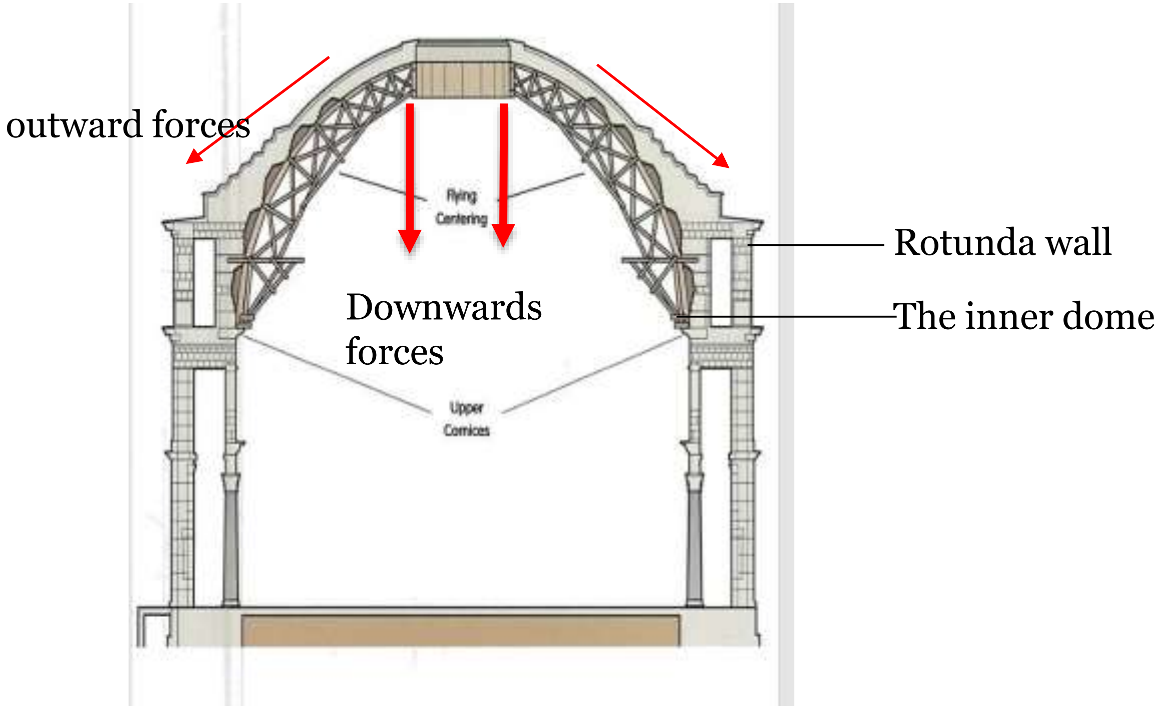
Workers assembled each row of coffers separately using scaffolding as shown in figure 1. While waiting for the row of concrete to harden, they moved on to another.



KEEPING THE DOME IN PLACE

The huge and heavy dome is kept in place because of the coffering inner dome. Recent engineering studies have
shown each coffer only reduce 5% of weight. 5% of a dome that weight 5,000 tons(227,000 kilogram) is a lot.
Rows of coffering also form ribs acting as stiffening element form preventing the dome form deflecting.

COFFERS



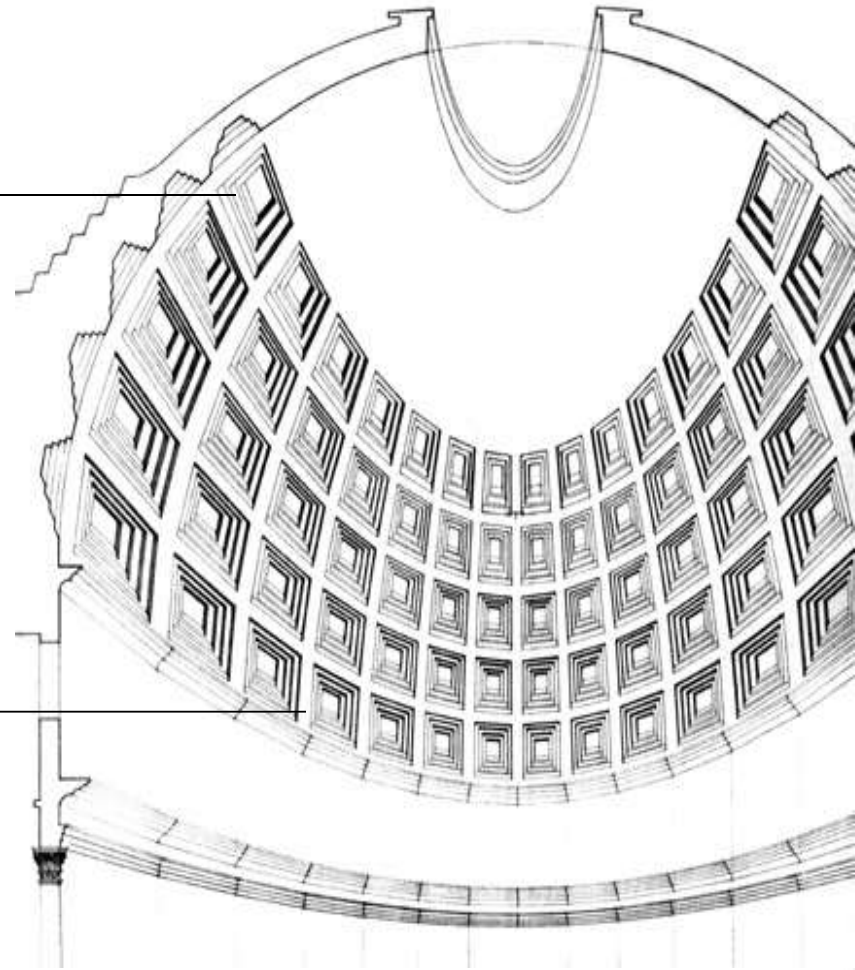
Because is a dome surface structure, its weight naturally go outward as well as downward. The weight pushing outward is called hoop stress. This hoop stress had been solved by starting the inner dome (coffer)inside the rotunda wall. The rotunda wall is higher than the inside dome and act as shoulder to hold the dome inwards. Therefore, from the outside the starting of the dome cannot really be determined.

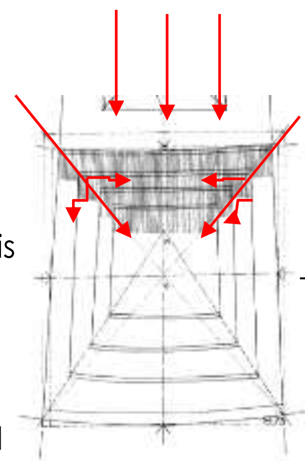
COFFERS

Coffer Design

Top row of coffer contain 3 recesses

The rest of the row of coffers have 4 recesses

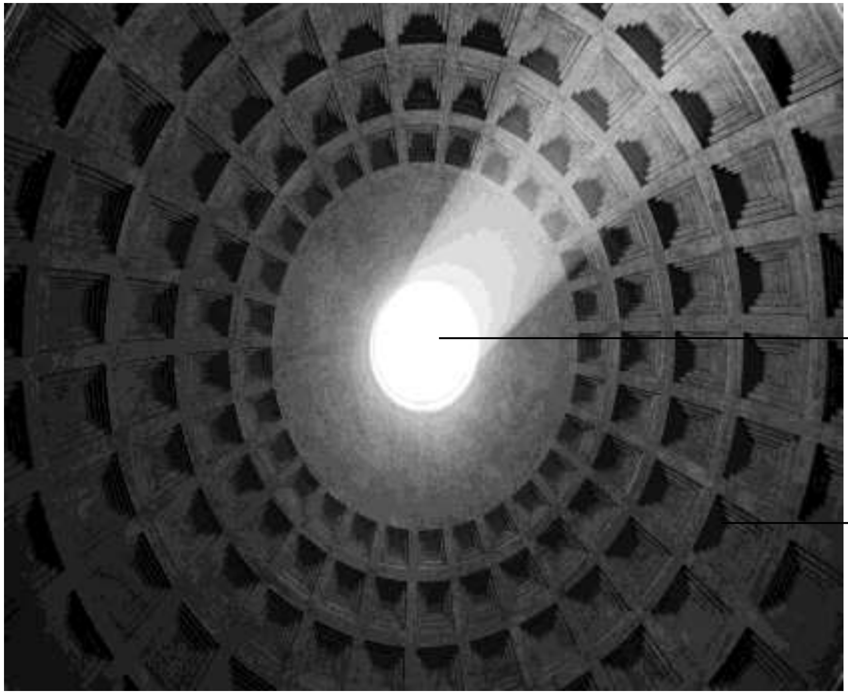




Forces is that distributed evenly throughout the surface is then breaking down into smaller forces in the recesses. Thus less down the forces carried by the whole dome.

The space between the top and the bottoms of the coffer remains constant, while the space between the side of each coffer diminish as they proceed up the dome, much like the line of latitude and longitude of a globe.

Coffer Design



The effect of the dome is spectacular, it was a surprise when one entered the rotunda. Ones eyes are carried up to the oculus which lets in enough light to make the whole area seem light and airy.

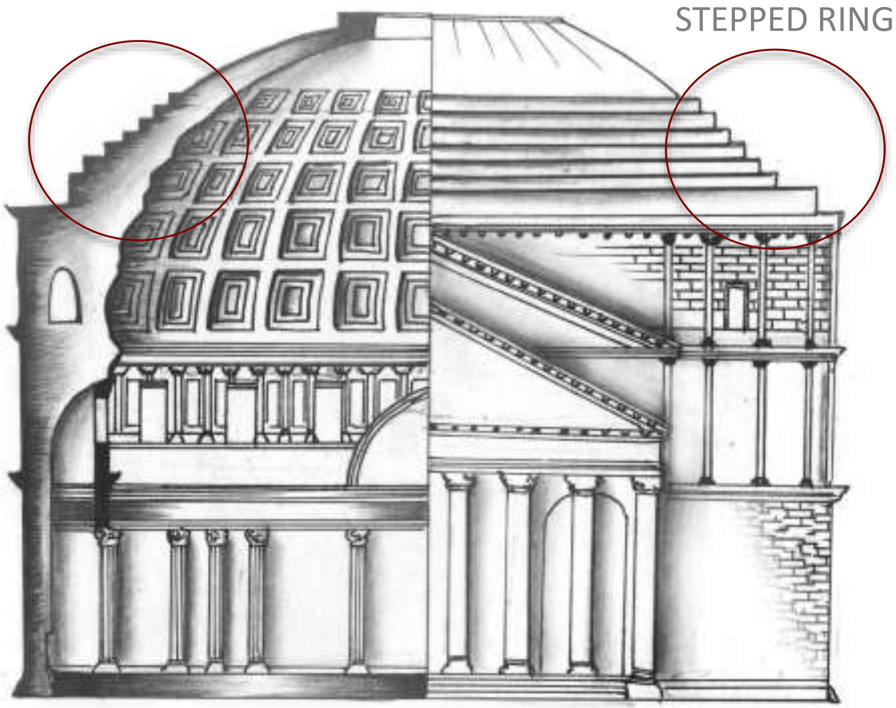
The coffers gives the effect of producing the magnitude of light and darks in the dome, constantly changing as the beam of light and its projected circle from the oculus moved with the sun. This gives one the impression that the building is dynamic and not solid and weighty, but light, airy and uplifting, like the sky outside on a clear day. The dome seemed to expand as one looks at it.

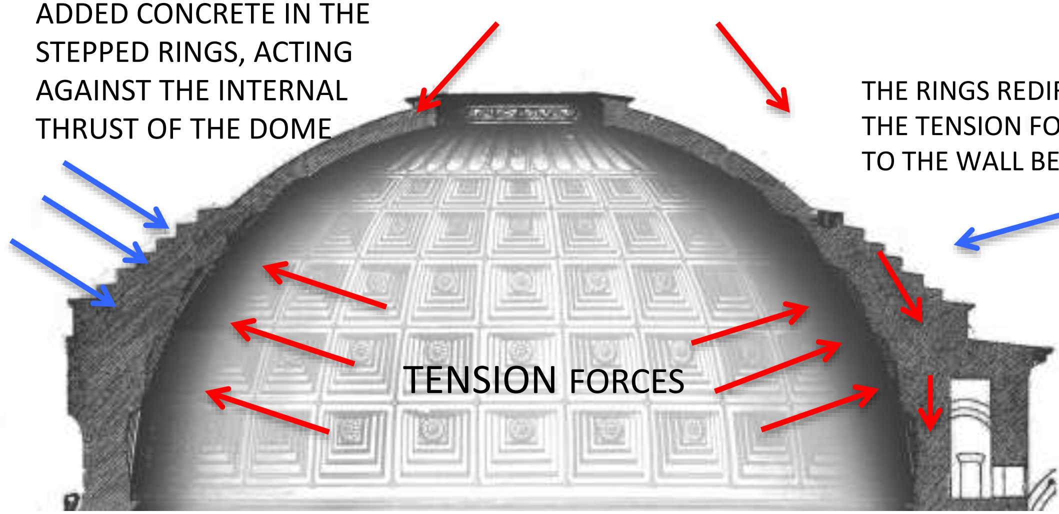
STEPPED RINGS OF THE DOME

On the outside surface of the pantheon Dome, there is a series of seven step- rings half way up the dome, and then the dome line changes into a circular line. There is 7 rings stacked on top of each other, and non uniform in diamter. The rings have its outside edge resting on the center of the ring below. It appears to be some 7.5 feet (2.3 m) thick with a horizontal distance to the next ring about this same distance. The remaining 6 step-rings are stepped inward much like placing a series of machine washers, one above the other with their diameters decreasing as they are stacked. The height of these 6 rings vary, and they are estimated to be 2'- 6" (0.8 m) on the average. The horizontal distance to the next of these smaller rings is estimated to be 4 feet (1.2 m). There is an exterior stairway leading through these rings to the oculus.

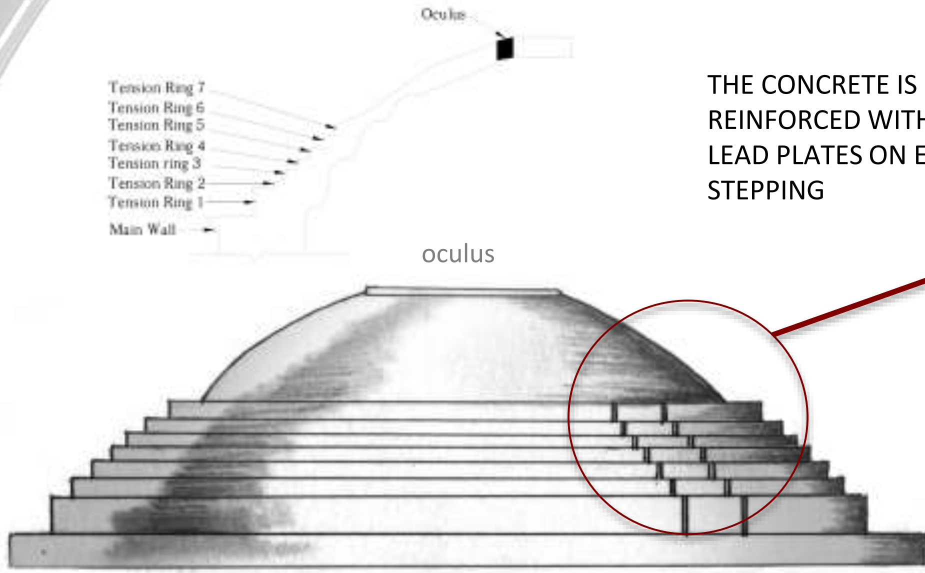
HALF SECTION/ ELEVATION OF MAIN STRUCTURE

STEPPED RINGS

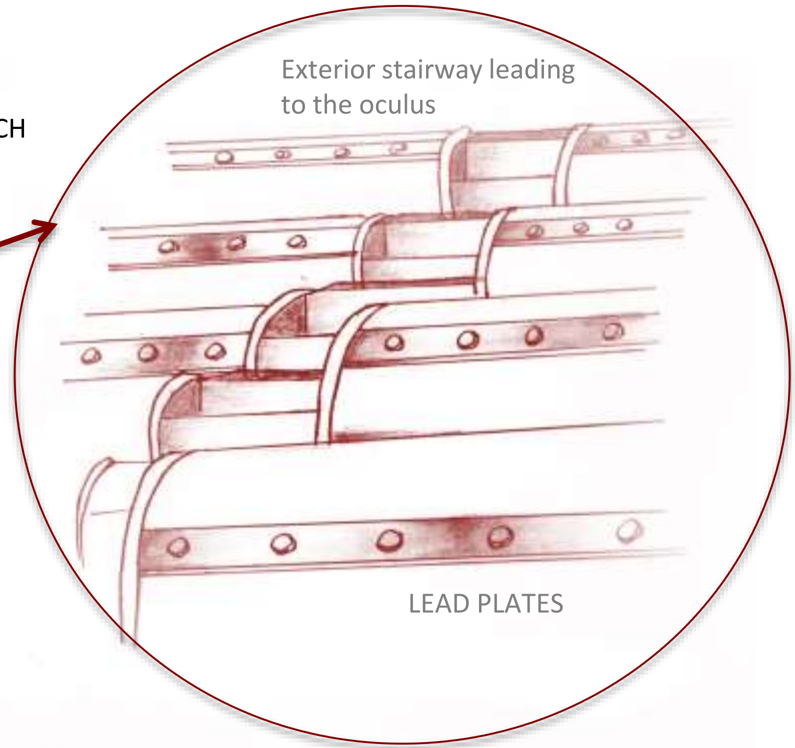




STEPPED RINGS OF THE DOME

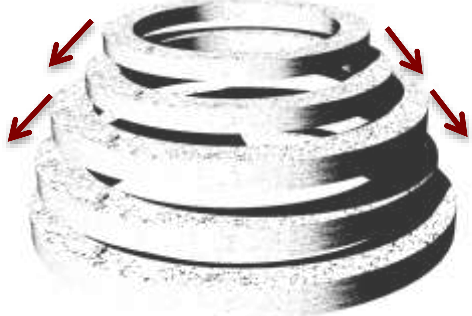


THE CONCRETE IS REINFORCED WITH LEAD PLATES ON EACH STEPPING



STACK CONCEPT OF RINGS

Weight of (dome + subsequent upper rings)



each ring is stacked on top of each other, the end of the upper ring starts at the centre of the ring below allowing the weight to be uniformly distributed across the concrete and eventually down to the wall below. The diameter of the rings decrease as they are stacked.

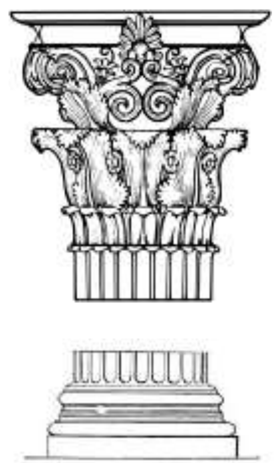
Conclusion: elimination of the stepped rings would cause the dome to be pushed outwards beyond the thrust line, and result in cracking of the dome, and possible Structure collapsing.

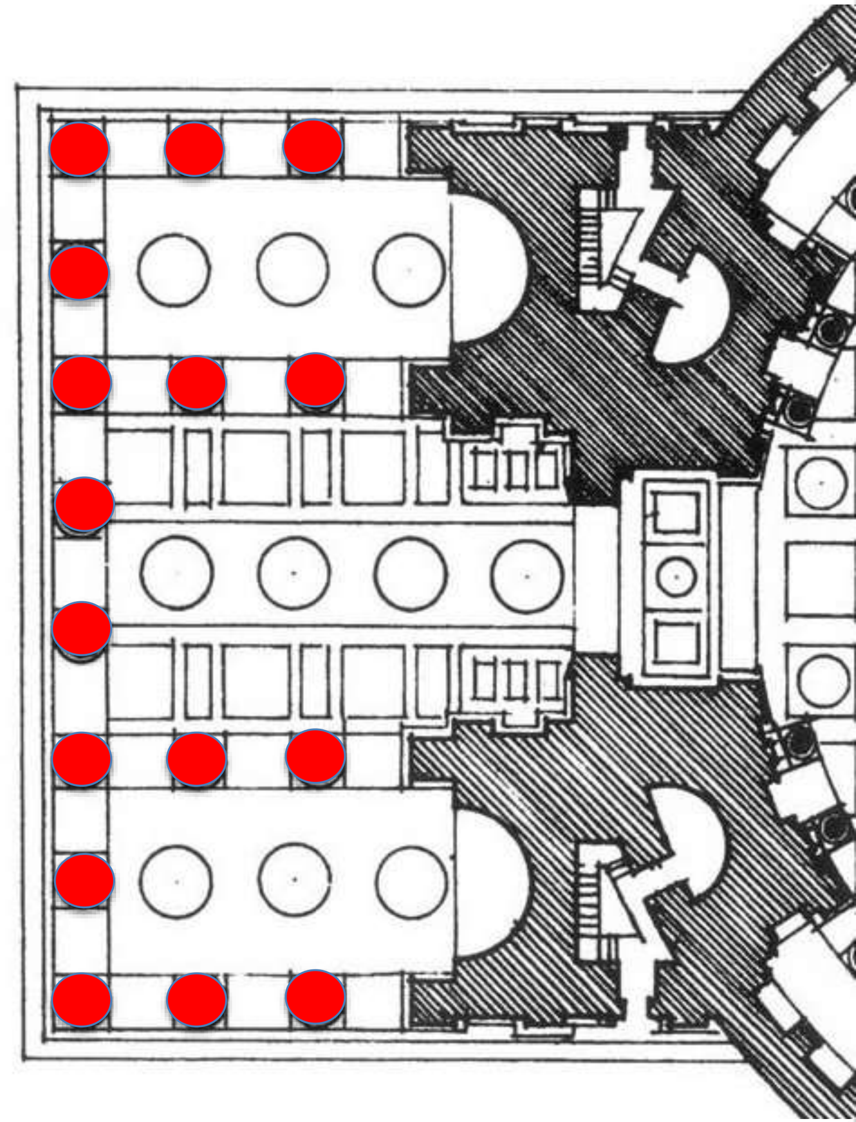
A column is an upright beam and a linear element- the bearing capacity is mainly provided by bending moment action, that is the couple produced by the tensile and compressive stresses at opposite edges of the same section of the beam multiplied by the moment arm/ distance measured between the point where forces are applied and the point that is pinned.

Columns in the Pantheon is mostly located at the portico, which consists of 16 towering columns that were conducted with Egyptian granite, porphyry and white marble bases. Standing at 39 feet (11.8 meters) tall and five feet (1.5 meters) in diameter, each column weighs about 60 tons and supports additional loading from the roof structure above. Inside, you will see a series of many more columns in colors of red, grey, and crème in various sizes and designs.

CORINTHIAN ORDER

The Corinthian order is the most decorative of the three styles of columns. Corinthian also uses the method of entasis to make the shafts appear straight to the human eye. The Corinthian capitals have flowers and leaves below a small scroll that connect to the shaft and end on a circular or square platform that is the base. All columns of the Pantheon are of this style.

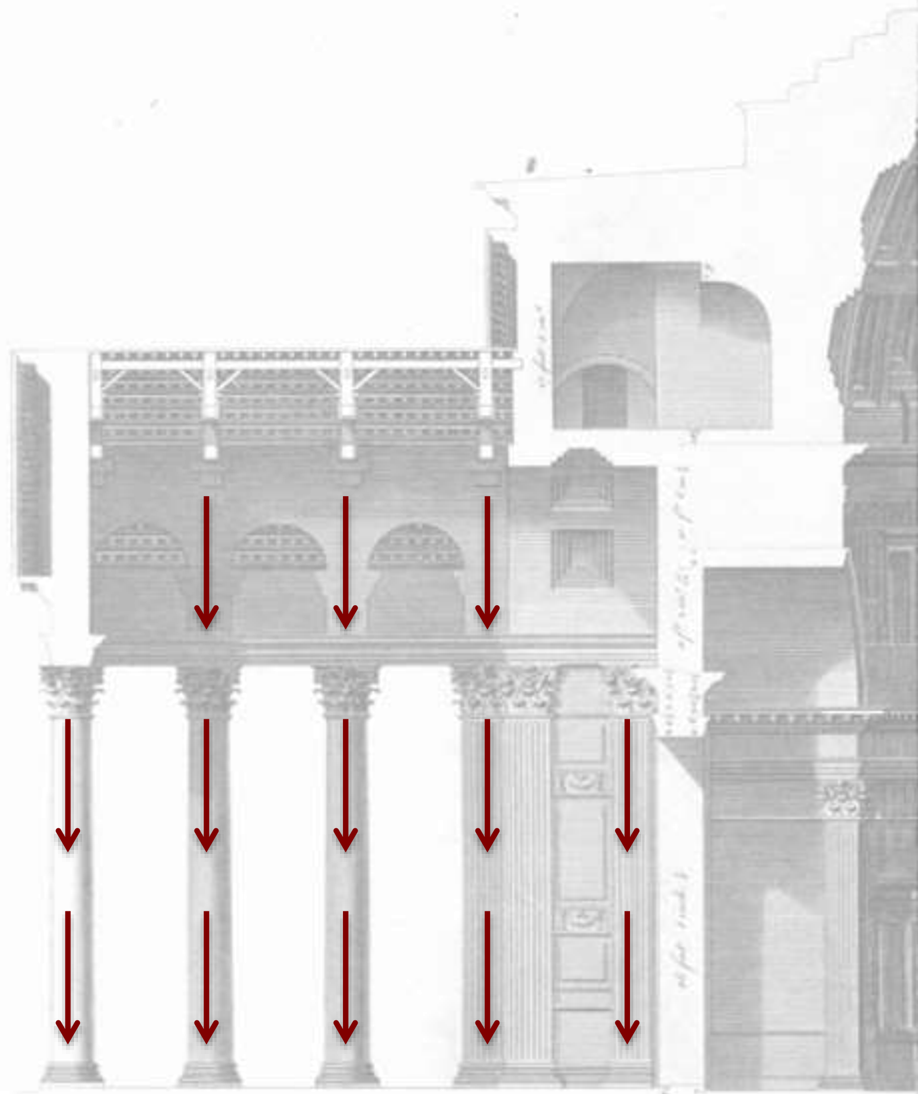




Positions of the 16 columns (red) in the portico

FUNDAMENTAL STRUCTURAL BEHAVIOUR (COLUMNS)

Columns can support a roof or a beam or they can be purely decorative. In the case of the Pantheon, most columns are used to create a load path for forces created by the weight of materials used on roof to the foundation in the ground. A strong construction stone, the granite within the columns of the pantheon has a compressive strength of 19000 psi.



The travel of compressing forces from the roof towards the foundation

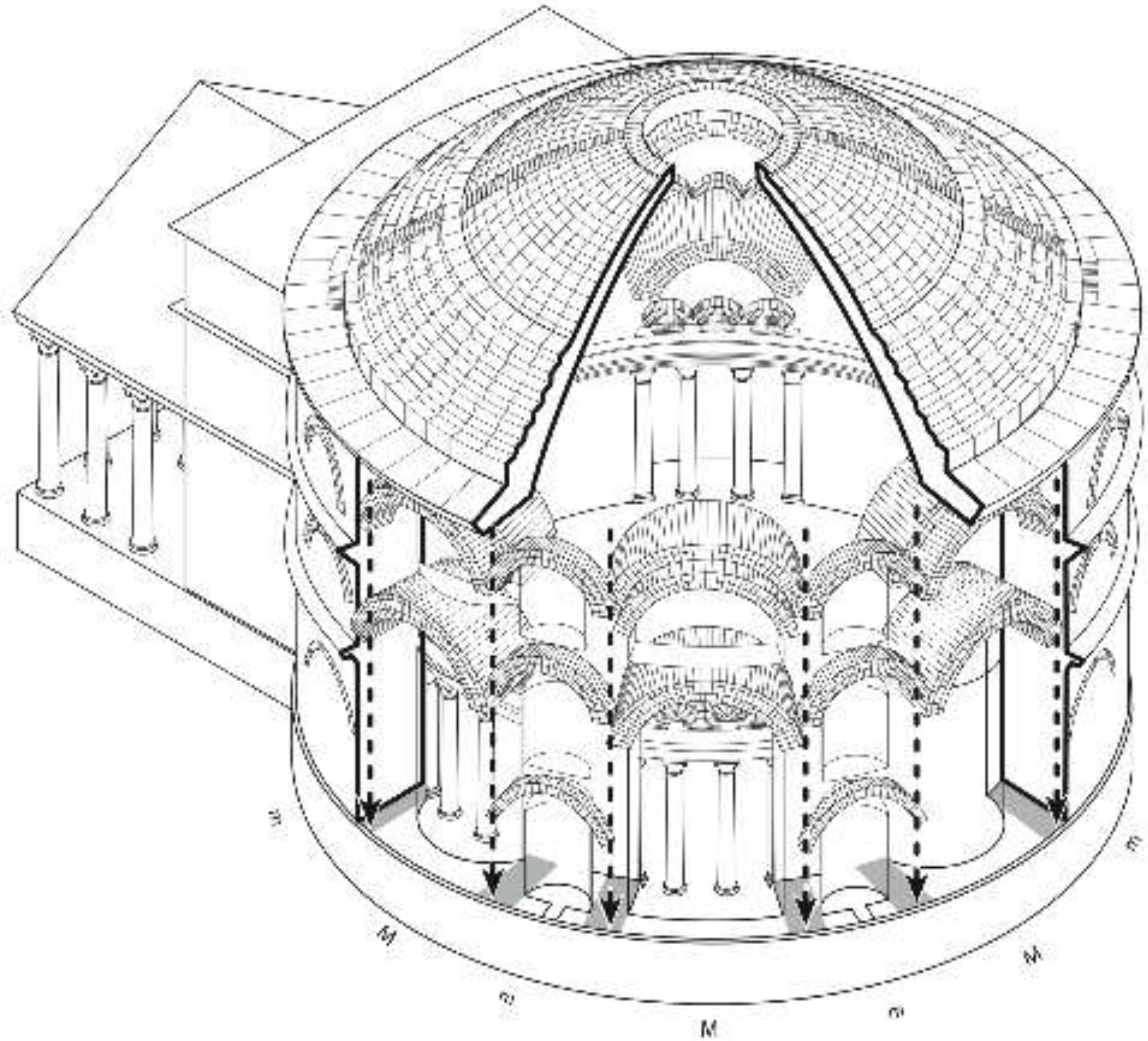
An arch is a structure that is usually made of stone, brick, concrete, or steel. (Figure 13.) Featuring curved contour, it is design to support or strengthen a structural design via its ability to distribute load. As in most curved elements, the couple produced by the internal stresses associated with the horizontal boundary reaction creates the bearing capacity in an arch. The arch can be classified as a construction technique where the elements of the structure themselves are in compression instead of tension in the material; thrust instead of pull at the abutments.

Most arches are built of wedge-shaped blocks- the top center stone is known as the keystone and is the final block to be inserted when assembling an arch. During construction, wooden scaffolding often supports arches prior to the removal of the frame. The finished product results in two arms of masonry arches press against a keystone to create a stable structure in which the moment produced by the two arms of masonry are canceled out.

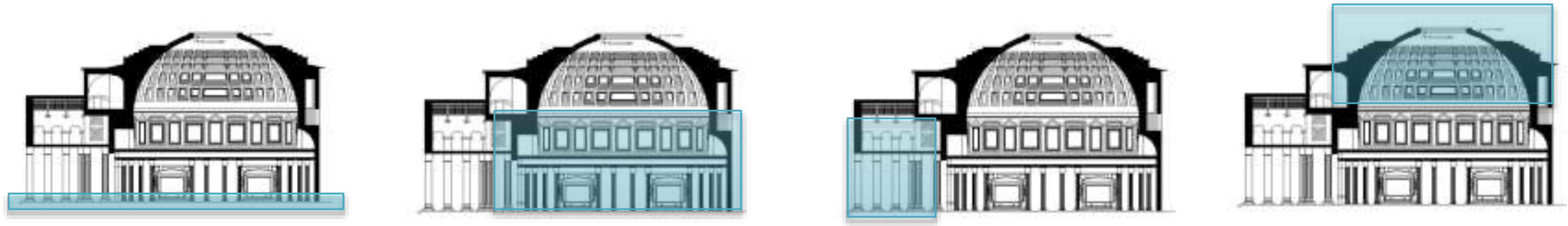
Arches on the rotunda wall visible on the exterior walls

The structure of the Pantheon is comprised of a series of intersecting arches. The arches rest on eight piers which support eight round-headed arches which run through the drum from its inner to its outer face. The arches correspond to the eight bays on the floor level that house statues.
The dome itself is supported by a series of arches that run horizontally round.

In other words, relieving arches direct the loads to the thicker parts of the wall between the niches. They provide a structural component to the wall that helps prevent excessive creep or settlement in any one place within the wall. Note that the distinguishable characteristics of concrete, ancient or modern, are that it gains strength slowly over a period of time and that it is susceptible to the phenomenon known as creep, which is the slow deformation of the material over time.



Drawing of structural system of arches/ribs in rotunda wall.



Pantheon Modeling Process

THE **MASS**

1.


2.


3.


1.First, we built a base of the pantheon which includes layers of steps. Then lift up to certain dimension to build the rotunda wall according to the plan drawings. (Refer to figure 1. 2. 3.)

4.


5.


6.


2.Columns of the front façade is made and try to join with the rotunda wall. (Refer to figure 4. 5. 6.)

THE OUTER LAYER OF **DOME**

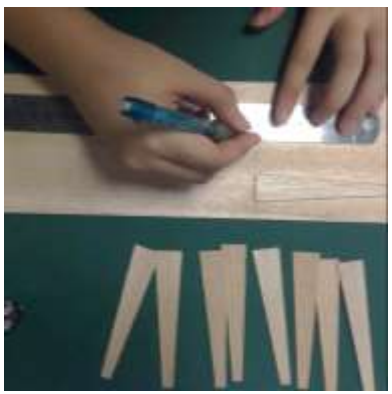
7.

8.

9.

(refer to figure 7. 8. 9.)
The outer layer of dome is calculated to gain the dimension to cut in balsa.

10.

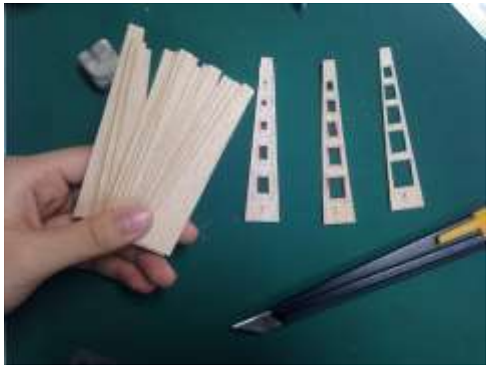


11.

12.

(refer to figure 10. 11. 12.)
Calculated and cut pieces are dipped into the hot water then bend to an ideal curve. It is then dried by hair dryer.

THE INNER LAYER OF DOME - **COFFERING**

13.


14.


15.


(refer to figure 13. 14. 15.)
The coffers are cut differently according to layer. After that is dipped in hot water to be ready for the bending session later.

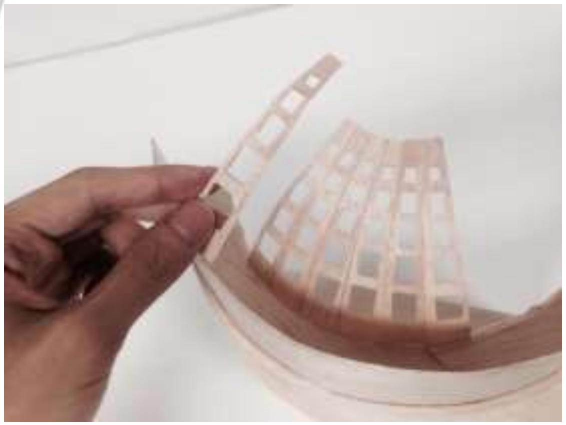
16.


17.


(refer to figure 16. 17.)
Dipped coffers pieces are bend using masking tape and dry it until achieved certain curve.

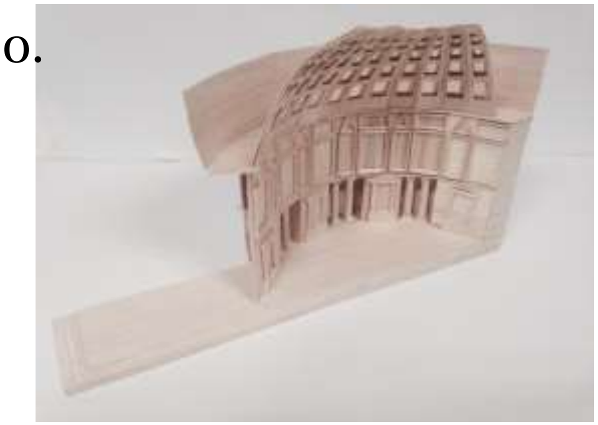
MODEL MAKING PROCESS

18.



19.

20.

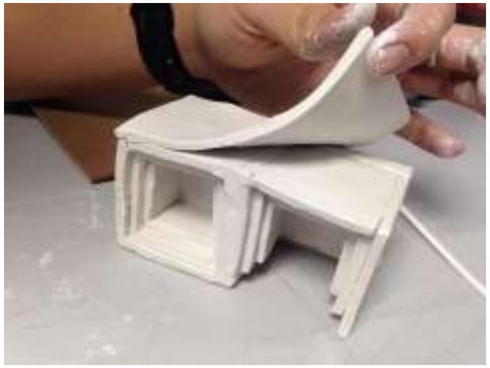


(refer to figure 18. 19. 20.)
Layers of coffers pieces are attached to the rotunda wall, one layer stacking on another layer to bring out the depth of the coffers like in the pantheon itself.

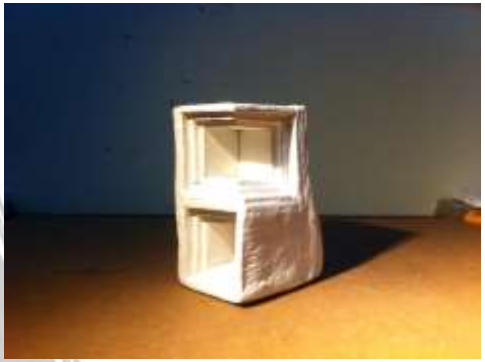
THE DETAIL STRUCTURE (COFFER)

21.

22.

23.


(refer to figure 21.22.23)
In order to achieve layers of coffers, clay are used and squares in different dimension are formed. Squares are attached to each other followed by dimension. Lastly, the outer surface is made to cover up the coffers.

24.

25.

26.


(refer to figure 24.25.26)
The details of the coffer is done with the grid bar representing the force distribution inwards each recesses.

Final product

Front view of the model

Side view of the model

DIFFICULTIES & **SOLUTION** IN MODELLING

1) Inaccuracy **of dimension**

Zero error happened all the time during the cutting. Therefore, it ended up resulting in different heights of the columns. Some of them might not be able to touch the ground. Therefore, things need to be cut precisely and measured accurately beforehand.

2) **Dome** dimension

Making dome is the hardest part in modelling Pantheon. As it involves a lot of calculation in order to make the dome by pieces of balsa wood. Making the curve into 2d and get its dimension. We divided the dome curve into 14 pieces of balsa wood to enhance the curve effect. However, some of them might not be joined perfectly and therefore left a gap in between. Problem are solved by bending every pieces into same curve to reduce down the gap .

3) Fragility **of Balsa**

Pantheon building might need a lot of bending. (the rotunda wall and the dome). Some pieces was broken and was hard to form certain curve that we wanted. Problem is solved by increasing the temperature of the hot water that dipped in and increase the time of dipping.

CONCLUSION

the Pantheon represents the highest achievement of Roman architecture, both formally and structurally. It combines boldness, scale, and mastery of every architectural art.

For whatever the reason, the Pantheon is the only structure of its age, size and span that has successfully survived the scourge of time and gravity and has remained pristine in splendor and beauty. While the Pantheon may be divinely protected, there are more earthbound reasons for its survival as well. We can attribute its longetivity to the quality of materials used. Perhaps it is because of very strong concrete with pozzolona cement that we are able to too can marvel at the wonder that Michelangelo once described to look more like the work of angels, not humans.

The whole combination of dome was one of the greatest creations the Roman ever did. Every part of the dome is needed to support each other. Besides, the detailing is even existed not only for aesthetic purpose but also functionally, to distribute forces to their respective parts. The wisdom of reducing the thickness of the dome and at last to be able to leave a hole(oculus) had made Pantheon remain amazing and respected by the modern generations. For whatever the reason, the Pantheon is the only structure of its age, size and span that has successfully survived the scourge of time and gravity and has remained pristine in splendor and beauty.

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