DOMES

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Introduction

- Domes are familiar to us all - St Paul's Cathedral and the Royal Albert Hall in London, and on the Royal Pavilion in Brighton.
- No national event is complete without a dome for its own sake such as the Dome of Discovery in the Festival of Britain, or the Millennium Dome (now known as the O2).

Definitions and Terminology

- A **dome** is an architectural element similar to the upper half of a sphere. Interpret "similar" very generously. Some domes are more like cones, the circular base may instead be polygonal, they may not be closed at the top.
- A dome can rest directly upon the ground, or on the walls of a *rotunda* or drum (circular or polygonal), or on a system of architectural devices used to accommodate the transition in shape from a polygonal space (e.g. a square) to the round or polygonal base of the dome.
- There is a huge amount of information on domes in Wikipedia.
- Early forms of dome were made of unworked stones and corbelled: that is with successive layers projecting beyond earlier ones.
- See the articles on trulli and beehive tombs in Wikipedia.

Arches and Domes

- In many respects, domes can be regarded as rotated arches, so they have some properties in common.
- In an arch, the intention is for the forces to be transmitted downward. In practice, some of the force is lateral, and at the base of the arch this can be a problem. This is known as “thrust”. Think of a bridge “spreading”.
- This is counteracted in various ways e.g. by buttresses.

Pantheon, Rome

- Built c126AD, it was commissioned by Hadrian to replace an earlier building by Agrippa (which had burnt down). Probably designed by Apollodorus of Damascus, so from the Greek technological tradition. He is also credited with Trajan's Column and with a bridge over the River Danube, used by Trajan in his wars against the Dacians.
- It was consecrated as a church in 609AD, when the Byzantine emperor gave it to the pope.
- https://www.italyguides.it/en/lazio/rome/ancient-rome/pantheon includes an interactive panoramic view of the interior
- https://romesite.com/pantheon.html includes a video on the history of the Pantheon
- https://en.wikipedia.org/wiki/Pantheon,_Rome
- In the exterior views of the rotunda, note the three cornices defining three "floors", the entrances to the hidden cells, and the arches built into the wall above them.

Pantheon, Rome – 2

- The dome is supported by a circular rotunda.
- The interior diameter is 43 metres, equal to the height from the ground to the top of the dome.
- The entrance and the apse opposite containing the high altar define the main axis. In between these are three chapels and four niches on each side.

Pantheon, Rome – 3

- A sphere of diameter 43 metres, sitting in the centre of the rotunda, would fit exactly into the dome.
- The roof is not closed, a hole of diameter 9 metres known as an oculus (eye) allows light (and rain) into the building. (There are no windows.) The floor slopes to the centre, allowing rainwater to be drained away.
- The walls of the rotunda are 6 metres thick, while the dome varies in thickness from 6 metres at base to 1 metre. All made from concrete, but the composition of the concrete varies: a much lighter mixture was used high up on the dome.
- The chapels contain the tombs of Raphael and other artists and of the first two kings of an united Italy.

Pantheon, Rome – the rotunda

- In between each pair of chapels, there is an empty cell (behind the niche), as there is above each of the recesses except the entrance and apse. So the wall of the rotunda can be regarded in several ways – as a honeycomb, or as two concentric walls with a gap between (each about two metres thick), linked by transverse walls. It is assumed that this was to reduce weight while retaining strength.
- These cells can be accessed from the outside, but not otherwise.
- In addition, the outside walls contain inbuilt arches corresponding to the structures within. It is thought these were intended to add strength to the wall and to protect the other structures within the wall.

Pantheon, Rome – the dome

- The dome itself is also a bit more complicated than at first sight appears.
- The lowest level is more or less part of the wall (which makes the dome seem shallower than the interior view shows): and it contains more of those inbuilt arches.
- The next level consists of step rings, essentially corbelled.
- The third layer would have been the most difficult to construct, probably using a wooden structure based on the ground to centre and shape the dome. Scaffolding would also be needed for the workmen.
- Finally, the oculus acts like a sort of keystone and also means the near-horizontal top of the dome is avoided.
- Roman concrete was applied almost dry, and the aggregate – stone, broken brick or pottery – was inserted into it. Brick facing might then be added, as can be seen on the outside of the Pantheon.
- Modern cements come in many forms, but include pozzolan cements, which approximate to Roman cements, using volcanic ash , slag and other materials.

Reinforcement

- The Roman Pantheon is said to be the largest unreinforced concrete dome in the world.
- But please note that the term reinforcement includes more than the steel rods we all see on modern building sites .
- Also included would be iron bands (like lines of latitude), ribs (like lines of longtitude) and various forms of buttressing.

Hagia Sophia, Istanbul

- Built at the command of Justinian I, building began in 532AD and the church was dedicated in 537 AD.
- The two men in charge were academics, Anthemius of Tralles and Isidorus (the elder) of Miletus, specialist engineers.
- There was a body of scientific knowledge some of it dating back to Archimedes, but it is not known how far it had progressed by this time.
- The 10,000 strong workforce was split in two, each responsible for one side of the building, in competition with each other.
- The dome itself has a diameter of 31 metres.
- The building was built of stone and brick, not concrete.
- Columns of marble, porphyry and other specialised stones were used to open up the interior space.
- Lots of windows lit up the interior, and the interior surfaces were covered in mosaics and other ornamentation (including gold leaf).

Hagia Sophia, Istanbul – 2

- This dome is not built on a circular support, but on four massive piers at the corners of a square.
- The four columns are linked by four great arches defining the N,E,S and W sides of the square.
- On top of the arches sit four pendentives: four triangular segments of a hemisphere. These effect the transition from square to circle.
- And on top of the pendentives sits the dome.
- https://muze.gen.tr/muze-detay/ayasofya
- https://www.history.com/topics/middle-ages/hagia-sophia
- https://en.wikipedia.org/wiki/Hagia_Sophia
- There is a Hagia Sophia in London, which has a dome on pendentives, and seems internally rather like the original, but much smaller

Hagia Sophia, Istanbul – 3

- The rest of the building is, essentially, devoted to holding the dome up.
- There is another consideration, that from the interior of the church, it should seem rectangular, going from W to E, for ritual purposes.
- So on each of the E and W sides, the support is given by a semidome linking two of the main columns to two secondary columns, amongst other things.
- On each of the N and S sides, support is given by two huge buttresses. (These are not solid: there are rooms on three floors linked by a staircase.)

Hagia Sophia, Istanbul – 4

- The building does show evidence of the problems it has had to face. Many of these affect the dome.
- Over time, gradual deformations caused by the forces acting upon the various components. The base of the dome is no longer circular, but slightly elliptical. The four main piers lean inwards. The arches, viewed from below, are no longer straight lines but bowed inward. Some of the other columns are, or were, no longer upright but at an angle (sometimes corrected by shifting the base).
- Earthquakes, subsequent or independent collapses, and repairs. There were major earthquakes in 542, 557, 740,790, 869, 984, 1343, 1509 and 1894. The dome partially collapsed and was repaired following the earthquakes of 557, 984 and 1343.
- The decoration throughout has been affected by the iconoclasts and by the adaptation to a mosque, though some has survived. (None of the original figurative mosaics survive, what you see is from 900 or later)
- The exterior has changed by the addition of minarets and the replacement of Orthodox structures by Muslim ones.

Other Istanbul Domes

- After the Ottomans conquered Constantinople in 1453, they built a series of imperial mosques, renowned for their architecture and for their internal decoration. They can be compared and contrasted with Hagia Sophia in design.
- The Suleymaniye Mosque , built between 1550 and 1557
- The Blue Mosque, properly known as the Sultan Ahmed Mosque, was built between 1609 and 1616
- The Rustem Pasha Mosque, famed for its Iznik tiles, on geometric and floral themes
- Other imperial mosques can be found in Bursa and Edirne, the first two capitals of the Ottoman empire as well as in Istanbul.

Guri Amir

- The tomb of Tamerlane (and others) in Samarkand
- The founder of the Moghul dynasty
- The tomb was originally built for his grandson and heir, in 1403.
- Heavily restored
- This is an example of an “onion” dome, which is narrower at the base than it is higher up. This has an important advantage in that it reduces thrust (I am told by TN, who has actually built a dome!)

Taj Mahal

- The Taj Mahal was built 1631-1653 by the Mogul Emperor Shah Jehan, in memory of his favourite wife Mumtaz Mahal. He is also buried there (having spent the last years of his life imprisoned by his son).
- The most spectacular of a series of imperial tombs, going back to the tomb of Tamerlane, the first Moghul Emperor, in Samarkand.
- Also an onion dome.

Duomo di Firenze

- Construction of the cathedral began in 1296. The octagonal drum was completed in 1413, with walls 14ft thick: the last part to be built was the dome, of which construction began in 1420 and ended in 1436.
- The design of the dome – octagonal, no external buttresses – had been specified by Arnolfo di Cambio in 1296 as part of the design of the cathedral. The baptistery is also octagonal.
- The design of the dome had been further restricted in 1367 by Neri di Fioravanti, who specified a 2-shell solution, comprising a thick inner shell and a thin outer shell. This followed the designs used in the baptisteries at Florence and Pisa.
- Span 44m, base of dome 62m above ground. Total height 116m, plus a bit for the lantern and orb at the top, I think.
- N.B. Duomo means Cathedral, NOT dome! The Italian for dome is cupola.
- https://duomo.firenze.it/en/discover/cathedral
- https://duomo.firenze.it/en/discover/opera-duomo-museum
- https://en.wikipedia.org/wiki/Florence_Cathedral

Duomo di Firenze – 2

- The problem was how to build it.
- The project was financed by the Woollen Guild (Arte della Lana) of Florence , a very wealthy organisation.
- A competition was held to propose and execute a solution. This was won by Filippo Brunelleschi, a goldsmith. His main competitor was Lorenzo Ghiberti, another goldsmith
- With the help of Donatello and others, he built a model to illustrate his method, though it was incomplete in order to maintain control! This model is in the museum (the Museo dell'Opera del Duomo) next to the cathedral.
- The design was based on a variant on the well-known 4/5th or acute 5th rule (actually more like a 5/6th rule in Brunelleschi's case). This applies to the 8 principal ribs only. Consider a pair of ribs on opposite sides of the dome. If the dome were hemispherical, then the ribs would each be a quarter of a circle with centre at the centre of the base of the dome. Considering each quarter circle separately, move the centre of the circle further away to a distance 4/5th of the distance across the base of the dome. The two resultant curves rise at a steeper angle and meet at a point. For the surface between neighbouring ribs, the surface is a straight line at any given height.

Duomo di Firenze – 3

- Since no external buttresses were allowed, thrust was contained by 4 (one source says 6) rigid iron-and-stone octagonal rings hidden in the brick-built inner dome walls. One ring was at the base, another at the top - forming an oculus. There was also a wooden ring.
- The outer dome is 2.5ft thick at the base, and 1.25ft thick at the top. The inner dome is 7ft thick at the base and 5ft thick at the top.
- There are 24 vertical ribs connecting the inner and outer domes: 8 of these are at the vertices of the octagon and are visible from the outside. The topmost ring acts a keystone for the 12 arches formed by the 24 ribs. There are horizontal passageways at various levels, and stairways connecting them, both cutting through the ribs where necessary.
- Scaffolding. Holes were left in the walls of the dome, for timber poles to be inserted. These were used successively to support short platforms for the work on the next stage up. Near the top, the platform was probably extended the whole width of the dome. No scaffolding from the ground
- Centring - framing used to support an arch or dome while it is under construction.
- TN drew attention to herringbone brickwork and its significance. Here is a quote from the Wikipedia article on Florence Cathedral, "A circular masonry dome can be built without centering, because each course of bricks is a horizontal arch that resists compression. In Florence, the octagonal inner dome was thick enough for an imaginary circle to be embedded in it at each level, a feature that would hold the dome up eventually, but could not hold the bricks in place while the mortar was still wet. Brunelleschi used a herringbone brick pattern to transfer the weight of the freshly laid bricks to the nearest vertical ribs of the non-circular dome."

Duomo di Firenze – 4

- Measuring. Because the dimensions were so large, direct measurements by lengths of string were not accurate because of sagging. Brunelleschi cleared a flat area near the Arno and drew a full scale plan of the dome, possibly at various heights. He did many calculations to estimate the dimensions and angles at various heights. And he, in effect, calibrated the string method by adjusting the figures obtained by using strings.
- Hoisting: Brunelleschi was famous for his technical innovations. These included devices taken from watchmaking, such as overdrive transmission (for winding long cables) and changeable gears in pulleys.
- Project Management. Ultimately by the Guild, deputed in various ways - by competitions, by the skilled masters of the Opera (who checked that Brunelleschi's proposals worked), by a succession of 4-man committees (who did play an active role) and by sharing the leadership between Brunelleschi, Ghiberti and (probably) the master mason of the Opera.
- Health & Safety. In the museum, there is a safety belt, to be tied to three guy ropes, for workers in dangerous areas

Duomo di Firenze – 5

- As with Hagia Sophia and the Pantheon, time has had an effect on the structure.
- Cracks have been observed, surveyed and reported since before completion. The main cause is the weight of the dome, about 25,000 tons.
- In 1694 there were two cracks with a maximum width of over 1”.
- In 1934, it was realised that the cracks varied in width according to season. In winter, the stones and bricks would contract, and the gaps would widen. In summer, the cracks would close up. In modern buildings, expansion joints are built-in. The dome was behaving like four half-arches linked below the oculus.
- In 1987, a system of 166 instruments of various kinds was installed to record temperature (of masonry and air) at various points, width of cracks, deviations from vertical, underground water level etc, readings taken every 6 hours.

St Paul's, London

- Old St Paul's Cathedral was commenced by the Normans in 1087 after an earlier cathedral was destroyed by fire. After many delays, numerous additions, a number of fires, and shoddy repairs, the cathedral was in a poor state and in need of renovation. Both Inigo Jones and Christopher Wren were employed to restore it, before the Great Fire of 1666 destroyed it.
- Wren's design for the new cathedral evolved through 5 stages, most including a dome over the crossing. The second model was in the form of a Greek cross. A model of his 3rd proposal (the Great Model) is on display in the cathedral, with 2 domes (one over the W end).
- The 4th proposal (the Warrant Design) gained approval, but he was allowed to make "ornamental changes", and he made many.
- So the completed building itself represents the 5th design.
- Wren died on 25th February, 1723, 300 years ago, and a number of events have been organised at St Paul's, to celebrate his life and achievements.
- https://www.stpauls.co.uk/
- https://en.wikipedia.org/wiki/St_Paul%27s_Cathedral

St Paul's, London – 2

- The warrant specifies a shallow dome (the first dome) over the crossing, supporting a drum with a dome (the second dome), from which rose a spire in 7 stages, like the spire of St Bride's, Fleet St.
- That shallow dome rests on 8 columns and the arches between them. This is a pendentive structure like that of Hagia Sophia, but based on an octagon (with unequal sides) rather than a square.
- In the built cathedral, there is a further development, in that a cone and a further dome are built over the second dome, and not a spire.

St Paul's, London – 3

- So, the dome proper (resting on a drum with 2 stages, itself resting on pendentives),
- comprises three nested elements: an outer dome, made of timber with a lead covering, a brick cone (18" thick), which supports the outer dome and the lantern, and an inner dome, also of brick, and also 18" thick.
- The inner dome has an oculus at the top, but what you see through it is the inner surface of the cone, suitably painted.
- There are wrought iron chains around the cone and around the foot of the inner dome. And buttresses
- Wren's St Paul's does not point East, as did Old St Paul's, but 15deg north of east, where the sun rose on Easter Day in the year the foundation stone was laid. The works took 35 years to complete, but Wren (at 76) lived to see his son place the last stone.

Capitol, Washington

The original design for the building was approved by George Washington in 1793; the building was burnt by the British in 1814, and has been expanded many times.

The dome was built in 1856-66, in cast-iron (4000 tons). The building faces west, with the Senate on the north, and the House on the south.

https://en.wikipedia.org/wiki/United_States_Capitol

https://www.aoc.gov/explore-capitol-campus/buildings-grounds/capitol-building/history

https://www.visitthecapitol.gov/

Royal Albert Hall

- Was paid for by the proceeds of the Great Exhibition of 1851.
- Opened in 1871.
- The architects were Captain Francis Fowke and Major-General Henry Scott, from the Royal Engineers.
- The dome consisted of a wrought iron frame with glass panels, and was designed by Rowland Mason Ordish (a prominent engineer of the day), so the interior was lit by sunlight during the day.
- Ordish worked on the Crystal Palace and on St Pancras station, and designed many bridges and public buildings.
- https://www.royalalberthall.com/
- https://en.wikipedia.org/wiki/Royal_Albert_Hall

Royal Albert Hall – 2

- This shows a test construction of the iron frame at the manufacturers factory in Manchester).
- It was then dismantled and transported to London by horse and cart!
- The hall is elliptical in plan, so presumably the dome is also.

Royal Albert Hall – 3

- The same page shows the dome in place
- On the left is the ceiling of the auditorium, presumably suspended from the frame.
- It looks a bit new: originally the auditorium was open to the glass roof. But this gave a very pronounced echo. A canvas awning was added, but this was not very satisfactory either.
- Eventually, in 1969, the present ceiling was constructed, with large acoustic diffusing discs (popularly referred to as mushrooms). Presumably the discs are attached to the underside of what you see.

Geodesic dome

- This is the Montreal Biosphere, by R. Buckminster Fuller
- https://en.wikipedia.org/wiki/Montreal_Biosphere

Church of the Annunciation, Milwaukee

- Frank Lloyd Wright, designed in 1956 and completed in 1961, after his death.
- Dome on a basin.
- It’s a Greek Orthodox church, and he referenced Hagia Sophia in his discussion of it, but it looks more like the Pantheon to me.
- https://en.wikipedia.org/wiki/Annunciation_Greek_Orthodox_Church

Baha'i Lotus Temple, Delhi

- Dedicated 1986.
- Architect Fariborz Sahba, originally from Iran
- Design consists of 3 sets of 9 "petals". The innermost set defines the area dedicated to worship. These petals approach each other at the top, but do not meet, the gap being filled by a steel and glass skylight, a sort of oculus.
- The petals consist of reinforced concrete faced with white marble from Mount Penteli in Greece (as did some of the marble for the Parthenon).
- All Baha'i temples must be 9 sided.
- The marble, like that of the Taj Mahal, is now becoming discoloured as a result of air pollution.

https://en.wikipedia.org/wiki/Lotus_Temple

https://bahaihouseofworship.in/

References

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- *Brunelleschi – The Complete Work* by E.Battisti
- *Brunelleschi's Dome* by Ross King
- Wikipedia, websites for the buildings concerned