The structural analysis of domes: From Pantheon until Reichstag

Müjde Altin
Dokuz Eylül University, Faculty of Architecture, Department of Architecture, Izmir, Turkey

ABSTRACT: Dome is one of the most efficient shapes in the world since it covers the maximum volume with the minimum surface area. Maintaining larger volumes with no interrupting columns in the middle with an efficient shape would be more efficient and economic. So, the use of domes will help having larger volumes with no interrupting in the middle. Because of this, domes and their development is examined in this study from the viewpoint of material capacities, construction techniques and structural properties. They all limit the size of the domes. By the examination of these buildings, the development of the construction techniques from the year 27 B.C. till today, 2000 A.C., are put forward.

In conclusion, a table consisting of all the domes that were taken in consideration here is obtained. All these show the limits of the material by which they are constructed, and the development at the construction techniques.

1 INTRODUCTION

Dome is one of the most efficient shapes in the world since it covers the maximum volume with the minimum surface area. And todays trend is to maintain large volumes with no interrupting columns in the middle. Maintaining this with an efficient shape would be more efficient and economic. So, the use of domes will help having larger volumes with no interrupting in the middle.

Domes and the development of the domes are examined in this study from the viewpoint of material capacities and construction techniques. These both limit the size of domes. Also, by the examination of these buildings, the development of the construction techniques from the year 27 B.C. till today, 2000 A.C., for over 2 milenniums are put forward.

In order to examine the development of domes, the world's biggest and most important domes are taken in consideration since they show the development in dome construction techniques better. For this reason, The Pantheon in Rome-Italy, Hagia Sophia in Constantinapole-Istanbul-Turkey, Florence Cathedral (Santa Maria del Fiore) in Florence-Italy, Saint Peter's Cathedral in Rome-Italy, Saint Paul's Cathedral in London-England and Reichstag in Berlin-Germany are examined. During this examination, the diameter (span), height, structural material, year of construction and structural properties of these domes are taken in consideration. The structural knowledge about these domes are gathered together and put forward in order to show the capacity of the materials used at the constructions of these domes. Tensegrity domes made of steel rods are not taken in consideration in this study because they have different working details and domes of more than 100 meters are constructed by that method.

As the time goes, new materials are being used at construction technology. In the early times, stone was being used at domes as in Hagia Sophia that was first built at 360 A.C. At the 17th and 18th centuries, brick was being used as in Saint Paul's Cathedral that was built between 1675 -

1710 A.C. Now in 20th century and in the 2000, steel is the new constructional material and it is being used as in Reichstag built between 1995 - 1999.

Steel is the newest material nowadays. It is being used in every part of architecture and new Reichstag is the newest way of usage of steel - usage of steel in a dome. Of course, this is not the limit of this material - steel; it is the beginning of the usage of steel in domes. The unlimited usage of steel in domes will be tried and seen after the new Reichstag. This is the first, not the last example! And steel domes with larger diameters are going to be built after the new Reichstag.

2 THE DEFINITION OF DOME

Dome is “a rounded roof with a circular base.” (Oxford Keys, 1980, p.112)

“It is one of the most efficient shapes for covering large areas, for it encloses a maximum amount of space with a minimum surface area... In theory there is almost no limit to the size of dome which can be constructed, and this provides a constant challenge to engineers. However, in practice the limitations on the size of domes has been closely associated with the development of available materials and construction techniques.” (Wilkinson, 1996, pp.101, 102)

3 THE EXAMINATION OF THE EXAMPLES:

In the earlier times, man used mud and timber. But the Romans demonstrated the structural potential of the dome shape. By using a form of concrete in horizontal layers, they constructed the Pantheon with the dome above with a span of 44 meters diameter. It is still the biggest span of the dome structures in the world even today, in the year 2000. It is still not equalled today. To show the development of the domes from the Pantheon till today, six examples are described and examined here as below:

3.1 Pantheon

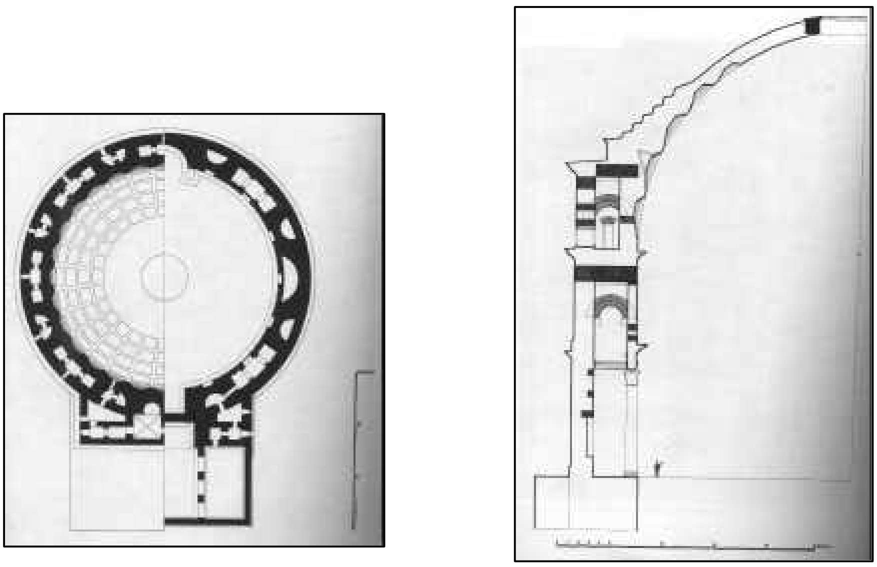


Figure 1 : The plan and section of Pantheon (MacDonald, 1982)

Architect: M. Vispanius Agrippa, Emperor Hadrian
Placement: Rome, Italy
Construction date: 27 B.C. -first constructed by M. Vispanius Agrippa.
118-128 A.C. -repaired by Emperor Hadrian.

Span: 44 meter diameter.
Height: It is nearly 45 meters as calculated from the section drawing.
Structural Properties: It is a coffered dome. There are 28 vertical, 5 horizontal ribs in the coffers.

The Pantheon was a temple in honor of the Olympic gods; in fact, the word pantheon is Greek for "of all the gods." It is the best-preserved of all the Roman monuments. The original Pantheon was constructed by M. Vispanius Agrippa in 27 B.C. The Pantheon we see today, however, is a reconstruction built by the Emperor Hadrian, perhaps after a fire. In A.D. 609, Pope Boniface VIII received the building as a gift from the emperor of Byzantium. He made it into a Christian church dedicated it to the Madonna and the martyrs.

This is the biggest dome of its kind in the world even now in 2001. A form of concrete was used at the construction of this dome; because of this, it still stands today. But when the concrete technology was lost, even though many domes were constructed of stone and timber,the limitations of weight and jointing techniques restricted their spanning potential.

3.2 Hagia Sophia Museum

Photograph 1: A view of Hagia Sophia

Architect: Anthemios and Isidoros
Placement: Constantinapole, Istanbul, Turkey
Construction date: 360 A.C. -first constructed
537 A.C. -by Anthemios and Isidoros the Younger
Span: 30.37 meters in one direction. (diameter)
31.87 meters in the other direction. (diameter)
Height: 55.60 meters.
Structural Properties: Its frame is constructed of 40 ribs. It has one skin made of stone and brick.

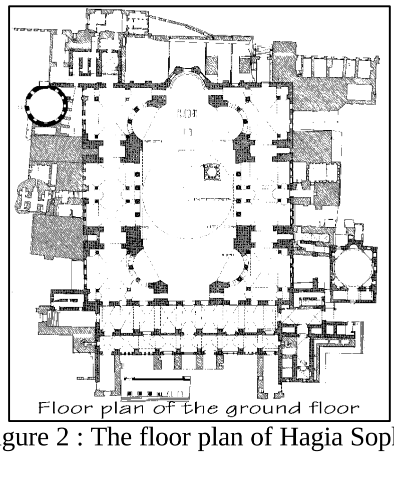
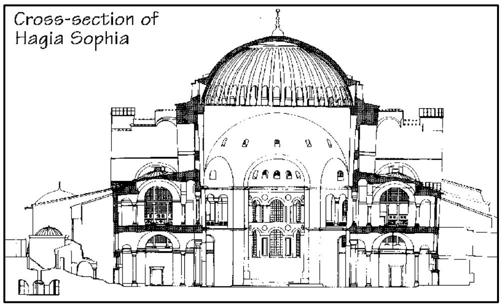


Figure 2 : The floor plan of Hagia Sophia



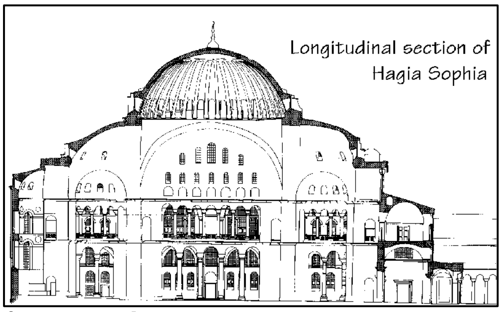


Figure 3 : Sections of Hagia Sophia

The Basilica or Hagia Sophia (in Constantinapole), now called the Ayasofya Museum is unquestionably one of the finest buildings of all times. Its dome rises 55.60 meters above the ground and its diameter spans 31 meters.

Between the years 537 and 1453, the building was used as a church for 916 years. From 1453 to 1935, it was used as a mosque. At the year 1935, it was made into a museum by Atatürk and used as a museum since then.

The architects Anthemios and Isidoros wanted to cover the basilica’s roof with not the usual way of covering with wood, but with stones. Hagia Sophia is therefore important to be the first example of this kind in the world.

The height of the dome is 55.60 meters.This large dome in the middle of the building is not circular. It maybe that it was originally circular and its shape had changed after the damages and the repairs. Its one diameter is 30.876 meters and the other is 31.877 meters, which gives an average of 31.37 meters. (Dirimtekin, p.28)

The large dome of Hagia Sophia rests upon 4 pendetives forming a square, and supported by 4 great arches resting upon the 4 massive piers in the middle of the building. The heavy thrust of the dome is received by the 2 semi-domes in the east and west. These large semi-domes are supported on one side by the 4 massive piers, and on the other side by two minor pillars in the east and in two in the west. The thrust of these semi-domes is received in turn by smaller domes (exedrae) and conveyed to the main walls.

3.2.1 The Dome

The main dome is a shell scalloped by 40 ribs and forty curved webs. “It is buttressed on the outside by 40 closely-spaced short ribs which frame small windows.” (Krautheimer, 1986, p.209) “The frame of the dome is constructed of 40 ribs, built in bricks, and 1.10 meters in width. Between those ribs are arched windows. The lateral thrust of the ribs is counteracted by the pillars outside. The windows form a perfect support together with the parts which fill the spaces between the ribs. (Dirimtekin, pp.46-47) “Parts of the dome fell down and were rebuilt after 558 (the reconstruction), 13 out of the 40 ribs in 989, and another thirteen in 1346 – but the design of Isidorus the Younger was not seriously altered.” (Mango, p.109)

The dome is constructed of light bricks and its interior is covered with mosaics. Decorative mosaic hands radiate from the crown to the base of the dome. Documents indicate that the crown was previously decorated with a mosaic representation of Christ the Pantocrator. Today, it is replaced by an inscription from the Koran which was created by Kazasker Izzet Efendi in the 19th century. The forty windows at the base of the dome are decorated with multicoloured mosaics.

Photograph 2 : A view of the dome and the ribs (Mango)

3.3 Florence Cathedral (Santa Maria Del Fiore)

Photograph 3 : Dome of Florence Cathedral (Murray, 1985)

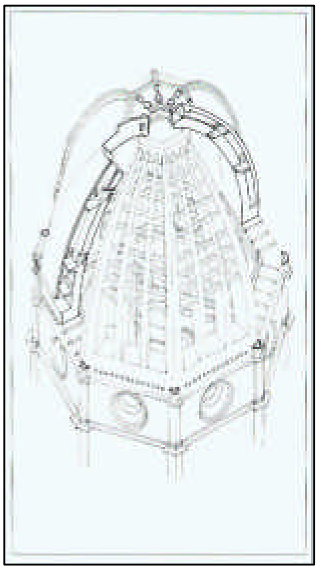


Figure 4 : Axonometry of the dome of Florence Cathedral (Murray, 1985)

Architect: Arnolfo di Cambio (the cathedral)
Filippo Brunelleschi (the dome)
Placement: Florence, Italy
Construction date: 1296 - 1436 - Construction of the whole cathedral.
1420 - 1436 - Construction of the dome.
Span: 42 meters diameter.
Height: It is mentioned as the half of its diameter; so it is about 21 meters.
Structural properties: It has 8 vertical ribs stiffened with horizantal elements.

The construction of the dome of Florence Cathedral was one of the germinal events of Renaissance architecture. The problem had been posed in the middle of the fourteenth century when the definitive plan for the octagonal crossing had been laid down.

In 1418, a competition of model was held in order to solve the octagonal dome of the Florence Cathedral. Filippo Brunelleschi's model was chosen the first. It was formed by steep stone arches whose inside was filled with bricks. This construction didn't have to have a scaffold as usual, so it brought a new construction technique to the architecture. Old Romans had developed this technique, and probably Brunelleschi had seen it at the old buildings of Romans.

The construction began at 1420 and finished at 1436.

3.4 Saint Peter's Cathedral

Photo 4 : The dome of St. Peter's Cathedral (Murray, 1985)

Figure 5 : The section of St. Peter's Cathedral (Murray, 1985)

Architect: Donato Bramante
Michelangelo Buonarroti
Placement: Rome, Italy
Construction date: 314 - 349 A.C. - first constructed.
1506 – 1591 – Repair of the cathedral.
1546 - 1591 - The construction of the dome. (by design of Michelangelo)
Span: 41.6 meters diameter.
Height: 117.6 meters from the floor.

The basilica of St. Peter is the heart of Christianity. It was built over the tomb of the prince of the apostles, St.Peter at the request of the Emperor Constantine after 314, but it was completed only in 349. In 1492 Niccolò V entrusted B. Rossellino to rebuild the church threatening to collapse. The new construction only began in 1506 under Julius II, based on a project by Bramante who wanted to perch the Pantheon on top of Constantine's basilica.

After his death Giuliano da Sangallo, Raphael, Baldassarre Peruzzi, Antonio da Sangallo il Giovane succeeded one another at the direction of the works. Michelangelo who took in charge in 1546, leaving the mark of his genius. He planned a church in the form of a Greek cross crowned by a grandiose dome. At his death (1564) the works, left in an well advanced stage, were continued by Pirro Ligorio, Vignola, Giacomo della Porta and Domenico Fontana. At the request of Paul V Carlo Maderno transformed the Greek cross into a Latin cross and added the present facade (1614). But in real, the dome belongs to Michelangelo and has finished in 1591.

In 1506 architect Donato Bramante, under commission from Pope Julius II, designed St. Peter's Basilica. Bramante died before completing the church, located in Vatican City within the city of Rome, Italy, so Florentine artist Michelangelo assumed the supervisory role and altered the design when the main stage of construction began in 1546. The church is shaped like a Greek cross and its prominent dome influenced dome design and construction for the next 300 years.

The brick dome 138 feet in diameter rises 452 feet above the street, and 390 feet above the floor, with four iron chains for a compression ring. The dome is 452 ft high (above the pavement) and is buttressed by the apses and supported internally by four massive piers more than 18 meters (60 feet) thick.

The diameter of the dome is 41.6 meters. According to the knowledge above, the height of the dome is about 117.6 meters above the floor. Bramante's design was a single masonry shell while Michelangelo's design was a double one.

3.5 Saint Paul's Cathedral

Architect: Sir Christopher Wren
Placement: London, England
Costruction date: 1675 – 1710
Span: 30.7 meters.
Height: 67.33 meters.
Structural Properties: It has 8 vertical ribs. It has two skins (made of brick) on 8 columns.

Photograph 5 : A view of St. Paul Cathedral's dome

Its style is Late Renaissance to Baroque. The Dome is among the largest in the world. It's main structure is of Portland stone from Dorset. St. Paul's, the largest cathedral in England, is Wren's masterpiece. With it, he brought a repertoire of new forms (the dome, for example) and architectural combinations into English architecture.

The central dome is made up of two skins which are on 8 columns. The height of the dome is 67.33 meters. (Dirimtekin, p.28) It has a lantern at the top. Into a regularly sub-divided rectangle, a dome that rests on 8 arches carried by columns has been placed. 4 of these arches also indicate a Latin cross.

One problem, for which Wren reached an interesting solution, was the tremendous weight and thrust of the dome upon the walls of the drum. In the case of St. Peter's in Rome and the Invalides in Paris, a double-columned butress had been employed to relieve the thrust of the dome. With Wren's plan calling for a colonnade about the drum, he devised the idea of a massive iron chain embedded in the large Portland stone around the base of the inner brick cone. (Bishop, 1938, p.56)

3.6 Reichstag

Architect: Sir Norman Foster
Placement: Berlin, Germany
Construction date: 1995 – 1999
Span: 40 meters.

Height: 23.5 meters.
Structural properties: It is constructed of 24 steel ribs (as counted in the photographs). They are bound together by the twin-helical ramp. It has one skin made of steel and laminated glass.

Photograph 6 : A view of Reichstag

Berlin will be the seat of government, the Reichstag will be restored as the parliament building. The English architect Sir Norman Foster won the award at the international competition. But the winning project was not built. This competition was held as if to choose the architect to design the new dome; not to choose the project to be built.

Restoration of the glazed dome will house a visitors' platform and provide natural light and ventilation. The Bonn Government is commited to move to Berlin in 1998-2000 and the building has opened on 19.April.1999.

The dome has only one skin made of steel ribs and supported by the twin-helical steel ramp. The filling of these ribs is only laminated glass and it only covers the dome, it doesn't have any structural property. The dome is carried only by the ribs and supported by the steel ramp.

The diameter of the dome is 40 meters, and the height is 23.5 meters.

People can climb up to the top of the dome by using the twin-helical ramp. By this ramp, movement only in one direction is possible, so you don't hit anybody while climbing up or down. This ramp goes up to the visitors' platform, also supports and carries the dome as well.

A thought was to create an intelligent (smart) building. According to this, the dome which was burned at the 2nd World War and collapsed at 1954 was designed to be a sunlight collector. By using laminated glass, transparency was provided as well as security.

At the center, there's a "light cone" which is made of laminated glass mirrors that has a very good quality of reflecting. By this cone, daylight is transferred into the whole saloon. The dome will also provide a visitors' platform and ventilation.

Photograph 7 : View of the Reichstag at night.

Photograph 8 : Construction of the dome

4 THE COMPARISON OF THE EXAMPLES

The examples examined in this study were constructed at different times, from 27 B.C. till 2000 A.C., in a period of over 2 thousand years. All of these domes are important because they all bring something new to the world architecture. They show the limits of the material by which they are constructed. And they also show that the architects of these domes examined and observed the old buildings of their time very carefully and learned some rules of science. So that they used these rules in the design of their domes and these domes are the significant examples of today.

It is unable to change the laws of nature; so there is a compression which occurs because of the gravitational force. The elements which form a structure transfer the forces and loads on them as compression at the point where they touch each other, towards the earth. This is also the same at the domes where a circular line of stones (or bricks) is constructed a little inside than the circular line under itself. Here in these domes, loads are transferred by the friction at the touching points as compression.

In the beginning, the Romans used a type of concrete to construct the dome of Pantheon in 118-128 A.C. And its span was 44 m. with a coffered structure. At the dome, the friction is increased by the help of the concrete used here. So the dome has a very large span and it still stands for more than 2000 years. The architects of Pantheon knew the forces and science very well and most probably they reached this knowledge by observing the ancient buildings around them.

Later on, in 537 A.C., Anthemios and Isidoros the Younger built the dome of Hagia Sophia with 40 ribs. So, it seems that, this is the first dome in the world which we know, having a frame constructed by ribs; not the dome of Florence Cathedral. Its one diameter was 30.37 m. and the other was 31.87 m. Anthemios and Isidoros knew that they had to construct a higher dome than the old one which collapsed, in order to let the dome stand-up. The reason is that, the material used is so heavy that in lower domes thrust cannot be beared. In order to carry this high thrust, 4 big arches and 2 semi-domes in nort and south support the dome also. And 40 ribs are constructed and this forms the structure of the dome.

In 1420-1436, Brunelleschi constructed the dome of Florence Cathedral, having 8 ribs. Its diameter was 42 m. (from corner to corner). The ribs are supported by beams at three levels. The filling between these ribs and beams is brick which is light in weight. Brunelleschi knew well that ribs and beams carry the main loads, and the filling only covers the dome. So it does not have to be very heavy, it must be light in order to lower the loads carried by the ribs and beams. Brunelleschi learned these rules in his visits he made to the ancient structures and buildings around Europe. So, it is really important and necessary to look at the historical constructions in order to learn what their designers know. Then it would be easier to find the best and the most efficient solution to our problems in construction.

Michelangelo designed a dome of having 41.6 m. of diameter at Saint Peter’s Cathedral between 1546-1591. Although it was designed and constructed after the construction of the dome of Florence Cathedral, its diameter was smaller than that of it with 41.6 m. Here Michelangelo tried construction of double-skin. By this way, again the loads are lowered while you still have the same depth as one skin.

The dome of Saint Paul’s Cathedral was important to have double-skin. Its diameter was 30.7 m. The dome is constructed on a drum. Thus it is carried by the help of this drum, having no supporting structures.

And the dome constructed at the latest time is Reichstag, between 1995-1999. It is constructed of steel which is new for today. It has a diameter of 40 m. The material is steel here and its capasity is used very well. It has only one skin.

All these examples show the limits of the material by which they are constructed; and they show the development at the construction techniques. When the stonework was not enough for enlarging the diameter, the new material brick was used, but with a new construction technology of double-skin. In this the way, the loads were lowered. When it was not enough, ribs were used. And light filling materials were also used. Now today, a new material “steel” is used to cover a span of 40 meters with only one skin. But strangely, the span of the dome of Pantheon is not still equalled! Maybe, it is the only example that will be equalled by difficulty in the future because of the mortar used in the type of concrete. This shows the importance of the material used at the construction of domes.

Hagia Sophia’s diameter was about 31.5 meters (average) by 40 ribs. By the help of 8 ribs and maybe the capacity of the shape “octagon”, Florence Cathedral’s dome diameter is larger than Hagia Sophia’s and it was 42 meters. The old examples were bound together with the walls and the walls helped to carry the loads of the dome also. But today in 2000, the dome can be put on a present building; this is possible with the material “steel” as in Reichstag. That is because it can carry the heavy thrust at the bottom of the dome.

In each example it is seen that the laws of science are being used like:

- Bearing of loads by friction,

- Increasing the friction,
- Supporting the structure by arches, semi-domes, smaller domes in order to stand against the thrust,
- Constructing the heavy domes (which are constructed with stone or brick) higher,
- Trying to construct lighter domes by using lighter materials (e.g. steel), or by using double skins without having no loss of structural load-carrying capasity.

And these are reached by observing the old structures around the world.

We can see this difference and the comparison of these six examples of domes briefly in the table shown in next page.

5 CONCLUSIONS

All the examples examined in this study show the limits of the material by which they are constructed; and they show the development at the construction techniques. When the stonework was not enough for enlarging the diameter, the new material brick was used, but with a new construction technology of double-skin. When it is not enough, ribs are used. And now today, a new material “steel” is used to cover a span of 40 meters with only one skin. But strangely, the span of the dome of Pantheon is not still equalled! Maybe, it is the only example which will be equalled by difficulty in the future because of the mortar used in the type of concrete.

Although the diameter of one-skinned Hagia Sophia had been enlarged by double-skinned St. Paul’s Cathedral; today it is enlarged again with only one-skin at Reichstag with the steel ribs. No matter what the filling is; here in Reichstag it is laminated glass. Although the diameter of the Florence Cathedral is more than that of Reichstag, most probably this is because of the capacity of its shape “octagon”. And maybe it’s because Reichstag Dome was built on a present building; so its diameter was known at the beginning and it could not have been changed. If we take only circular planned domes in consideration, we see that steel is the best material to enlarge the dome diameter.

As a result, in order to enlarge the dome span, we should firstly look at the historical domes, understand how they were built; then think of using steel. This is the only way of development in structural technology.

Table 1: Table of Domes.

	Dome of Pantheon	Dome of Hagia Sophia	Dome of Santa Maria Del Fiore	Dome of Saint Peter’s	Dome of Saint Paul’s Cathedral	Dome of Reichstag
Placement	Rome Italy	Constantinapole, Istanbul Turkey	Florence Italy	Rome Italy	London England	Berlin Germany
Diameter (Span)	44 m. The diameter of the opening at the top is 8.23 m.	30.37 m. (in one direction) 31.87 m. (in the other direction)	42 m.	41.6 m.	30.7 m.	40 m.
Height	Nearly 45 m. (From the drawing)	55.60 m.	About 21 m.	117.6 m. from the floor.	67.33 m.	23.5 m.
Structural Material	A kind of concrete	Stone + Brick	Stone ribs + Brick filling-up	Stone and brick	Brick	Steel
Year of Construction	27 B.C.-first constructed 118-128 A.C. (repaired and changed by Emperor Hadrian)	360 A.C. -first constructed 537-1453-used as a church 1453-1935-used as a mosque 1935- ... -being used as a museum	1296-1436 1420-1436-Construction of the dome.	314-349 A.C. –first constructed 1506-1591 –repair of the cathedral 1546-1591 –construction of the dome.	1675-1710 (constructed)	1995-1999 (the dome was constructed)
Structural Properties	Coffered dome. There are 28 vertical, 5 horizontal coffers.	The first ribbed dome of the world architecture. It has one skin made of stones.	It has 8 vertical ribs stiffened with horizontal beams.	It has 8 vertical ribs.	It has 2 skins (made of bricks) on 8 columns.	Constructed of steel ribs. They are bound together by steel ramp. It has one skin made of steel and laminated glass.

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