Transactions on the Built Environment vol 39 © 1999 WIT Press, www.witpress.com, ISSN 1743-3509

Bramante's design for the dome of St. Peter's Cathedral in Rome. A study using experimental stress analysis techniques

F. Krauss
Aachen University of Technology
Lehrstuhl für Baukonstruktion (Tragwerklehre)
Fakultät für Architektur
Reiffmuseum Schinkelstraße 1, 52056 Aachen

Abstract

Bramante's design for the cupola of St. Peter's Cathedral in Rome was not realised. It can be discussed as to whether or not his design could have actually been constructed. This question was researched in two studies, using planar, (2-dimensional) and spatial, (3-dimensional), models of light chains. The research was also prompted to assist future comprehension of maintenance, service, and repair of the historic domed structures.

1 Introduction

In 1506 the construction of the St. Peter's Cathedral in Rome began, using Bramante's design and under his supervision. Bramante's successors, among others master builders Raffael, Antonio da Sangallo jun., Michelangelo and della Porta, repeatedly modified the design. The cupola was completed in 1593 by della Porta.
Bramante's initial intention was to build the cupola as a 1 to 1 reproduction of the Pantheon Dome, built in the 3^{rd} century. Bramante's design incorporated the dimension of the Pantheon, a hemisphere of 42 m inner diameter, but instead of the 8 m thick exterior walls, Bramante's design contained 4 high pillars with connecting transverse arches. Above these, a drum (tambour) of 80 columns and 8 wall blocks supported the dome.

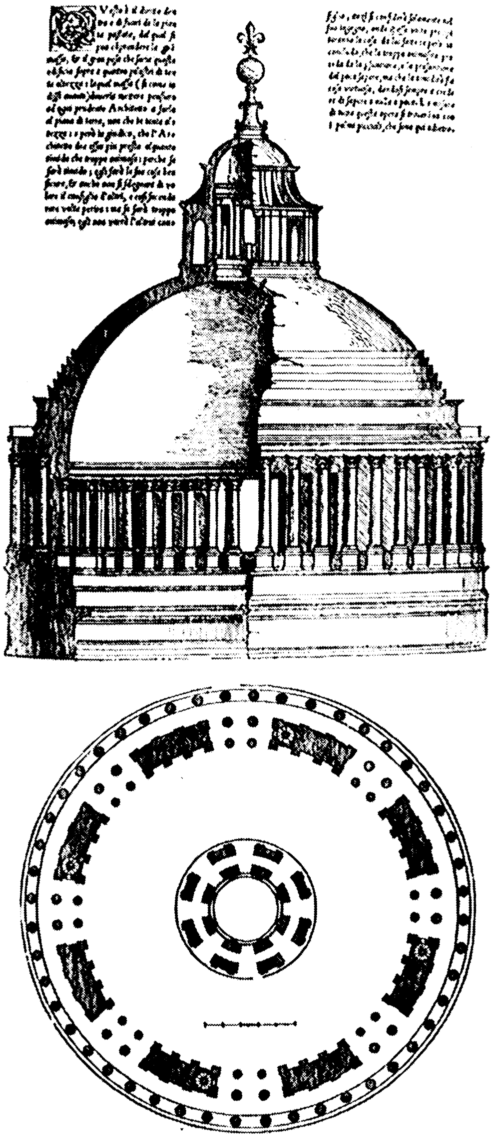

Figure 1: Sertio: Bramante's cupola Section and elevation ground-plan of drum and lantern

Transactions on the Built Environment vol 39 © 1999 WIT Press, www.witpress.com, ISSN 1743-3509

Unlike the Pantheon, Bramante's design also incorporated a lantern. The weight of the lantern, however, would have called for a different form of dome, similar to that of Brunelleschi's cupola in Florenz, or as St. Peter's cupola which was in fact later realised by della Porta.

The fundamental question arising is the credibility of Bramante's design, i.e. could the dome have been erected on the pillars which Bramante had planned and begun to construct?

This question was studied at the Aachen University of Technology, Dep. of Building Structures (RWTH Aachen, Lehrstuhl für Baukonstruktion (Tragwerklehre)).

As previously stated, both a 2D(planar) and a 3D(spatial) study was carried out. Both studies were based on the fact, that the tension line of the chain is the inverse form of the pressure line of the arch. [1] In both studies it was stipulated that the construction is not able to sustain any tension forces and that as one unit, the 4 pillars, the tranverse arches, the drum and the dome must be stable without the assistence of other parts of the cathedral.

2 Two-dimensional (planar) study

Using an inverted photo of Bramante's cross-section plan of the dome (source of Photo: [2]) as reference, a light copper link chain was used to form a model (scale 1 : 50), thus enabling the tension form of the chain to be measured and compared at any stage to Bramante's design.

The chain was loaded at 24 points with the dead weight of both the cupola and the lantern.

In the first steps with the full weight at each point, the chain's form deviated greatly from that of the cupola. i.e. the dome could so not have been built. It would have collapsed. (figure 2)

Subsequently the weights of the dome and lantern were altered using varying weights and types of stone and hollow spaces in different areas of the construction.

This method of using different stones and weights had previously been employed in the construction of the Pantheon-Dome in the 3rd century [3] [4]. We may therefore assume that Bramante was aware of this method. We can not assume, however, that he was aware of the law that the chain line is the inverse form of the arch line. This fact was first mentioned by Robert Hooke (1635-1703).

In the study step by step the dead weight was changed and redistributed to achieve the required chain line to correspond with the design of the dome. At step 36 we found a line running within the inner third of cupola's thickness, the so called core. In the lantern we had assumed ½ material weight, in the upper part of the cupola 2/3 and in the under part of the cupola full dead weight [5]. This load distribution was applied to the following 3D study. (figure 3)

Transactions on the Built Environment vol 39 © 1999 WIT Press, www.witpress.com, ISSN 1743-3509

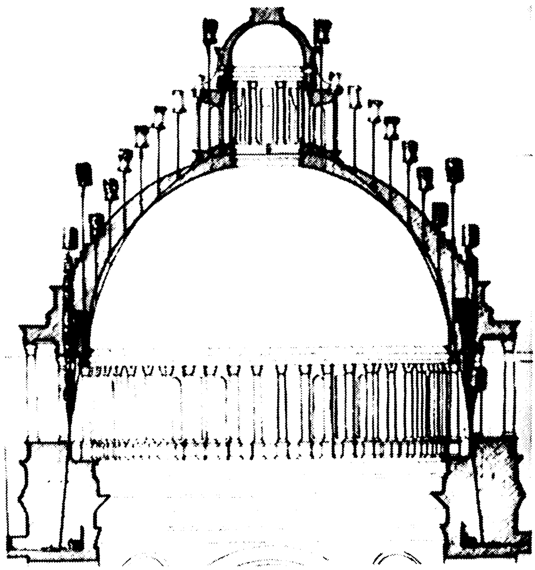

Figure 2: Planar study, step 9

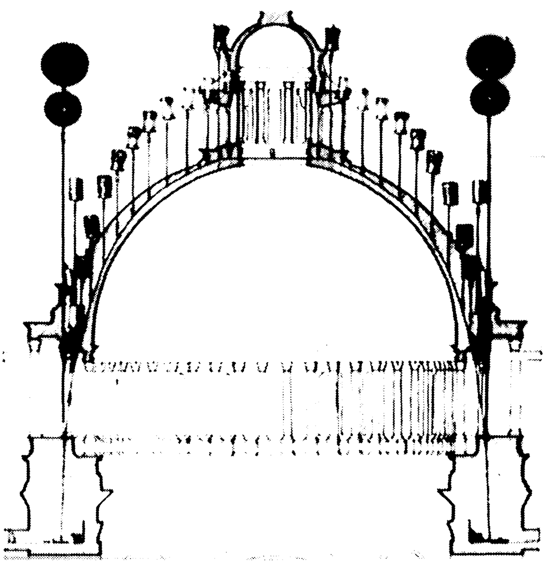

Figure 3: Planar study, step 36

Transactions on the Built Environment vol 39 © 1999 WIT Press, www.witpress.com, ISSN 1743-3509

3 Three dimensional (spatial) study

For the 2 D, planar, model undisplaceable supports for the cupola had been proposed. In reality, however, it is more complicated. The forces may run differently in different directions, i.e. from arch-top to opposite arch-top or from one pillar to its diagonal opposite. (figure 4) This action between dome, arches and pillars can only be analysed actually using a 3 D model.
The cupola part of the model was built with 12 light copper chains hanging in the meridian directions. The eye was formed by a metal ring with 24 holes for the chains.
These meridian chains were supported by stronger chains representing the transverse arches. Four meridian chains running directly to the pillars were taken directly to the pillars' bottom.
The resulting force of the dome, the transverse arches and the dead weight of a pillar is passing the joint on each pillar's base at a point on the diagonal line of the square formed by the four pillars. After some trials this point was assumed as far outside, to have caused the extreme permissible open joint in the pillar's base, i.e. up to the centre line of inertia of the pillar's ground plan.
The dead loads of the dome, the arches and of the pillars were simulated by plastic covered rods of lead. (figure 5)

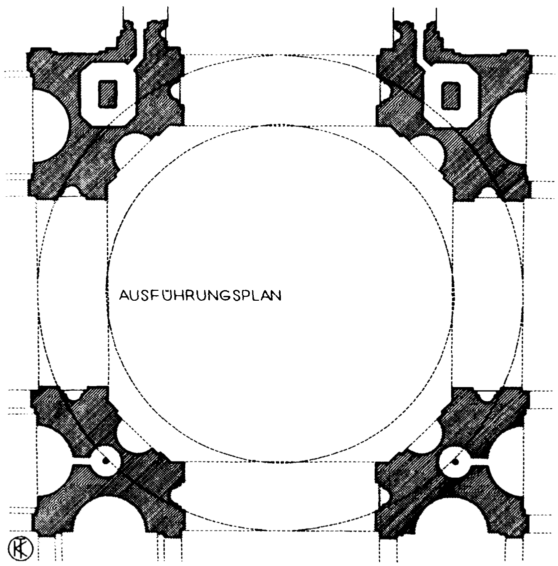

Figure 4: Ground-plan of the pillars

Transactions on the Built Environment vol 39 © 1999 WIT Press, www.witpress.com, ISSN 1743-3509

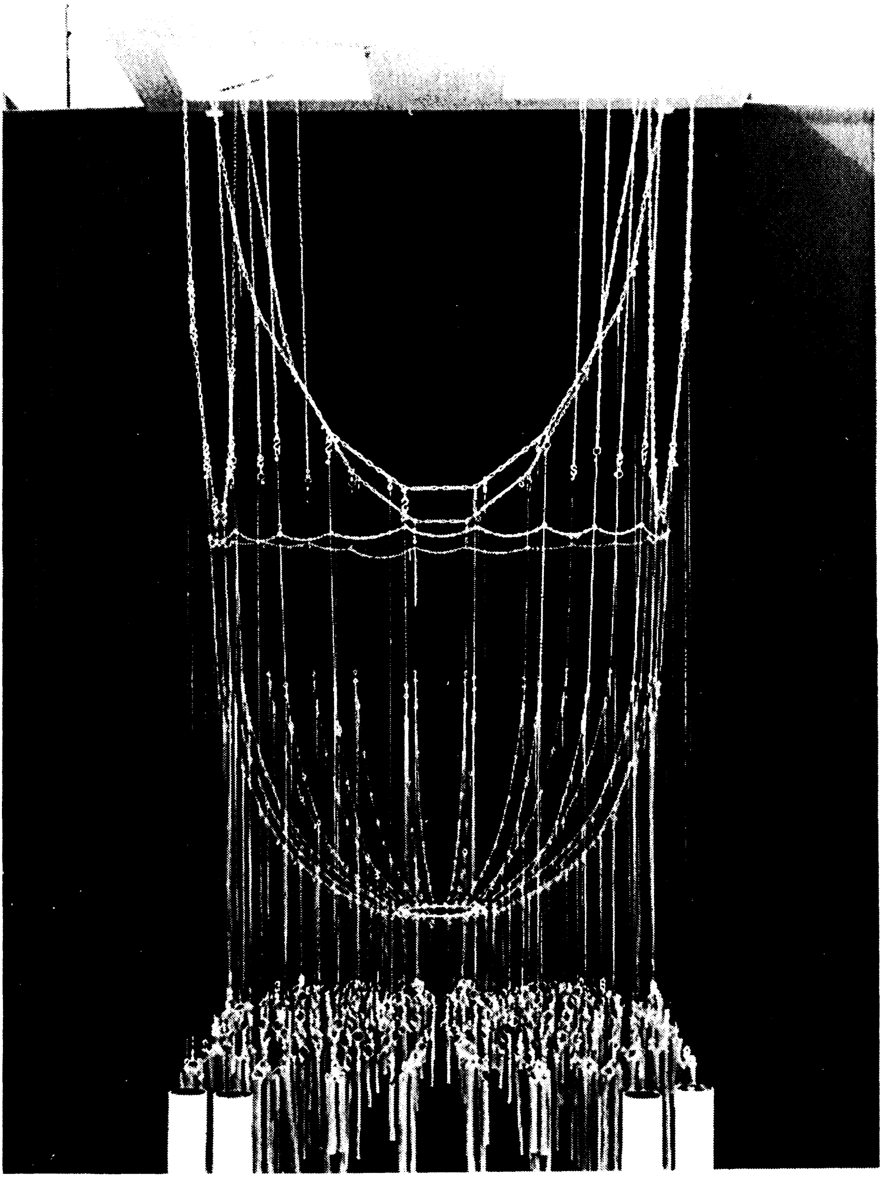

Figure 5: Spatial study, model 1:50

4 Criteria

1. In the two dimensional trial we had found a load distribution that caused a force line running in the inner third of the cupola's thickness, i.e. the core. Even if this were not possible in the three dimensional trial, at each point of the cupola we had to find at least a force line running in the inner two thirds of the thickness.
2. The most vulnerable zone is the drum. It had to be tested whether or not it's columns and wall blocks could sustain the horizontal forces.
3. In the base joints of the four pillars, the force line had to run within the inner zone. This is already guaranteed by the disposal of the model. (see 3,-3D study)

5 Measurements

The measurements, taken by hand and carried over into the designs, can be seen in figure 6. The diameter - measurements were checked:
- at the height of the drum's top
- at the height of the drum's buttom
- in the round-running center-line of gravity of the „big ring", „big-ring" meaning the section of the transverse arches in their zenith, this section running around the whole construction.

The diameter measurements were taken in direction from one arch zenith to the opposite one and diagonally from one pillar to it's opposite. Measurements within the cupola were taken from the 2D study and amended by affinity distortion according to the measurments of the „big ring".

6 Results

The meridian pressure line between opposite arch tops is steeper than the diagonal one from pillar to pillar. At the height of 61 m, (drum's bottom), the difference of the radius shows:

top – top 24,10 m	diagonal 25.15 m	difference 1,05 m

Criterion 1: The dome's pressure line runs in all directions within the inner 2/3 of the construction thickness.

Criterion 2: The stability of the drum is not sufficient. The horizontal component of the force would cause the columns and wall blocks to collapse. It would have been necessary to combine the round columns with the wall blocks to radial plates, as done so by della Porta in the realised construction.

Criterion 3: The pillars are stable.

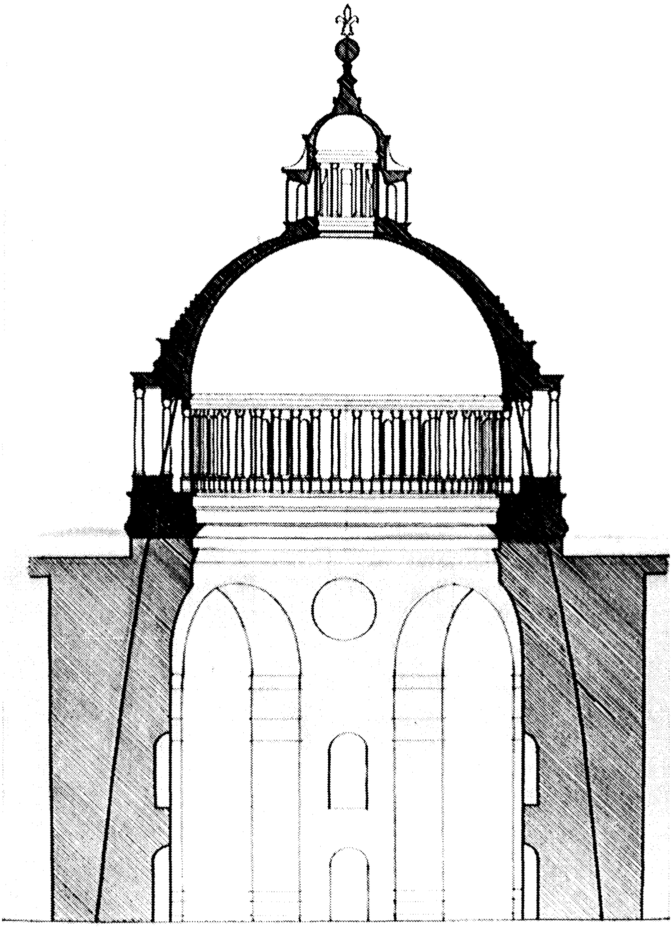

Figure 6: Pressure-line in diagonal section

7 Conclusion

The different behavior of the meridian forces between the arch zeniths and in the diagonals between the pillars, may be an explanation for fractures found in historical domes existing today. This should be considered when repairing these constructions.

8 References

1. Giovanni Poleni: Memorie istoriche della gran cupola del Tempio Vaticano. 1748.
2. Franz Graf Wolff Metternich, Christof Thoenes: Die frühen St.-Peter-Entwürfe 1505-1514. Ernst Wasmuth Verlag, Tübingen 1987.
3. Dierk Thode: Untersuchungen zur Lastabtragung in spätantiken Kuppelbauten. Studien zur Bauforschung 9, Kaldewey-Ges., Darmstadt 1975.
4. Rainer Graeffe: Zur Formgebung von Bögen und Gewölben. In: Architectura, München u. Berlin 1986
5. Franz Krauss, Christof Thoenes: Bramantes Entwurf für die Kuppel von St. Peter. In: Römisches Jahrbuch der Bibliotheca Hertziana. Band 27/28, 1991/92. Ernst Wasmuth Verlag, Tübingen 1993

Source of figures:
Figure 1, 4: [2]
Figure 2, 3, 6: partially taken from [2]
Figure 5: R.M. Nissing