ABSTRACT: The recent investigations on the Brunelleschi’s Cupola of Florentine Cathedral were devoted above all to identify masonry structure and to analyse the construction of the two domes (inner and external shells) in connection with the real building problems found in the works. Exact information on the characteristics of brick masonry has been obtained. Other important data have been supplied by georadar investigations, demonstrating that the inner dome is made of two (intrados and extrados) curtains with interposed a different masonry. These new studies have been put in relation with the surveys of the dome, reaching original conclusions, far from the common mythicized interpretations of Brunelleschi’s Dome. In the construction a fundamental role was played by the executive slowness.

1 INTRODUCTION

Twenty years ago a first book on Santa Maria del Fiore, the Florentine cathedral, was published, as a result of new investigations started from the facade, the aisles and the nave (Rocchi 1988). In some way, the constructional sequence carried on by the builders was followed, as the works in Arnolfian period started just from the facade demolishing part of the naves of Santa Reparata, the ancient cathedral.

Recently a fourth volume of the series has been published and this includes the studies on Brunelleschi’s dome (Rocchi C.d.Y. 2006). These recent investigations were related above all to define the masonry structure and the execution of the two domes (the inner and the outer ones) in relation with the real problems found in the works.

2 THE DURATION OF THE DOME BUILDING PHASES

In the initial segment, including the first corridor, the dome was built in pietraforte (a local sandstone). In April 1422, above this level, the dome was made only of brick masonry and in June 1425 (Saalman 1980) the macigno (another Florentine sandstone) tie of the second corridor was under construction. Presuming that the faces of these eight sided cloister vault were raised nearly uniformly, the execution of this first brick dome segment was completed in about thirty-nine months.

From March 1426 building proceeded above the second corridor; from June 1429 the macigno ties of the third corridor started to be supplied and in July 1433 were all be put in place. Given the fact that the date 1430 has been found scratched on the plaster just below the floor of this passage, 1430 can be assumed
as the year of completion of the second dome segment. So, including the year 1430, the dome portion between the second and third corridors was built in fifty-eight months.

The construction of the upper section, between the third corridor and the lantern, started in July 1433, was concluded by March 1435, as the following year the serraglio (the lantern ring base) was begun. So this final segment was built in twenty-one months.

It has been possible to evaluate the average raise of the wall per month in each of the three dome sections, putting in relation the building period with the height of the built masonry. For the first section of the dome, high 5.50 m and built in 39 months, this average value corresponds to a 14 cm masonry per month; for the second section (12 meters in 58 months) the value is nearly 21 cm per month; in the third section (15 meters in 21 months) 71 cm per month. On this basis, the brick courses laid each month would result about two, three and ten respectively in the three sections.

Limiting the working period to ten months per year, due to weather conditions, the values of dome elevation are nearly the same: respectively 17, 27 and 94 cm masonry per month in the three sections. The results would not be different from the previous ones. In the years 1422–1430 the dome works proceeded very slowly: up to the third corridor the wall was raised less than a brick course per week; on the contrary, a relevant increase is recorded in the upper part built between 1433 and 1435.

It is necessary to consider that above the third corridor the relevant narrowing if the dome reduces the built masonry volume to nearly 1/3 in comparison with the masonry of the second section. However, even considering such a difference, which caused a consequent reduction of the employed masons due to the less space available on the scaffoldings, it is evident the increased speed in the construction of the upper part of the dome.

It could seem contradictory that works proceeded quicker just where the brick beds inclination was greater. However at this level a centring was probably laid resting on a system of beams inserted in openings correspondent to the small passages opened to the inside of the cupola. The openings were then partially walled up to build the present oculi.

3 THE HERRING-BONE APPARATUS

Most of the recorded herring-bone bonds is located between the second and third corridor, where a very irregular laying of the bricks and relevant variation of their inclination are visible.

After the dome intrados survey, the zenith angle of the herring-bone traces has been measured. It has been verified a very wide range of the inclination (from circa 31° to 55°) among the eight faces of the dome and among the herring-bone bonds of the same face, with the prevalent inclination from 36° to 40°. It depends on the different way of laying the bricks, using more or less quantity of mortar in the joints, as an evidence of the unequal way of working of the different teams of masons.

In particular, in the South-East face of the dome much more inclined herring-bone bonds than elsewhere have been recorded. It seems to prove the
The knowledge of the wall apparatus has been deepened thanks to the detachment of plaster parts executed during the restoration works of the wall paintings. The detailed survey drawings (Dalla Negra 2004) and the casts of the masonry prove the irregularity of the herring-bone bricks, laid with continuous and varying rotations on the plane of the dome face, using mortar joints often thick as much as the bricks. The rows of the vertical bricks are discontinuous: somewhere the inclined herring-bone row is interrupted by a number of horizontally disposed bricks, and then it starts again inclined. The interruption of the herring-bone pattern is located both in the middle of the dome faces, and in the corners. In this point there is nearly no wall toothing: nearly all the bricks, unbroken or fragmented, arrive just at the corner. In the few cases where a single brick bridges the faces, it is not a special element but a ordinary brick cut to adapt to the corner; so there is no evidence that special V-shaped bricks have been used to build the corners, at least where the plaster has been detached and the wall apparatus has been visible.

It has to be considered that the stone ties of the third corridor probably determined some interruption of the inclined lines of the herring-bone bricks. The same interruptions should be caused by the correspondent stone ties of the second corridor; but at this level it was impossible to record them because of the absence of wide visible herring-bone bond segments.

Also the extrados of the inner dome has been examined, at least in many parts with no plaster. The same characteristics as the intrados have been found: often there is no continuity in the herring-bone lines, adjoining bricks have different rotations, and thick mortar joints are used.

The removal of part of the tiles, made possible to take a stereo-photogrammetric survey of a meaningful sample of the outer dome extrados. The resulting information on the herring-bone bonds is comparable with that previously acquired: different inclinations, discontinuities, variable thickness of the joints, irregular brick disposition even in short segments of the herring-bone bonds.

The information now available on the herring-bone bonds is insufficient to make a comparison between the wall apparatus of the intrados and the extrados of the same dome portion. The available surveys discontinuous, limited to only few samples and related to parts located on different levels. Nevertheless they appear really meaningful to make some considerations on the herring-bone structure in the whole of the dome. It is interesting the wide variation in the horizontal distance (measured along the brick courses) of two adjacent herring-bone bonds. At the intrados of the inner dome this measure is known in all the parts where the plaster was detached: in the corner between the East and the North-East faces, at the height of about 15 meters above the inner gallery, these distances are cm 95, 100 e 110; in the North and the North-West corner, at the height of 25 meters above the gallery, are
Figure 6. The georadar diagram of the inner dome displays two symmetrical discontinuities (at the intrados and the extrados) in the brick masonry, and a different inner core.

Figure 7. The drawing represents the wall structure of the Cu-pola, basing on georadar investigations. The inner dome is made by two outer layers where herring-bone bonds are present, and by an inner core where bricks are probably laid on simple curved beds (corde blande) (Rocchi C.d.Y. 2006).

cm 45, 60, 90; in the North and the North-East corner, at the height of 27 meters above the gallery, are cm 45, 50, 60; in the North face, at the height of 29 meters, the greatest variability has been recorded, as the herring bones are distant cm 10, 15, 25, 30, 45, 50, 55. At the extrados, above the third corridor, at the height of the second horizontal arch (circa 26 meters above the gallery) the distances among the herring-bone bonds vary from 85 to 110 cm, so they are much greater than the ones recorded on the intrados at about the same level.

Also the wall apparatus recorded on the outer shell has great variability (in the same sub-horizontal brick course two adjacent herring-bone bonds may be divided by half brick or many bricks) and discontinuity in the herring-bone lines (short segments made by few bricks, sudden changes in their inclination, splitting of herring-bone bonds, ...).

In the case of herring-bone bond crossing the dome masonry through its total thickness following a unique curve centre, very different dimensional data should be expected: two adjacent herring-bone bonds distant 60 cm on the intrados of the inner dome, on its extrados the distance should be 65 cm and on the outer dome respectively 68 and 70 cm, distances only limitedly greater than the ones recorded on the inner intrados. The dimensional heterogeneity that has been recorded in the building is totally different, even if the relevant slowness of the works should have made easy to control the geometry of the herring-bone lines.

For these reasons it seems improbable that the herring-bone bonds cross radially the whole of the dome following a unique alignment to the centre. It is more reasonable that the intrados and extrados herring-bone bonds of the inner dome are not continuous, but belonging to two different masonry layers. The existence of two distinct layers, the inner and the outer parts of the wall, has been proved by georadar investigations, and can also be supported by considerations relating to the building technique used in the works. Moreover, it seems proved that the herring-bone bonds of outer dome are totally independent from those of the inner dome.

4 THE BRICK MASONRY FACING THE RIBS AND OCULI PASSAGES

In the space between the two shells, at each corridor level, very refined brick masonry can be observed on the walls of both the passages through the ribs and to the oculi opening inside the cupola. Here the bricks, homogeneous in size, are laid with regular and very thin joints and likewise the herring-bone bonds are very accurate.

Examining in detail the bricks of the passages, some misleading wall patterns can be detected: some bricks apparently part of a herring-bone row are illusory, as a single brick, laid using its largest face outwards, has been carved in order to simulate the thin sides of four different bricks. Other special brick elements of the passages are used to form the vertical corner of the abutments in masonries laid on inclined beds.

The georadar investigations carried on in the corridors revealed a difference between the masonry of the outer part of the wall and of its internal nucleus. So it can be affirmed that, apart from the herring-bone bonds, on the wide faces of the dome a nearly usual masonry (thick joints, irregular bricks, somehow irregular laying of the elements, ...) was executed, while the very refined brick facing was limited to the passage walls; hence some diffused misunderstandings on the real wall quality, supposing that the whole dome
brick masonry was represented by that one of the passages. On the contrary, it seems even possible that the passage facing was placed during further restoration works.

Next to the *serraglio* the situation is the same: the intrados masonry of the inner dome is very confusing, with irregular and segmented herring-bone bonds, whilst in the passage at the base of the *serraglio* the visible brick masonry is as accurate and refined as the one just examined in the lower passages. So this kind of masonry appears once more to be only a facing, and this is also confirmed by the outer face of the same *serraglio* wall, visible at the top of the space between the two domes: under the plaster a usual thick joint masonry, the same found everywhere but in the passages, emerges.

5 THE ARCH CONNECTIONS BETWEEN THE RIBS

It is meaningful the superimposition of the detailed survey of the just described extrados masonry of the outer shell on the measured drawing of the sub-horizontal cantilever-arches located on the intrados between the corner and intermediate ribs.

Above all it has to be underlined the peculiarity of their masonry structure: in the lower part headers are laid to form a segmental arch thick one brick, while above this arch some courses of stretchers follow the brick laying of the ribs and of the outer dome. The bricks of these cantilever-arches, however laid, are connected to the ribs and the outer shell; those ones above the segmental arch are laid together with the bricks of the shell (at least at the lower levels, as proved by the presence of herring-bone bonds in some of them). The segmental arches continue beyond the extrados up to the external surface of the shell, as documented by the superimposition of the upper cantilever-arches and the extrados survey. The plaster absence in the extrados of the outer dome gives the opportunity to identify nearly the total straight-arch of a cantilever, and partially a second straight-arch placed at the same level on the opposite side.
The reducing cross section of those arches, typical of cantilevers, and the consequent wider section in correspondence of the corner ribs, transfers on the latter ones most of the stresses. Furthermore, it can be imagined that the thickening of the cantilever-arches at the corner rib could allow to cross them diagonally and to make possible the laying of a continuous iron tie, shaped as a multi-sided polygon and so much more effective.

6 THE CORDE BLANDE

The corde blande, the curved laying of brick courses, progressively increasing from the base to the top of the dome, are well documented by the survey of the dome extrados. This special laying system was caused by works needs, as it was necessary to give continuity to the differently inclined brick beds in the two corner ribs and in the central part of a single face. The consequent curved laying of the bricks was got and made progressive not only with varied thickness of the mortar joints, but introducing discontinuities in the herring-bone row and in the sub-horizontal masonry between them as well as.

A further aspect has to be kept in mind. At the intrados the dome corner, measured from the gallery to the base of the lantern oculus, is only a little more than 39 meters, while at the middle of a face the corresponding length is 3 meters shorter. In the works, this different length (nearly 10%) required a greater number of brick courses in the corners, and this necessarily caused further irregularities.

During the construction these work adjustments were made easier by the masonry discontinuity given by the herring-bone bonds, that caused the included parts of masonry to be independent the one from the other. For this reason such adaptations are nowadays nearly invisible when examining the wall.

The marble mouldings at the external base of the lantern are apparently curved, and so they seem to reply the curved line of the corde blande. In fact, the masonry which supports them is straight and the curved line of the mouldings is caused by the brick masonry settling, which was not followed by a correspondent subsidence of the marble covering of the corner ribs. Here the joints between the elements are extremely reduced and so subject to only limited dimensional reductions for plastic deformation or shrinkage. On the contrary, these phenomena are relevant in all the walls of the dome, built with thick joint masonry (Petrini 1989).

7 IRON BARS EMPLOY

In the masonry of each aisle vault and of each nave transverse arch of Santa Maria del Fiore iron ties were inserted. This can be considered the start point of a new construction technique (iron reinforced brick vaults) carried on and increased in the construction of the Cupola of Florentine cathedral.

Many iron elements are visible at the intrados of the dome: eyes, different in size and located on the faces at regular levels, or metal straps at the corners. Up to
now their presence has been put in relation with the necessity to fasten intrados suspended scaffolding, or to fix corner wooden centring (Dalla Negra 1995). The same works praxis has been proved to be previously utilized in the construction of aisles and nave of the church, where iron elements used to fix centerings have been found in transverse arches and diagonal ribs of the nave vaults.

Some iron bars inserted in the dome masonry are visible. They could be part of a more extended tying system, which probably has played a relevant role in building static condition.

At the dome spring, just above the inner gallery, where should be located the first stone tie, many eyed iron bars stick out of masonry among stone cantilevers. The bars probably cross nearly the whole of the dome masonry.

Detailed observation has been made at the level of the third corridor in the space between the shells at the North-Eastern side of the dome. Here many iron elements are visible: a radial bar laid aside a central rib; two transversal bars inserted at the intrados of stone ties; a third bar, protruding from the masonry of the inner dome in coincidence of its set back. In this last case, the bar position, almost parallel to dome extrados, indicates that probably this element is the anchor of an iron tie crossing radially the main shell.

Broader investigations to find out iron presence in the dome were carried on by metal-detectors by Italian Army (Compagnia Genio Guastatori della Brigata Motorizzata “Friuli”). Exterior wall stripes and floors were examined at the level of the three corridors. Georadar investigations made later on the inner dome revealed signs, probably related to the presence of iron bars.

Basing on these investigations, it comes out that the builders kept in mind the different behaviour of the two shells, placing reinforcing iron bars mainly in the corridors. In any case it has been ascertained the conspicuous use of radial iron bars in the stone masonries at the dome spring. Here the presence of large stone elements could have required a widespread use of iron cramps, unnecessary in brick masonry.

The late introduction of the cantilever-arches, starting from the second corridor, probably suggested also the usage of almost continuous perimetral iron bars. This kind of hooping, present in a more recognizable form at this level, seems absent above the third corridor.

Figure 13. Survey of the extrados summit of the outer North-Eastern shell. The projection on the outer surface of inner ribs and canti-lever-arches points out the exact coincidence between the intrados arch of the latter and the vertical bricks of the survey. The herring-bone bonds, though irregular, also go on intermediate ribs.
The use of metallic connections along the rib corners is probably a consequence of the difficult toothing of ribs and herring-bone masonry of the dome. Anyway all that proves, even if in outstanding structures as the dome and nave of Santa Maria del Fiore, the widespread usage of iron reinforcements in Medieval and Early-Renaissance buildings.

REFERENCES


