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THE SECRET OF THE CUPOLA OF FLORENCE'S DUOMO[1]

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It may seem strange to include the word 'secret', which suggests mysterious adventures, in the title of a scholarly conference, but apart from the fact that secrets are very much a part of scholarship, in this case the term is valid. Unknown to this day is the way in which the mechanical structure of architecture's revolutionary Florentine Cupola was worked out.

Detailed architectural notebooks documented the preparatory processes and the actual stages of construction of the Cupola. At the beginning of the XVth century, only the covering of the crossing, a 42 m diameter octagonal space, remained unsolved, on the otherwise nearly completed building that had been begun in 1296. The task of vaulting the space seemed impossible, for however experienced the Gothic building's master-craftsmen were, they had never constructed a large size cupola. The only known example, the ancient Roman Pantheon, built 1300 years earlier, has doubtless one of the most magnificent interiors in the history of architecture, but the semicircular cupola, placed on a circular drum, does not have the look of imposing mass from the outside.

According to a project accepted in 1367, the Cupola of Florence's Duomo was to be constructed with high groined vaults. This type of vaulting necessitated a support frame or scaffold that was to remain in place until the facing arches met, and could support each other.

Besides the enormous space of the open octagon, what made the task even more difficult was the fact that the arches began at the height of 55 meters, whose scaffolding — according to approximate estimates — would require huge amounts of supporting materials, great length of time to prepare, and enormous expenditure.

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In vain did the Cupola Building Workshop seek the advice of expert carpenters, and so in the summer of 1418 it announced a competition for the solution of the problem of the Cupola. The prize winner was to receive the huge amount of 200 gold florins. The relative value of the amount can be judged from the fact that the salary of the subsequent construction foremen was 3 gold florins per month.

The majority of the 17 contestants were carpenters or stonemasons, but the winners were two goldsmiths. One of them, LORENZO GHIBERTI, was a sculptor with an established reputation as an artist; the other was FILIPPO BRUNELLESCHI, who had as yet not produced any known significant work, but who had immersed himself in the study of architecture, with the detailed measurement and examination of ancient buildings and their structural principles. It was he then who formulated the 12-stage program of clear and concise instructions for the shape, size, and structure of the cupola, the necessary building materials and procedures to follow. It is obvious in the last stage that the project was to be carried out without scaffolding.

This daring plan aroused general doubts right from the start, and added to the growing opposition, fuelled by those who could not understand, or were simply jealous of the brilliant plan advanced by the artist.

Notwithstanding, finally in the summer of 1420 the plan was accepted and the construction was begun under a tight working schedule. An average of 50 workmen were employed on the site, while many more labored elsewhere, preparing the materials and transporting them. Only extraordinary circumstances interrupted the superbly organized workshop's schedule that BRUNELLESCHI directed: for example the heavy snowfall in 1423, and in 1429–30, the war against Lucca. Sixteen years later, in the summer of 1436, the last stone of the vault's closing ring, weighing 700 kilograms, was put into place, and the matchless masterpiece was born.

It is seemingly easy to write all this down today, and to recount it, but to actually see it through, over 16 years' time, and to constantly coordinate all the complex phases of production, to solve the day-to- day problems, all the while struggling against the constant petty objections — only an extraordinarily gifted person, a genius, was able to handle the task. It is a reassuring fact to know that BRUNELLESCHI could proudly watch the rise of the cupola, and that perhaps he forgot all the hardships upon seeing the project completed.

The unbelievably daring construction method naturally fascinated all the architects. The younger ANTONIO DA SANGALLO made structural plan drawings of the cupola in the first half of the XVIth century, and inscribed these as depicting 'brick vaulting construction, without scaffolding'.

The first authentic diagram appeared in the work of GIOVANNI BATTISTA NELLI in 1688. The exact and attractively drawn pictures of the exterior portions were copied as engravings in the XVIIIth century, and were used later as the bases of much of the subsequent research. The one great defect of these is that the clearly visible brickwork is not shown. Two hundred years later, however, Josef DURM attempted to depict largely those portions and their structural mechanism, which are not visible, for he postulated that it was here that the secret of the unsupported construction lay.

Numerous surveys and diagrams have been made since, without significant differences in the measurements. In order to understand the structure, the following data are necessary: The octagon is ca. 42 meters wide, and its diameter ca. 45 meters. Of the two shells, the interior one bears the weight, but it is rather thin, relative to its height of ca. 33 meters measuring 2.22 m at the base, and 2.0 at the top. The exterior shell does not even measure 1.0 at its springing, and only 40 cm at the top. The intervening space swells to almost double its size, from 1.30 meters to 2.60 meters. The increasing space and the structural interpenetrations determined the planning of the staircase leading to the lantern; on the uppermost section, for example, they carved the steps out of the thickness of the interior shell. Three ambulatories were constructed for horizontal access: the first follows the point at which the two shells spring, the second is located about 9 meters higher, and the third some 11.5 meters above that. Decisively important for the structure are the corner ribs holding the two shells together, but integral parts of the framework are the pairs of upward-arching ribs that spring from the eight sides of the vault, as well as the nine interconnecting horizontal bands which are laid out from bottom to top. The entire framework therefore is composed of 24 upward-arching and 144 horizontal ribs, all of which organically interlock with the intermediate walls. This is the key factor in the construction process. The stability of the structure is further established by the stone and wood annular ribs, which are laid out in a total of four succeeding tiers, from the level of the root of the spring, to the closing at the top. Openings in the structural elements mark the placement of the ambulatories and stairs. According to the plans of 1420, annular rings made of iron rods were also to be used for the stability of the structure. In 1977 an attempt was made to locate these with magnetic devices. Although a continuous iron ring was not located, the placement of numerous shorter and longer, unconnected, horizontal and vertical isolated iron rods were found. Detailed analysis could certainly discover the reason why the longer horizontal rods are to be found mainly near the interior surface of the ribs.

The multiple reinforcement of the rib structure does not in itself warrant the possibility of construction without scaffolding. It is generally accepted that BRUNELLESCHI's revolutionary discovery lay in the creation of a masonry construction assured the progressive stabilizing and balancing of the elements of weight and mass. The bricks are not laid in even horizontal bands stretching between the corner ribs, but in slightly tilted, festoon-like bands. Within this regularly laid fabric, and worked in a herringbone pattern, are ribs that spiral from right to left, beginning at the height of the second ambulatory, that is, at about 9 meters from the drum, and that are ca. 1.16 meters apart. It is this masonry technique, together with the rib structure, that somehow ensured the necessary stability of the construction in all the cross-sections, and made the scaffolding unnecessary.

Over 550 years have passed since the completion of the cupola, and although there has been no major serious damage, incidental damages have been noted. Already in 1492, lightning struck the lantern that had been completed in 1471, and this happened repeatedly in the XVIth century. In January 1601 the most serious injury to date occurred that affected the entire cupola on which fissures began appearing in 1639. These grew to such width by the end of the XVIIth century that an examining committee recommended the laying of iron chains for reinforcement. This was never carried out, however, but several decades later the Cupola was again thoroughly examined. It was again decided to lay the iron chains, but once more this was not realized. This is the time during which the recently discovered series of measurements were carried out by the renowned astronomer LEONARDO XIMENES in 1757. In summarizing his research, he precisely described thirteen cracks, and ascertained that the Cathedral together with the Campanile, tilt slightly southward, toward the Arno.

Thereafter, the most recent examinations were not begun until 1934, when the 500th anniversary of the Cupola was to be celebrated. Participating in the work of the committee was PIER LUIGI NERVI (1891–1979). Measurements of the fissures were continuously taken over a period of several years, which determined that they were caused by changes in temperature. During the Second World War the research work was halted, and resumed with accelerated tempo in the 1970's. This was precipitated by the fact that several sections of the fresco in the Cupola had fallen down. (The fresco, depicting the Last Judgement, was begun by GIORGIO VASARI in 1572, and completed by FEDERICO ZUCCARI in 1579). A special commission was formed in 1975 for the thorough examination of the entire Cathedral structure. The chairman, SALVATORE DI PASQUALE, professor of structural engineering of the Department of Architecture of the University of Florence, reported on the proceedings and results in an international meeting in 1983. The commission determined that the fissures occurred during the initial construction, and that they had grown gradually, according to circumstances. The stability of the structure is not threatened, however, because the necessary reinforcements can be carried out upon the slightest indication of the controlling device mechanisms. Professor DI PASQUALE is one of those scientists who wish to support with new research the traditionally held notion according to which the interaction of horizontal ribs and the herringbone masonry brickwork ribs of the octagon transforms the vaulting under construction into a rotational body . According to this, the scaffolding was unnecessary because the hoop stresses generated self-sustaining activity in each stage of the vaulting.

The results of the research did not entirely prove supportive, and the opponent's opinions were also voiced. Of special note is the theory that BRUNELLESCHI approached his task in a much more scientific way than has been generally assumed to date, and the result of his calculations is the dynamic interplay of the corner ribs and masonry, a cause–effect relationship which brings about the constant stability of the structure. Opponents of the theory body rotation of cite mainly the fact that to date no one has been able to locate the exact placement of the herringbone brick ribs in the structural mass as a whole.

A brief reference to the different opinions of the experts is enough to demonstrate that the secret of the structure is still unsolved. The examination of the cracks must proceed, however, and every new examination may bring us closer to the discovery of the play of forces.

An extraordinary proposal was submitted by five Italian architects, and in 1987 they were already able to report on the results, at an international meeting. They completed the most up-to-date analyses, measuring for example the structural and dynamic distribution of weight, the vibrations caused by traffic, and the drafts of wind, as well as artificially caused vibrations, with the help of a network of automatic sensors. The examination was aimed mainly at the cracks permeating the thickness of the entire structure, but extended also to the irregularities of the drum and the four supporting pillars as well.

After summarizing the results, they intend to create the mathematical model according to which the stability of the structure can be perfectly achieved. We can be reassured of the fact that the Cupola will keep researchers occupied for some time to come. The instruments used will obviously become more and more sophisticated, but almost as important, beyond the necessary gaining of practical experience, will be the repeated awakening of the basic sense of pure theoretical curiosity which has so often spawned new knowledge. Men of the Renaissance were also driven by curiosity to constant experimentation and research. The incomparable Cupola must also have been built as a result of the spirit of experimentation and discovery. We hope that it will proclaim for many centuries to come the triumph of architectural knowledge and imagination, and that someday someone will come along, who will solve the mystery contained in it for over 550 years.