Building Brunelleschi’s Dome: A Practical Methodology Verified by Experiment
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Figure 1 Filippo Brunelleschi, Dome of Santa Maria del Fiore, Florence, 1420–36 (authors’ photo)
Building Brunelleschi’s Dome
A Practical Methodology Verified by Experiment

The octagonal dome of Santa Maria del Fiore in Florence is a stupendous achievement of early Renaissance architecture, not only on account of its great span and height but also because of the astonishing fact that it was built entirely as a self-supporting structure.1 It is one of the most studied historic structures in the world and has inspired endless fascination among those who have sought to discover how its builder, Filippo Brunelleschi, managed to achieve what he did (Figure 1). This has been an enduring quest because he left no models or drawings—not even a sketch—to indicate his construction methods. He probably kept the essential details to himself.

Much lies hidden and inaccessible within the dome, making it difficult to infer the precise details of its structure, let alone how Brunelleschi went about building it. The records of the Opera del Duomo (Cathedral Building Committee) include the written specifications of 1420, together with two later amendments, all of which were probably drafted by Brunelleschi.2 While the dome as built conforms very closely to these documents, they provide little insight into the building methodology.

The 1970s and early 1980s saw a marked development in scholarship on the dome, most notably in the observations and ideas presented variously by Rowland Mainstone, Salvatore di Pasquale, Paolo Rossi, and Howard Saalman.3 Their work is the foundation of today’s theoretical understanding of how the dome may have been built, and it commands widespread acceptance in academic circles. In 1970 Rowland Mainstone gave a good overview of the background leading up to the building of the dome and discussed the details of its specifications.4 In a 1977 paper he developed the idea that Brunelleschi set out “to build the dome as if it was a circular one in spite of its actual octagonal form.”5 He hypothesized that Brunelleschi had found a way to construct an octagonal vault as though it were a round dome. Theoretically, this would allow the octagonal form to be constructed as a self-supporting structure without full centering, provided it contains “within its thickness at every stage of construction similar continuous rings to those of the true circular dome.”6

This conception necessarily requires that the mortar beds assume the conical form found in a true circular dome, in which successively higher beds are increasingly inclined toward the central axis. The hypothesis is that each successive mortar bed is defined by a section of a cone (Figure 2). Each cone shares a common vertical axis, which coincides with the central vertical axis of the dome, and the vertex points downward.7 Where each theoretical cone intersects the octagonal shape of the rising vault, a sagging line of conical form is produced. That is, the theory proposes that the dome was built as a series of horizontal conical sections, becoming ever steeper as the dome rises. The mortar beds...
become ever more curved with the rising segments of the dome. Salvatore di Pasquale confirmed the presence of such curved brick beds in 1977, when he measured large areas of the exterior of the outer dome, which was stripped bare of its tiles. Giovanni Fanelli, however, has recently challenged the concept of circular rings within the thickness of the octagonal shell of the dome, which he considers “to be both misleading and unnecessary for a correct interpretation.” Instead, while apparently adhering to a circumferential construction methodology, he ascribes the stability of the dome during construction to the completion of each successive octagonal ring, so that all eight segments lean against and support one another.

Mainstone’s analysis was most seriously challenged in the early 1980s by Paolo Rossi. He objected to the circular dome concept and to its dependence on the contrivance (deus ex machina) of a notional circular dome only 0.44 meters thick (3/4 braccia, 1 braccio = 0.584 meters), contained within and carrying the weight of an octagonal dome that was 2.2 meters thick (3½ braccia), so that 80 percent of the dome was dead weight (peso morto). He further objected to the analysis because it gave “neither importance nor a particular functional role to the main corner ribs, and, in short, does not consider the dome as an integrated structure and therefore essential in all its parts.” Rossi placed paramount importance on the herringbone bricks and in particular on their self-supporting role, which, he believed, permitted construction of the octagonal dome without the use of full centering.

We find Rossi’s main objections well founded and do not accept that Brunelleschi set out to build the dome as though it were circular, as is generally held, nor do we accept that he intended to build a circular dome inside an octagonal form. Theoretical models are of assistance in understanding the idealized geometric structure of the dome’s construction, but they are of very limited use in explaining how Brunelleschi faced and overcame the practical challenges in the actual construction of the dome, which is the key purpose of this paper. This means that it is necessary to understand how Brunelleschi went about building it, brick by brick, with the tools and means available at the time. This is quintessentially a practical matter, not a theoretical one. He was a brilliantly talented man who warned that one is easily misled by theory when one does not have to subject ideas to a practical test.

We therefore take leave of the ongoing theoretical debate and begin afresh; the reasons for doing so will become evident. We shall argue that practical considerations made it impossible for Brunelleschi to build the dome in the manner described by Mainstone, and that these same practical considerations lead inevitably to the conclusion that the dome could only have been built using a radial methodology. By this is meant a method employing a system of radial cords that intersects the central axis and is attached to a fixed reference frame. This method enables the position, orientation, and inclination of every brick comprising the dome to be determined during construction. It also circumvents the practical difficulties associated with constructing all eight sides together as if in a circular manner, whereby each course of brickwork is completed around the octagonal ring before commencing the next. Instead, each of the eight segments or webs of the dome can be built largely independently of the others, while facilitating adjacent segments to be joined seamlessly as construction proceeds. Although it can never be proven that Brunelleschi used this method, the large-scale practical experiment conducted by Massimo Ricci (our coauthor) shows that Brunelleschi could have used this radial method, and we shall demonstrate that he probably used a very similar technique.

**Building Brunelleschi’s Dome**

Construction of the one-fifth scale model began in March 1989 and continued on and off until 2007, taking longer than Brunelleschi took to build the dome. The model is a very substantial structure, built entirely in terracotta brick made to scale, the whole measuring some 11 meters across at its base and weighing hundreds of tons. It was built without the aid of full centering and employed only the methods and means available to Brunelleschi. It incorporated everything that was then known about the dome’s construction, including the herringbone brick pattern and the curved mortar beds. The public authorities granted permission to...
build the model in Parco dell’Anconella on the south bank of the Arno in Florence’s eastern suburbs, where the semi-completed open dome stands today (Figure 3). The intention in building the model was to demonstrate the practicality of a radial methodology that Massimo Ricci had proposed earlier as a theoretical solution. What was not realized at the time was that this undertaking would lead to revelations and discoveries that appear to link the radial methodology used to build the model and the actual methodology used by Brunelleschi.

The main difficulty Brunelleschi faced was how to construct safely a pointed dome of approximately 45 meters internal diameter—beginning 55 meters above the ground—on top of an octagonal drum whose walls were 4.25 meters thick. Everyone was astonished when he proposed to build it as a self-supporting structure from start to finish, without full centering and all its associated scaffolding. He proposed building two concentric octagonal shells with a walkway and stairs in between. The two shells were to be tied together and made rigid by 24 ribs: eight major ribs—one rising from each corner of the octagonal base, and 16 minor ribs—two rising inside each segment of the octagon. All 24 ribs were to converge toward the center with the rising dome.16

Brunelleschi was awarded the commission and began work in August 1420. He brought the dome successfully to completion in 1436 without apparently ever disclosing his method of construction. It is estimated that some four million bricks were used and that the dome weighs more than 25,000 tons.17

This exploration of how Brunelleschi built the dome comprises four interrelated topics. First, a step-by-step account is given of the methods used to build the model. For the sake of clear communication these methods are often described in the context of the full-scale dome and on the assumption that they were used by Brunelleschi. Second, the difficulties experienced in building the model are shown to correspond to the challenges Brunelleschi is likely to have faced. Third, it is demonstrated that the construction principles applied to the model could have been used by Brunelleschi. Fourth, physical and documentary evidence is cited to show that the construction principles and methodology used for the model could be the same as, or very similar to, those employed by Brunelleschi.

Throughout this paper, “model” always refers to Ricci’s 1989–2007 model, and “dome” always refers to Brunelleschi’s original. Having first explained their meanings, Italian terms are retained for centina, quinto acuto, spinapesce, corda bland, and gualandrino. The discussion deals with the following aspects of the model’s construction:18

1. The platform base: how and why the main working platform was built to serve a dual role.
2. The axes of the dome: determining an operative center and axis corresponding to each pair of symmetrically opposite segments of the octagonal dome.
3. The internal corner profiles: a practical method of fixing the “pointed-fifth” profile at each corner for all stages of the work.
4. The ribs of the dome: how the location, width, and thickness of each major and minor rib was determined and controlled.

5. The geometry of the dome walls: a practical method for defining and building the dome’s surface between corners.

6. The function of herringbone brickwork: how the herringbone lines were determined and how they governed where every brick in the dome was laid.

7. The “slack-line” mortar beds: how the curved mortar beds are the natural result of the dome’s octagonal shape in combination with the radial construction method.

8. The curvature of the dome—how deviations from the dome’s desired curvature were identified and corrected during its construction.

The Platform Base

Inside the dome, at the level of its upper gallery, is a series of large square putlog holes in the walls at the springing point of the cupola. Each hole is 0.584 meters (1 braccio) on each side, and there are six of them on each of the eight sides (Figure 4). The lower face of these holes is level with the stone floor of the gallery, and all forty-eight thus share the same horizontal plane. This degree of precision is extraordinary if these putlog holes were only used by Brunelleschi to secure the main working platform around the inside of the dome. The question that arises is why Brunelleschi would go to such trouble and expense to make these forty-eight holes so carefully if their only purpose was to support a simple deck for the workers. Anyone with practical site experience would realize that this degree of precision could be justified only if the platform was required to do much more. Brunelleschi was hardly a spendthrift, still less was the Opera.

The platform was required to serve two important functions. First, it had to be strong enough to bear—over the many years of the dome’s construction—the weight of heavy blocks of stone and hoisting machines, supplies of bricks and mortar, and workmen. Second, it had to be built as a precise and stable structure so it could also serve as a fixed reference plane when taking measurements to build the dome.

The work platform was supported on thick wooden beams cantilevered from each side of the octagon (Figure 5). To provide for this, the lowest 3 meters or so (5 1/4 braccia) of the dome walls were built as a solid sandstone structure, taking care to leave six square putlog holes on each face of the otherwise solid shell. Each hole was about 2.3 meters deep and into them were fitted long precut chestnut beams, which projected as much as 10 meters into the central void. These huge beams were almost certainly supported from below by struts set at an angle. Although the surviving records of the Opera are unclear on this point, the forty-eight beams may have been purchased piecemeal over a period, probably from nearby Pistoia. The weight of the solid masonry walls was required to counterbalance the expected load on the cantilevered platform. This explains why Brunelleschi had to build this initial section of the walls as a solid masonry structure; it was not merely to serve as the foundation for the cupola. When the chestnut beams were securely fitted, the working platform was laid around the whole internal perimeter.

The Axes of the Dome

The base octagon at the springing point of the dome is not perfectly regular, the difference between the longest and shortest sides being 0.57 meters. If he had not already known about it, Brunelleschi must quickly have discovered the irregularity when he established the intersection of the four corner diagonals across the void (Figure 6). This meant that a single center and axis could not be determined for the base-octagon. But it was nevertheless essential to have some such center point if the dome was to be built.

Each pair of adjacent diagonals intersects at a unique center, producing four operative centers for the dome (Figure 7). Each center defines a vertical axis, which is shared by two opposing sides of the irregular octagon, and each center is independent of the others from a constructive viewpoint. The vertical axes through each of these four centers could serve as the references for construction on the corresponding paired faces. For each diagonal, Brunelleschi appears to have fitted a 45-meter length of light iron chain across the void between diagonally opposite corners. (The chains may have...
Figure 5 Main working platform for the dome (authors' drawing)

Figure 6 Irregular octagonal base (authors' drawing)

Figure 7 Four operative centers (authors' drawing)
been made by Nanni di Frosino.26 When fixed in place, the four diagonal chains produced a starlike pattern spanning the void, and throughout the dome’s construction these diagonals served as a reference for plumb lines dropped from the rising corners above. This pattern is probably the “star of the cupola” mentioned in the records of the Opera.27 The hooks that Brunelleschi fitted as fixing points for the diagonal chains were positioned at the corners in the floor of the upper gallery; what appear to be their well-worn remains are still visible today.28

The fact that the base octagon is irregular can be accommodated if the builder adopts a radial method of construction, which in turn necessitates working with each pair of symmetrically opposite sides.29 The practicality of this method was verified when building the model. The four diagonals of the model actually intersect at one common center because, unlike the real dome, it is built on a perfectly symmetrical octagonal base. But it was still possible to replicate on a smaller scale the various constructional difficulties that confronted Brunelleschi. The solution was simply to work with each pair of symmetrically opposite sides as though the base-octagon of the model was also irregular.

The Internal Corner Profiles

The internal vertical curvature at each of the eight corners of the dome was specified by the Opera to be “pointed-fifth” (quinto acuto); this curvature was therefore a given. It is defined as an arc of radius equal to four-fifths of the dome’s interior base diameter. The span measures approximately 45 meters, so four-fifths is 36 meters. The eight centers of these radii, one corresponding to each corner, are called the centers of quinto acuto, and they fall inside the dome on the base plane of the octagon (Figure 8). Because Brunelleschi would have needed physical access to all eight of these centers, it is very probable that he foresaw the need for the working platform to extend far enough across the void to allow each center of quinto acuto to be located on its floor. This explains why the platform had to extend about 10 meters from the walls and why the chestnut beams had to be so thick.30

It was essential to have a practical system for defining and controlling the internal vertical curvature at each corner as the dome was raised. Each corner had to be built to precisely the same curvature to ensure that all eight met at the top. For this purpose Brunelleschi appears to have used eight pine templates to serve as “partial centering.”31 Each is called “centering” because when clamped in position, its edge profile defined the inner curvature in the corner (Figure 9). It is called “partial” because it covered only a small section of corner curvature. It was also movable and could be unclamped and shifted vertically upward in the corner as building work proceeded. The Italian term centina (plural centine) is used henceforth to denote this partial centering.32

On the model, a centina was initially clamped tight against each of the eight internal corners at the base. The working edge of each centina was pre-formed to precisely the vertical curvature required at the internal corners—that is, the quinto acuto curvature. Each centina stayed in place until the walls being built around it were raised to almost its full height. It was then unclamped, shifted upward so that half its height was above the top of the rising walls, and re-clamped in its new position. Care was needed to ensure that the centina was always aligned with the vertical radial plane corresponding to the corner diagonal below (i.e., with the vertical radial plane passing through the corresponding central axis and corner). This was done by dropping a plumb line from the top edge of the centina to the corner diagonal to check its alignment before clamping it in position. This was repeated each time the centina was repositioned.

When moving the centina upward on the model, a second control and adjustment was required to ensure that the profile of the centina’s working edge was always aligned precisely with the quinto acuto curvature defining the corner. The control device for this comprised a length of cord fixed to the appropriate center of quinto acuto curvature defining the corner. The cord’s free end was marked at a distance equal to the
quinto acuto radius. By pivoting the cord from its center of quinto acuto so that the marked end moved vertically up and down along the working-profile of the centina—which was at the same time held in alignment with the vertical radial of the corner diagonal below—one could adjust and position the centina exactly as required before clamping it in place. This procedure worked well on the model. A length of wood or measuring stick positioned against the inner edge of the centina and aligned with the bisector of the corner angle allowed the thickness of the wall to be determined and checked as the model cupola rose.

On Brunelleschi’s dome, each centina may have been up to 4 meters in height; this is inferred from the vertical distance between metal eyes found close to each corner, which were probably used for securing the centina. To ensure that his centina templates had the correct quinto acuto profile, it appears that Brunelleschi may have traced them directly from full-scale drawings of the dome. He had apparently cleared and leveled a very large area on the bank of the Arno to allow full-scale tracings to be made. This would have allowed him to check the measurements for each stage of the work from the safety of the ground. If it took about a week to lay one complete course of bricks around the entire perimeter and thickness of the dome, each centina would have stayed in place for up to a year before being moved. Assuming that the dome structure was naturally self-supporting while being built, the use of the centine in the manner described gave the builder full control of the vertical curvature in each corner and allowed him to dispense completely with full centering and its mass of scaffolding.

The Ribs of the Dome

As mentioned, the inner and outer shells of the dome are joined and bound together by an integrated system of twenty-four ribs. The integration of all the ribs with both shells is so complete that there is no visible evidence of the presence of these ribs on either the internal surface of the inner dome, even with its brickwork exposed, nor on the external surface of the outer dome stripped bare of its tiles. The presence of the ribs is evident only when one climbs between the two shells. This integration was achieved by building the two shells and the ribs as a single structure, employing the same principles and construction procedures throughout. The term “ribs” is perhaps misleading, in that it implies supporting structures distinct from the two shells. It is better to think of the inner and outer shells as being one and the same solid structure, which is hollowed out between the ribs; this conveys the character of what Brunelleschi built.

The white marble that is so prominent on the external corners of the dome is commonly taken to be a decorative covering for the main corner ribs underneath, but this is not the case. The marble conceals something else: a separate underlying brick structure that projects proud of the external dome surface at each corner (Figure 10). These corner brick projections are hidden by the marble, but they are clearly...
visible—and exaggerated—on the model (Figure 11). The corner projections are not extensions of the corner ribs; in fact they have nothing to do with the ribs. Their function is different, and they were built independent of the principles and procedures used to build the two shells and ribs. They serve a surprisingly important purpose in the construction of the dome.

All twenty-four ribs taper uniformly as they rise toward the oculus. They commence above the lowest 3 meters of the dome, which was built as a solid stone structure; above that point the dome divides into its two component shells. The starting location of each major and minor rib—including its width and radial thickness—had to be determined and then controlled as the ribs rise and converge. It was first necessary to mark the desired starting location and width of each rib on the walls of the dome close to their springing point. This was done at a height of 1.72 meters (3 braccia) above the floor of the upper gallery, where a series of iron hooks were fitted to mark permanently the position of the rib side faces near their base.39 Each side of the octagon was specified to have two minor ribs, with half a full rib at each corner. Therefore six hooks per side, aligned horizontally, were needed to define the launching points of the rib side faces. These hooks are visible today at eye level on the upper gallery on the inner face of the dome (Figure 12). They had been hidden from view and forgotten for many years beneath old electrical conduit, and they were only rediscovered during work associated with the fresco restoration in the early 1990s.

The radial depth of the rib side faces through the dome shells can be determined by following the same logic and procedure used to locate each of the four vertical axes of the dome: that is, by making use again of the symmetry shared by each pair of opposite sides of the irregular octagon. Starting with one pair of sides, two hooks positioned directly opposite each other were joined with a long length of cord (Figure 13). The cord was required to intersect the central vertical axis corresponding to the paired sides. The procedure was repeated for the remaining five pairs of hooks. This allowed one to locate the vertical planes that defined the radial depth of each rib side face by extending the line established by the cord through the dome wall.
As construction progressed, each rib rose vertically and curved inward. As it did so, a plumb line was dropped periodically from the topmost point of each rib side face to ensure its continued alignment with the corresponding cord below. This procedure easily defined the two side faces of each rib as it rose; it also allowed the rib taper to be readily checked as it rose and curved inward.40

However, to locate the side faces of the ribs over their full depth—which is 4.25 meters at their base—a cord similar to that used for aligning each centina could have been employed. As construction proceeded, this cord was pulled taut from the highest point of the plumb line at the rib side face and through the corresponding central axis. The line of direction traced by this cord located the vertical plane defining the full depth of the side face. This proved to be a straightforward procedure on the model; by repeating it periodically as construction proceeded, it was easy to determine the two side faces of each rib at every stage. A similar procedure could have been used on the dome; it was certainly available to Brunelleschi.41

The presence of the iron hooks in the dome walls can be linked to both Brunelleschi and the procedure just described. The building specifications of 1420, which were probably drafted by Brunelleschi, provide only the absolute minimum of information about the rib dimensions: that is, the width of the major and minor ribs at their base and also the height at which the ribs and separate shells were to commence (the width of the minor ribs was later reduced by a quarter to make the dome lighter).42 All the remaining measurements and the tapering curvature of each rib as it rose can easily be worked out by using the system of cords and hooks described here. This methodology was corroborated through an independent computer simulation that calculated dimensions of all the ribs over their full height. These dimensions matched those in the dome almost exactly, the maximum difference being only 4 cm. 43

It is now accepted as fact by the Opera, which has responsibility for the dome today, that the combination of these iron hooks with the methodology described here accurately defines the location and dimensions of all the ribs in the dome at all heights.44 It is not unreasonable to infer that these hooks were fitted by Brunelleschi and used by him for this purpose. This, in turn, implies that a radial methodology, based on the shared symmetry of each pair of opposite sides, was used when building the dome.

The Geometry of the Dome Walls
Brunelleschi had to devise a practical method for defining the geometry of the dome segments between adjacent corners during construction. He had to build each segment in conformance with that geometry, ensuring that it also adhered to the quinto acuto curvature, so that, as the dome rose, each segment curved inward uniformly toward the corresponding central axis and all eight segments met at the oculus. A practical solution can be derived from the following theoretical considerations.

Each corner of the octagon is 36 meters from the corresponding center of quinto acuto that lies across the void. Between two adjacent centers (A3 and H3 in Figure 13), a curve can be defined on the floor of the platform whose every point is also 36 meters from a corresponding point on the
The line joining a point on the curve to a segment of the dome must intersect the corresponding central vertical axis. Thus F3 is 36 meters from F1, and so on, in Figure 13. This newly defined curve is concave with respect to the side of the octagon opposite. The curve resembles the arc of a circle, but is actually the arc of a conchoid. This arc can be used to determine the position of the bricks and the curvature of the dome segment being built opposite. Eight of these conchoid arcs, one for each side of the octagon, were laid out on the platform of the model; they were then used as a reference system for positioning the bricks and obtaining the correct curvature of the shells of the model cupola. The three-step method used to construct this system of conchoids will be described as if it were on the full size dome.

First, use was again made of the symmetry shared by opposite sides of the octagon, together with the same system of cords and hooks that was used to guide the construction of the ribs (see Figure 13). On each side of the octagon, the cords already tied to each of the six hooks were tagged 36 meters (the quinto acuto radius) from points of attachment. The tagged positions on the cords overlapped the working platform and could easily be accessed from there. A plumb line was dropped from the tags to allow the 36-meter points to be marked on the floor of the platform. During construction of the real dome, the platform floor was about 1 meter below the cord (allowing for the thickness of the platform and the beams supporting it). Joining the marked points established the conchoid curve on the platform floor. Adding a few additional points gave better definition to the conchoid arc. At its extremities, the conchoid intersected the two corner diagonals at their respective centers of quinto acuto. Only the portion of the arc bounded by two adjacent corner diagonals was required. This procedure was repeated for each side of the octagon.

Second, having traced the conchoid arc on the platform floor, a reverse procedure was applied: that is, from the conchoid back to the opposite segment of the dome. Since the conchoids can be derived from the flat surfaces of the octagonal dome, a straight line can be obtained from a conchoidal curve. Successive points along the conchoid are required to serve as points at which is secured the end of a special new cord, called the “mobile cord.” This mobile cord can be pivoted from any point B on the conchoid, ensuring that its line-of-direction passes through the corresponding central axis C (Figure 14). When tagged at 36 meters and elevated slightly, the “mobile cord” accurately locates the intrados of the inner shell, and thus the inner edge B1 of the next course of bricks. This mobile cord determines precisely where the bricks are to be laid as the wall rises course by course, and establishes their correct orientation.

Third, the mobile cord is marked at three points beyond the 36-meter tag. This allows it to locate in one efficient operation the intrados and extrados of both shells of the dome opposite, at points B₁ to B₄ (see Figure 14).

The practicality of this procedure was fully verified when building the model. Each side of the octagon generates its own conchoid arc, and together the eight arcs comprise a geometric pattern on the platform floor. This pattern resembles a flower with eight petals, and Ricci refers to it as “the flower [fiore] of Santa Maria del Fiore” (Figures 15, 16). Before building the model, Ricci had proposed the conchoid curve as a part of a radial-based system for determining how successive courses of bricks should be laid. Its practical
Figure 15  Star of the Model (authors’ photo)

Figure 16  The eight conchoids create a flower pattern on the work platform (authors’ drawing)
application was established only during the model experiment, as a logical progression from the use of cords and hooks to locate the side faces of the ribs. This system of eight conchoid arcs is simple and experimentally tested, and it lies at the heart of the radial methodology used to build the model. It controlled the curvature of the model dome as it rose.

Brunelleschi must have devised his own system of curvature control for building the full-scale dome. He may have devised a system similar to the one used for the model; and it makes sense that he should have done so. He very probably used the cords and hooks to locate the rib side faces in the manner described above, and so he was then only one step away from the conchoid system. If he did not adopt the conchoid system, it is unclear how he controlled the curvature of the dome.

The Function of Herringbone Brickwork

One of the best-known features of Brunelleschi’s dome is its herringbone brick pattern (Figure 17). It is called spinapesce in Italian and “herringbone” in English because the pattern resembles the spine of a fish. The pattern is created by laying stepped lines of bricks vertically on their long edges (i.e., knife edges) rather than flat, so that they stand proud of the adjacent horizontal brick courses laid face down.

It is widely accepted that the spinapesce had two main purposes. First, the system provided local structural support during construction by bonding each new course of bricks to earlier courses, thereby permitting Brunelleschi to build the dome without full centering and scaffolding. Second, as the dome rose and its segments converged, adjacent lines of spinapesce locked the increasingly inclined, flat-laid bricks together, preventing them from sliding off while the mortar was wet.

Experimentation with the radial method of construction has undermined these assumptions about the two-fold function of the spinapesce. The experience of building the model revealed what appears to be a much more fundamental and hitherto unsuspected role for the spinapesce, providing further evidence of how Brunelleschi went about building the dome. Stated briefly, construction of the model showed that the radial method requires every brick to be positioned in accordance with a single governing principle, and of this the spinapesce is the physical manifestation. The working out of this principle will now be elaborated.

The position and angle of inclination of the spinapesce bricks on the model was determined by the mobile cord, tracing a line-of-direction from a point on the conchoid, though the central axis, and on across the top of the wall, thus locating where the next line of spinapesce bricks was to be laid (Figure 18).

The elevation or point at which the mobile cord intersected the central vertical axis of the model climbed up that axis as construction of the model dome progressed. This central axis and the point of intersection, therefore, had to be determined at every stage of the work. (Achieving this in the dome by direct physical access to the four operative centers was not possible without first building a labyrinth of scaffolding—and this Brunelleschi did not do. So he must have found another solution, because otherwise the dome could not have been built.) The point of intersection was determined on the model by another simple device made up of two intersecting cords, each fixed to one of two adjacent centers of quinto acuto on the work platform. The free end of each cord was elevated, aligned with its corner diagonal, and fixed to the external surface of the corresponding corner (Figure 18). The two cords thus fixed in place henceforth are referred to as the “fixed cords.” They intersect at the central vertical axis—thereby locating it, and they will do so provided two conditions are met.

The first condition is that the elevated ends of the two cords must be fixed at equal heights. To ensure equal height, it is necessary to have a point of reference at each corner that is independent of the model dome. This was accomplished...
by building a vertical brick structure, proud of the surface, on the external face at each corner of the model dome (Figure 11). As noted, these corner projections also exist on the actual dome beneath the white marble trim. Although Brunelleschi mentions in the specification of 1420 that marble would cover the corners of the outer dome, he says nothing about the underlying brick structures. It is unclear therefore whether he knew as early as 1420 that these brick structures would have to be built, or he discovered the necessity for building them later.

The second condition is that the fixed cord must bisect the corner angle. This is important because only the bisector is aligned with the vertical radial plane passing through the corresponding corner diagonal below. That is, the fixed cord is required to be vertically above and aligned with the diagonal chain below. The alignment is obtained by dropping a plumb line (from points E1 and A1 on Figure 18) to the corner diagonal. This procedure was verified on the model. Brunelleschi could have used this same procedure and adhered to the two conditions as described, thereby making it relatively easy to control the vertical rise and inclination of the dome during its construction.

However, it was learned on the model that centine positioned in the corners would block the paths of the fixed cords and prevent them from bisecting their respective corner angles. This was one of several unforeseen technical problems encountered while building the model, and it resulted in work coming to a standstill. A solution had to be found. Unless each fixed cord bisects the corner angle, the spinapesce structure could not be built.

Eventually it was realized that the fixed cord could pass unhindered if the centina was shifted sideways by a few centimeters, just sufficient to allow the fixed cord to bisect the corner angle. This did not interfere with the function of the centina, although it meant that the curvature of the internal corners of the model cupola was now determined by the corner edges of the centina (Figures 19, 20). This solved the problem on the model.

This experience with the model suggests that Brunelleschi would have encountered the same problem if he had used a radial method of construction. He may have solved it in a similar manner, and if so, might have left evidence in the form of metal brackets or clamps for holding the centina in an offset position in the internal corners of the dome. Some remnants of old fittings in poor condition had long been visible through the plaster in some corners about 15 meters above the upper gallery, but their origin and purpose was unknown. Then, during the fresco restoration in the early
1990s, these remnants were examined and found positioned and configured exactly in the manner required for securing centina in the offset position (Figure 21). When metal detectors were used to explore all eight corners, remnants of additional brackets were discovered beneath the plaster at the same height in each corner, exactly where they would be if a system of centina, as described earlier, had been used.\textsuperscript{52}

This evidence for the offset placement of the centina supports the inference that Brunelleschi built the dome in a manner that depended on constant reference to the corners and the use of fixed cords. This is also consistent with the use of a radial system of construction and not with a rotational or circular dome construction method.\textsuperscript{53}

The radial method of construction allowed each web or segment of the model dome to be built with some independence of the adjacent segments, at least up to the level attained by the model as it now stands. In other words, the stability of the model cupola up to this height did not require each course of bricks to be completed around the entire circumference of the octagonal ring before beginning the next course. Work on each segment could proceed at quite different rates without adverse effect, and segments were sometimes many courses ahead of their neighbors. This is not to imply that any segment by itself was a stable cantilever; clearly, it would fall inward without the support of the adjacent segments if construction pressed too far ahead. Nonetheless, the radial methodology used for the model allows the builder considerable flexibility.\textsuperscript{54}

To locate and build the courses of spinapesce on the model, the mobile cord was pivoted from a point on the conchoïd and aligned with the central axis at a point fractionally above where the two fixed cords intersected—this alignment was easily done by eye. Holding the “mobile cord” taut in this position located both the direction and inclination of the next course of spinapesce. These bricks were then positioned vertically on the wall and mortar was applied immediately (Figures 22, 23).
It made practical sense on the model to decide where the very first line of a series of *spinapesce* should start, and then to space these 0.35 meters apart (equivalent to 1.75 meters in the dome). Nine sets of *spinapesce*-laid brickwork comprise each web of the model, as in the actual dome. Only when it was decided where on the wall the first brick should be laid, was the corresponding position for the end point of the mobile cord on the conchoid curve determined. That is, the conchoid served as the final reference to ensure that the *spinapesce* was correctly aligned through the central axis. The *spinapesce* bricks were laid immediately in accordance with the line-of-direction so defined. The mobile cord was then rotated to where the next line of *spinapesce* was required and, at the same time, its position on the conchoid was also shifted until again aligned by sight with the central axis. When the mortar binding the vertically laid bricks had set, the intervening bricks between two adjacent sets of *spinapesce* were laid face down. This procedure was verified when building the model, and the students acting as bricklayers became adept at it.

Practical shortcuts were discovered. For example, in laying a line of *spinapesce* the greatest care was needed with the two bricks defining the inner surface of the inner shell and the external surface of the outer shell. These two bricks were laid first; then the intervening bricks in the same line of *spinapesce* could be laid by means of a straightedge, without direct reference to the mobile cord. Use of the straightedge was an important shortcut. The laying of the flat-laid bricks in between adjacent lines of *spinapesce* followed, with the single course at the intrados and that at the extrados laid first and the mortar allowed set. Only then were the remaining flat-laid filler bricks—which required the least skill—set in place. Thus the *spinapesce* governed the position, direction, and inclination of all the bricks.55

On the actual dome, the lines of *spinapesce* would have shown the bricklayers where and how to lay each brick. They would have made it easy for bricklayers working in eight separate teams at great heights to know exactly what to do, even though they were probably not privy to the underlying principles of Brunelleschi’s method.

Most scholars of Brunelleschi’s dome have limited their view of the function of the *spinapesce* to the stabilization of each course of bricks and to their structural role in bonding new and earlier courses during construction. The experience of building the model raises questions about the primacy of these functions. First, if the main function of the *spinapesce*
was to wedge the bricks together on acutely inclined planes, then its use would probably have been restricted to where it was most needed, that is to near the top of the dome, at an angle of 50 degrees and above, where the incline is most pronounced and friction is no longer adequate to hold the bricks in place. But Brunelleschi was already using the *spinapesce* at the elevation of the second walkway, where the incline is only 20 degrees, and—although the brickwork evidence is still hidden beneath plaster—he may even have begun using it in the lowest courses of brickwork. In either case, given that he used *spinapesce* very early in the dome’s construction, he must have had another important reason for doing so. Second, laying *spinapesce* bricks is a very time-consuming procedure that greatly complicates the work. This was very obvious when building the model, and it must have been much more so on the full-size dome. No one would choose to use it more extensively than was absolutely necessary. Third, *spinapesce* introduces weakness in the structure because the courses of flat-laid bricks are broken again and again by the lines of *spinapesce*. Brunelleschi would certainly have known about this structural deficiency, but the main function of *spinapesce* must have been so fundamental that he tolerated the problem.\(^56\)

The experience of using the radial methodology to build the model suggests that the primary function of the *spinapesce* was to establish the orientation and inclination of the bricks comprising the dome, guiding how and where each brick was to be laid. This essential function struck us as obviously fundamental when building the model, taking precedence over other considerations concerning the role of the *spinapesce*.\(^57\)

To summarize, the single governing principle stems from the system of conchoids on the floor of the main platform. That system implies the adoption of a radial methodology. For each segment of the model cupola, the orientation and inclination of all the *spinapesce* bricks was determined by attaching the mobile cord to successive points on the conchoid and ensuring the cord’s intersection with the central axis. When a new line of *spinapesce* bricks was completed, the course of filler bricks laid flat between adjacent lines of *spinapesce* was easily positioned, and so on. This accounts for all the bricks comprising the model and, by implication, the dome.

### The Slack-Line Mortar Beds

The brick courses are laid on mortar beds between adjacent corners in a manner that resembles the concave curve traced by a rope or line held slack between two points at equal height. This curving of the mortar beds and brick courses is usually referred to as *corda blanda*—literally “slack-line.” At the base of the dome these beds are horizontal, but as the dome rises the curving gradually becomes evident and, toward the top, pronounced. The *corda blanda* is replicated in the model (Figure 24; see also Figure 3).

It is a generally held view that the *corda blanda* was a deliberate design feature, adopted by Brunelleschi for structural reasons: to help ensure an unbroken course of brickwork through each corner of the dome, where two adjacent segments of the shell meet.\(^58\) This plausible theoretical view has been bound up with the theory that the dome was built as if it were circular. In the context of that theory, however, no one has determined the practical procedures that governed how successive *corda blanda* mortar beds were laid.\(^59\) This difficulty can be resolved with surprising ease and elegance when the radial methodology is considered.

The experience of building the model suggests that the assumption that the *corda blanda* was contrived by Brunelleschi for structural reasons is almost certainly not true. It was demonstrated on the model that the so-called *corda blanda* is the natural and inevitable outcome of building the octagonal dome by the radial method of construction based on the conchoids (Figure 25). The same mobile cord used to determine the lines of *spinapesce* also traces out the *corda blanda* at all elevations as an unintended bonus. If Brunelleschi did use a radial method of construction identical or similar to that proposed here, then the *corda blanda* was inherent—a natural consequence of the construction system. This explains why Brunelleschi says nothing about it in the building specifications.\(^60\)

It has been suggested that if the *corda blanda* in the dome was laid out by using the conchoids scribed on the platform and the mobile cord, it should be possible to show that the *corda blanda* takes the form of a conchoid arc (Figure 25) and not a circular arc, as would be the case if the mortar beds...
reflect a series of conical sections (see Figure 2).\(^6\) This is a plausible proposition, but it overlooks an important practical matter. The differences generated by the two types of arc are very small—smaller, in fact, than the errors that would naturally occur from using a very long mobile cord and from laying the bricks on thick mortar beds.\(^6\) These likely errors make it impossible to determine definitively what curve actually generated the *corda blanda*, short of reviving Brunelleschi and asking him directly. However, the precise form of the *corda blanda* in the dome is not germane. To focus attention on it is to miss the point because the dome was built with bricks, not with numbers or mathematical niceties. What really matters is that Brunelleschi knew that he was working with an arc that did the job; it worked. It seems he did not bother at all about the form of the *corda blanda*; it was automatically generated—so unimportant that he did not mention it.\(^6\)

The *corda blanda* in the model allowed all the ribs—major and minor—to be built integrally with the shells of the dome, so that shells and ribs were one and the same construction and thereby very strong. This was done simply by following the lines of *spina pesce* as they gradually ascended diagonally, as though in a continuous spiral around the octagonal walls. In this way the *spina pesce* passed through each corner rib without discontinuity, joining adjacent webs and the two shells together seamlessly. The continuity of the *spina pesce* bricks at and through each corner of the model was not affected in the least by the corner ribs (Figures 26, 27). This is exactly what one sees in photographs of the internal corners of the inner shell of the actual dome: the lines of *spina pesce* continue through the corners as if the corner ribs were not there (Figure 28).
It is not so much the spinapesce but rather the corda blanda that allowed the dome to be self-supporting throughout its construction. It did so by ensuring that each course of bricks was always held in compression, which would not have been the case otherwise. This compression results from the fact that the lowest point of the corda blanda occurs at the center of the web between two corner ribs, and the highest points occur at each corner. As each segment of dome rises, it also curves inward toward the corresponding central axis. It follows that for each course of bricks, the highest points of the corda blanda (in the corners) will have curved inward toward the central axis more than the lowest point of the corda blanda in the middle of the wall. This was critical for the stability of the dome during construction, ensuring that brick courses always remained in compression.64

While we are convinced that Brunelleschi did not deliberately contrive the corda blanda, his design made brilliant use of it. It would appear that he understood intuitively the static implications.65

Controlling the Curvature of the Dome

Prior to building the model cupola, Massimo Ricci’s theory of radial construction suggested that the control of curvature would require that a new set of conchoids be traced on the platform floor every time a fresh course of bricks was laid.66 Fortunately, this turned out to be unnecessary because the differences arising from use of the same conchoid for successive courses are minute; even after many courses, the differences are insignificant. As a result, new conchoids were needed only very rarely (Figure 29). This suggests that the actual dome could have been built accurately and safely by stopping to measure out a new set of conchoids on only four or five occasions during the entire construction.67

Even so, the building procedure developed for the model required that each set of spinapesce be laid using the mobile cord and the conchoids laid out on the platform floor. Strict adherence to this procedure proved to be time consuming and tiresome for the bricklayers, threatening to undermine the practicality of the system. In a departure from the authorized procedure, the bricklayers soon found a way around the difficulty by running two parallel cords between adjacent centine to establish where the first spinapesce brick of each new line should define the extrados (and the last brick define the intrados) (Figure 30).68 In this way, after the first

Figure 28 Intrados of the inner shell in the dome with plaster removed (photo: Ministero per i Beni e le Attività Culturali)

Figure 29 Mobile cord pivots from the conchoid on the model’s platform; hooks indicate an earlier conchoid (authors’ photo)

Figure 30 Two parallel lines fixed between two adjacent corners at the intrados represent the gualandrino on the model, repeated at the extrados (authors’ photo)
few lines of spinapesce had been laid using the mobile cord and conchoid, many additional lines could be laid without their use.\textsuperscript{69} The two parallel cords allowed a good approximation of the required curvature to be achieved with ease. But this did not eliminate the need for the mobile cord and conchoids; periodic use of them was still necessary to correct deviations arising from this unauthorized method. After initial objections, it was realized that this ad hoc way of working was feasible, and it was adopted in building the model. Deviations of several centimeters were detected after about fifteen courses. This would be equivalent to three or four months’ work on the actual dome and, if repeated there, would have been five times larger and unacceptable. Thus a local reference system alone was not sufficient to determine the geometry and curvature of the dome; periodic use of an independent system was essential.\textsuperscript{70}

The two parallel cords used on the model may correspond to the “three-cord device” first referred to by Brunelleschi in the report of 1425 (\textit{gualandrino con tre corde}).\textsuperscript{71} Two cords were sufficient to guide the bricklayers on the model, but three parallel cords may have been required to serve the same function on the dome. Although no one knows what Brunelleschi’s\textit{gualandrino} device looked like, he almost certainly used it as a local reference system to help control the curvature of the dome segments. The fact that the device was not mentioned before 1425 suggests that its use might have been triggered when his bricklayers encountered difficulties like those experienced in building the model. Brunelleschi’s bricklayers might have discovered a similar unauthorized but effective solution, obliging him to permit the\textit{gualandrino} to be used.\textsuperscript{72} Skilled tradesmen have always resorted to practical shortcuts whenever possible, and such liberties were hardly unknown in Brunelleschi’s time.

The use of the\textit{gualandrino} would have allowed Brunelleschi to keep the essence of his method of construction to himself. The overt and constant use of the system of conchoids and mobile cord soon would have led Gherardo da Prato (who despised Brunelleschi) to discover the radial method. (It seems he almost did.) Brunelleschi could not allow this. By using the\textit{gualandrino} for everyday work he could limit use of the mobile cord and the conchoids to times when no one else was around. By doing this surreptitiously every two or three months, he could check for deviations while keeping his method to himself—and unrecorded.\textsuperscript{73}

This speculation about the link between the two-cord device used on the model and Brunelleschi’s three-cord\textit{gualandrino} is supported by some collateral evidence. There is clear evidence of deviations from the desired geometry in the actual dome; these were later corrected. This implies that a daily rule-of-thumb method was occasionally corrected by an independent reference system, just as on the model.\textsuperscript{74} Eugenio Battisti refers to the cupola needing continuous adjustments and measurements during its construction.\textsuperscript{75} This also corresponds to the experience on the model. The 1425 report contains a concise but cryptic statement about the\textit{gualandrino}: “attach . . . three cords, both on the inner and outer faces.”\textsuperscript{76} The simplest and most likely explanation of this is that “the inner faces” are the intrados of the two shells and that the “outer faces” are their extrados. If so, the three parallel cords were moved up the sides of the dome when required, to locate the next portion of curved surface to be built.\textsuperscript{77}

**Conclusion**

As construction of Brunelleschi’s dome progressed, successive openings were left through the ribs for four levels of walkway linked by stairs, which led from the drum to the lantern base. Below the lantern base, these openings through the ribs would have facilitated the movement of workmen and materials, and were left open as wide as possible for the duration of the dome’s construction. The openings were made up to the height of the stone lintels, which are clearly visible just above head height. Only after the dome was closed were the openings and passageways at the levels of the second and third walkways and the stairs linking them faced with the brickwork that is seen today. This brickwork could not then have been laid in accordance with the principles and procedures described for building the dome. Almost everything about this facing brickwork is cosmetic and appears to be designed deliberately to deceive and to perplex. In this it has been singularly successful, because it reveals nothing about how the dome was built.

The numerous deceptions make sense only when the brickwork is compared with what would have been visible if the principles and procedures used in building the dome been applied. They include (1) lines of spinapesce appearing out of nowhere and ending just as suddenly; (2) a complete absence of spinapesce in some places where it should be present; (3) a curve of\textit{corda blanda} between the second and third levels inexplicably running up through a minor rib when it should be running down; (4) use of special corner facing bricks at the main ribs (not used in the dome itself); (5) a degree of fineness in the mortar beds that is quite unnecessary and unlike the much thicker beds of mortar in the real structure of the dome and ribs above lintel level; and (6) brickwork disguised to appear in an impossible arrangement (Figure 31).\textsuperscript{77} Brunelleschi probably directed the building of this deceptive brickwork; it would have been in keeping with his character and secretive ways. If so, it reveals a mischievous sense of humor. One can imagine how he might have delighted in contemplating the
bewildering effect of the many false clues on those who, down
the centuries, would try to make sense of them.79

Debate about Brunelleschi’s method of construction
has been going on for a very long time because no hypoth-
esis has emerged that satisfies all of the known facts. The
radial construction methodology described here may be an
exception. Its appeal is fourfold. First, it brings together all
the elements of the dome and the problems of its construc-
tion under a single comprehensive solution. Second, the
hypothesis has been shown to work by building a model
using only the techniques available to Brunelleschi. Third,
the hypothesis has an elegance and simplicity that ring true.
Fourth, there is good factual and circumstantial evidence to
support the hypothesis. Some additional evidence is offered
by way of conclusion.

In late 1425 or early 1426 Giovanni di Gherardo da
Prato submitted a document to the Opera in which, inter
alia, he accused Brunelleschi of deviating from the quint
acuto curvature that was specified for the dome. Gherardo
had made some drawings with explanatory text on a parch-
ment to illustrate how Brunelleschi was at fault. This docu-
ment survives in the Florentine State Archives (Figure 32).80

The essence of the accusation was that Brunelleschi was not
aligning his brickwork with the center of the dome, which
was considered to be best practice in construction of this
nature. Gherardo argued that the structure would therefore
be unsound and likely to collapse. He attributed this to
Brunelleschi’s ignorance and saw it as an opportunity to dis-
credit him fatally. (They disliked each other intensely and
even exchanged cutting invective in sonnet form.)

Gherardo’s main drawing and text have been interpreted
in this general sense. But there is also a small drawing on the
parchment that appears to depict two concentric octagons,
each inscribed within its own circle (Figure 33). The area
encompassed by the outer circle is colored red, except for
that portion between the inner and outer octagons, which is
colored white. There is also what looks like a black dot on
the circumference of the inner circle and, finally, some text
of uncertain meaning. No one has made sense of what this
smaller drawing represents or what its text means. However,
in the light of the hypothesis described here, an interpreta-
tion becomes evident. Gherardo’s small drawing appears to
depict the main working platform of the dome (the white
area between the two octagons). What appears in Figure 33

Figure 31 Deceptive brickwork arrangement (authors’ photo)

Figure 32 Parchment of Gherardo da Prato (photo: Ministero per i Beni e le Attività Culturali). See JSAH online for a high-resolution, zoomable image
to be the inner circle is revealed by close inspection of the original parchment to be not a circle, but a figure that comprises eight separate arcs, each drawn free-hand. These arcs could represent the pattern of the eight conchoids drawn on the platform. The outer circle, in contrast, is indeed a circle and is clearly drawn with a compass; this could have served as an aid to drawing the octagon within it. (If the outer circle was used to draw the outer octagon, then it is a simple matter to draw the inner octagon without scribing a second circle.) The four corner diagonals are also shown. Finally, what appears in photographs to be a black dot on the “inner circle” is actually a hole in the parchment; this hole could mark the fastening point for the end of the mobile cord on one of the conchoid arcs. This was the cord used to define the spinapesce and hence the position of all the bricks of the dome.81 This small drawing thus constitutes documentary evidence of indisputable provenance that is in full accord with the radial construction hypothesis.

Although Gherardo’s allegations were not strictly wrong, nothing came of them. But while studying Brunelleschi’s work, he may have come to understand in detail much about the architect’s intentions and methods. The man who set out to have Brunelleschi removed from office may have been the one who came closest to discovering his method.

Figure 33 Gherardo da Prato’s small drawing on the parchment (authors’ photo). See JSAH online for a high-resolution, zoomable image.
Brunelleschi replied to Giovanni di Gherardo with a sonnet that goes right to the heart of what he believed. It indicates that he saw his work on the dome as inspired, that he was supremely confident in his own ability, and that he placed paramount importance on practical knowledge and experience. Without those practical fundamentals, he says, one is easily led astray, and they are prerequisites to understanding “how art at its most profound taps into Nature’s secrets to realize human dreams.”

When inspired from above, a man can reach his true essence,
Free from physical and base limitations,
Thereby enabling him to make wise and sound decisions,
(Not so for Giovanni who presents but the semblance of reason).

Erroneous judgment is easily defeated by its most dangerous enemy, which is practical experience. The wise man has nothing hidden apart from what is not, Simply because what is not does not exist. One who has no practical knowledge is easily misled And does not understand how art at its most profound Taps into Nature’s secrets to realize human dreams. Therefore should Giovanni destroy all his sonnets, Lest they sound ridiculous when all the dancing starts In celebration of that which he now thinks impossible.82

Notes
1. Many of the ideas advanced here emerged from the experience of constructing a one-fifth-scale model of the dome, which was conceived and conducted by Prof. Massimo Ricci of the School of Architecture, Florence University, a coauthor of this paper. He has spent thirty years seeking to understand the practical issues Brunelleschi must have faced when building the dome. His five published papers in Italian on the subject between 1983 and 2001 chronicle the development of his hypothesis and, in 1989, he began putting his ideas to the test by building the model. His two coauthors first consulted him in 2005 to seek clarification on several technical issues and saw the need for his thesis to be brought together as a whole and presented in more accessible form. This paper is the result of a collaborative effort by all three.


6. Ibid., 119.


10. Ibid., 191.


18. We say nothing about the stone chains and their structural role in containing the bursting forces in the dome. This is partly because others have dealt with this subject, but mainly because their role is subsidiary to the purpose of this paper, which is seeking to understand the main method of construction used to build the dome.


20. Observations of the authors.


22. Observations of the authors; Fanelli and Fanelli, Brunelleschi’s Cupola, 2004, 23.

23. Observations of the authors; Guasti, La cupola, 1996, 62.


27. Ibid.

28. Observations of the authors.


30. Observations of the authors.


33. Observations of the authors.


37. Observations of the authors.

38. The term “spurs” (sproni) better conveys to us the reality of what Brunelleschi built; nevertheless we have kept to the more usual term “ribs” throughout. Fanelli translates sproni as spurs; Mainstone prefers ribs, as do Prager and Scaglia, see Frank D. Prager and Gustina Scaglia, Brunelleschi, Studies of His Technology and Inventions [1970] (New York: Dover, 2004).
40. Ibid.
41. Observations of the authors.
44. Based on the hypothesis of a radial methodology, Ricci had postulated some years before both the existence and function of fixings similar to these iron hooks in the dome. When they were uncovered he was consulted about them and is officially credited by the Opera with the discovery of their significance: Ministero per i Beni Culturali e Ambientali, Commissione di studio per la salvaguardia del monumentale complesso della Cattedrale di S. Maria del Fiore, con particolare riguardo alla stabilità della Cupola, Florence, Prot. N 7742 A166 Allegati 2+1, 1987.
46. Ibid., 1983, 13–42.
49. These are the same corner projections mentioned earlier under “The Ribs of the Dome,” above.
52. Ibid.
54. Observations of the authors.
55. Observations of the authors.
57. Observations of the authors.
59. Ibid., 191.
60. Guasti, La cupola, 1996, 10–11, 38–41; Observations of the authors.
61. The case of a circular arc is theoretical, not practical, because the same circle would have to pass through all eight centers of quinto acuto on the platform floor, which is impossible given the irregularity of the base octagon.
62. The distance from the conchoid through the central axis to the extrados of the corresponding wall segment on the dome would require the mobile cord to be up to 40 m in length.
63. Observations of the authors.
65. Observations of the authors.
67. Observations of the authors.
69. Observations of the authors.
73. Observations of the authors.
76. Guasti, La cupola, 1996, 40.
77. Observations of the authors.
78. We found three brickwork arrangements like this in the dome along passageways not open to the public. These apparently impossible arrangements might have been made to look as they do by workmen other than Brunelleschi’s; but against this is their obvious similarity as deliberate deceptions to the other examples cited, implying that all of them were probably done during Brunelleschi’s time.
79. Observations of the authors.
82. Authors’ translation from Tantorli and Robertis, L’Accademia della Crusca, 1977, 22.