Laser scanner surveys and the study of the geometry and structure of the dome in the Basilica della Madonna dell'Umiltà in Pistoia

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Abstract The Basilica di Santa Maria dell'Umiltà is one of the most important monuments of the city of Pistoia, and among the most significant legacies of Italian Renaissance architecture. The building of the temple was decided upon in order to celebrate the occurrence of a miraculous event which took place on 17 July 1490 in the small parish church of Santa Maria Forisportae, the place of the present Basilica.
The conditions of marked deterioration have attracted the attention of the Ministry for Cultural Heritage, the Bishop's See of Pistoia and the Pistoia and Pescia Savings Bank Foundation, who by the drawing up of a protocol agreement on 5 March 2008 have allowed the first restoration interventions, planned and carried out by the Superintendence for Architectural and Landscape Heritage of Florence, Pistoia and Prato of Florence.
It is into this context that we are placing our contribution stipulated between the Superintendence and our Department.

Keywords Surveying, laser scanning, architecture, structural analysis, cultural heritage

1. INTRODUCTION

The present work aims to show the first results of the profitable cooperation between University research institutes, ecclesiastical institutions, banking foundations and the Ministry for Cultural Heritage and Cultural Activities in the definition and realization of a complex conservation intervention.
Our studies, aimed at the definition of a 3D data base in support of the project of the restoration and consolidation of the Basilica dell'Umiltà of Pistoia, have been conducted with well-established surveying techniques, such as topography and photogrammetry, united with more innovative techniques like threedimensional scanning systems.

2. CONSTRUCTION AND RESTORATION

The building of the temple was decided upon in order to celebrate the occurrence of a miraculous event which took place on 17 July 1490 in the small parish church of Santa Maria Forisportae, the place of the present Basilica (Cipriani 1992, Belluzzi 2002, Rauty 1992).
The change of the name and the definitive metamorphosis of Santa Maria Forisportae into the Basilica dell'Umiltà were ratified by the Bull of Pope Leone X in 1515.
The conception of the geometrical structure of the church was made by Giuliano da Sangallo, the architect of Lorenzo the Magnificent, assisted by his brother Antonio, and by Francione and Pollaiolo;

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but the instigator of the construction was the Pistoian architect Ventura Vitoni; and later, in the mid-15th century, Giorgio Vasari was responsible for the design and realization of the majestic dome, which distinguishes and defines the city profile, being the fundamental reference point in the definition of the urban identity of the city of Pistoia (Belluzzi 2002, Quinterio 1997).
The monumental complex is composed of a succession of different bodies of buildings which correspond substantially to the successive phases of its construction through the ages. The building activity of the octagonal prism became so scarce that there was the risk that the unfinished structure would suffer decay. Cosimo I granted the necessary finances for the completion of the sanctuary and named Giorgio Vasari as the designer of the dome. He consolidated the existent structure, as he considered it to be incapable of supporting the weight of the roof, he raised the edifice beyond the third cornice to give a solider impost base to the dome. In the spring of 1569 the dome was completed in its load-bearing structure, but only a few years later the first cracks were reported. Vasari himself carried out the first restoration operations: he inserted chains to the inside and outside of the new extensions (Bargiacchi 1890). But due to the continuing presence of the cracks, the Granduca Francesco I entrusted the consolidation project to Bartolomeo Ammannati, who traced the instabilities back to Vasari, in particular the great weight of the lantern; he inserted four chains in the dome, strengthened the piers, judged to be jointly responsible for the sagging of the roof, and he built the undersides of the arches in stonework in correspondence with the chapels, thus cancelling the original decorations (Fossi 1973).
The remedies of Ammannati allowed the overcoming of the most acute phases but did not eliminate the causes of the problems, which reoccurred cyclically. Three other chains were then added externally and, in the middle of the 1700s, also the internal dome was encircled because of the detachment of the middle ribs of the masonry compages of the dome.
From this moment, little is heard until 1935, the year in which Superintendent Poggi asked the engineers Niccoli and Sanpaolesi for a deep study of the static conditions of the Vasarian dome. Sanpaolesi observed numerous cracks in the piers and the two calottes; he also noticed worrying detachments between the two calottes and between the two calottes and the ribs.
The last restoration was carried out in 1966 with the work of Superintendent Albino Secchi, who substituted two Vasarian chains, revised the roofing by once again making good the cracks with cement mortar and by restoring some elements of the decorations (Romby 1992, Tonietti et al. 1993).
From this date, the prolonged absence of interventions of either maintenance or conservation of the monumental complex has caused a general state of decay.

2. 3D DIGITAL SURVEY

The spatial articulation of the structure, the geometric complexity of the ambient and of the vaulted spaces, the richness of the decorations, all these have called for the integration of different measurement techniques (classic topographical and satellite systems, and 3D scanning systems and digital photogrammetry). The preestablished objective was that of supplying info-graphic representations with high levels of detail, metrically correct and in conformity with the finality of the survey and the scale of graphic restitution individualized as most opportune for the analysis of both the structure and the decorations.

2.1 Survey planning

The planning phase of the survey represents a fundamental part of the whole acquisition process. In the specific case of the Basilica, given the large dimensions of the construction (Table 1) and the complexity of the space, due to both the spatial articulation and the decorative richness, the acquisition process has involved a careful survey and the drawing up of a programmed register of the survey (Table 2) (Tucci et al. 2011).
The major difficulties faced during the acquisition phase are related to:
- the need to reach some restricted spaces of the structure (for example, the vertical connections, the angular ways which narrow from bottom to top, the compressed space between the two calottes at the level of the impost of the done up until the lantern);

- the need to document the high level of detail in some decorative elements (for example, the lacunars in the vaulted space and the large domes of the vestibule, the arch undersides of the minor and major chapels, the church ornaments, the balustrades with small bronze columns, the marble dossals and the high altar);
- the importance of defining the thickness of the masonry so as to reveal the external parameter. This finality, probably the most time consuming, has involved the individualization of some spaces surrounding the Basilica to plot the externals, in particular the dome. The dense urban building tissue in which the architectural complex is placed inevitably implies the shortened acquisition of surfaces due to the impossibility of obtaining the appropriate distances (between about 80 and 120m). From this, there was the need to raise where possible the scanner to the level of the windows and the surrounding terraces.

Table 1 - Main characteristics of the surveyed building

Dimensions of the building	about 60 m x 25 m
Max difference in height into the church	about 61 m (from the ground floor to the top of the cross on the dome)
Surveyed area at ground floor	about 1.500 m^2

2.2 Survey campaigns

The in situ work has been carried out in five measurement campaigns (Table 2).

Table 2: Summary of the activities during the five campaigns

	1st campaign	**2nd campaign**	**3rd campaign**	**4th campaign**	**5th campaign**
Times	April 2008	July 2008	October 2008	January 2009	April 2009
Instruments	1 scanner phase shift 2 total station 1 calibrated digital camera	1 scanner phase shift 2 total station 3 digital camera	1 scanner phase shift 2 total station 2 gps 3 digital camera	1 scanner time of flight 1 total station 2 digital camera	1 scanner phase shift 1 total station 2 digital camera
Working team	2 (6 people)	2 (6 people)	2 (6 people)	1 (3 people)	1 (3 people)
Working days	6	4	4	3	3
Scan positions	46	48	19	4	47
Points	about 370 million	about 820 million	about 420 million	about 16 million	about 1,5 billion
Files sizes	10 GB	18 GB	8 GB	1 GB	20 GB
Topographic vertices	19	14	16	0	0
Targets	51	70	37	15	263

The metrical survey has been done in relationship to the priorities given by the Superintendence: the vestibule, the octagonal hall, the sacristy, the annular corridors of the second and third kind, the tambour and the impost of the dome.

2.3 Topographical framework and reference system

A topographic net, including the internal and external vertexes of the Basilica, has been created. The measurement operations have been conducted with both a total station and geodetic GPS receivers. The total station was used for the survey of the internal network of the complex and also for a large part of the external network. The use of the GPS along the streets adjacent to the church has not been possible because of the tall buildings which limit the reception of the satellite signals. The use of the

GPS has however been fundamental in surveying some vertexes in elevated positions not directly connected to the total station net. The net was important in three successive measurement campaigns:
- *Campaign I:* the realization of the principal network of the framing includes the vertexes of the exterior of the Basilica, along via della Madonna, and in the interior in the portions of the vestibule, including the attic, the ground floor of the octagonal Hall and in some rooms of the manse;
- *Campaign II:* the completion of the ground survey of the rooms of the manse and the survey of the 'ring' corridors between the ground floor of the octagonal hall and the impost of the dome;
- *Campaign III:* the extension and completion of the external network through new ground vertexes, on the lantern and on the structures in elevation.
All the vertexes have been materialized in a permanent way and accurately monographed in order to describe the locations and coordinates in the pre-established reference system. The maximum planimetric range of the network, which is presented elongated in the parallel direction of via Madonna, is equal to circa 480m x 170m, while the proportional development ranges from 0 to circa 47m (Figure 1).

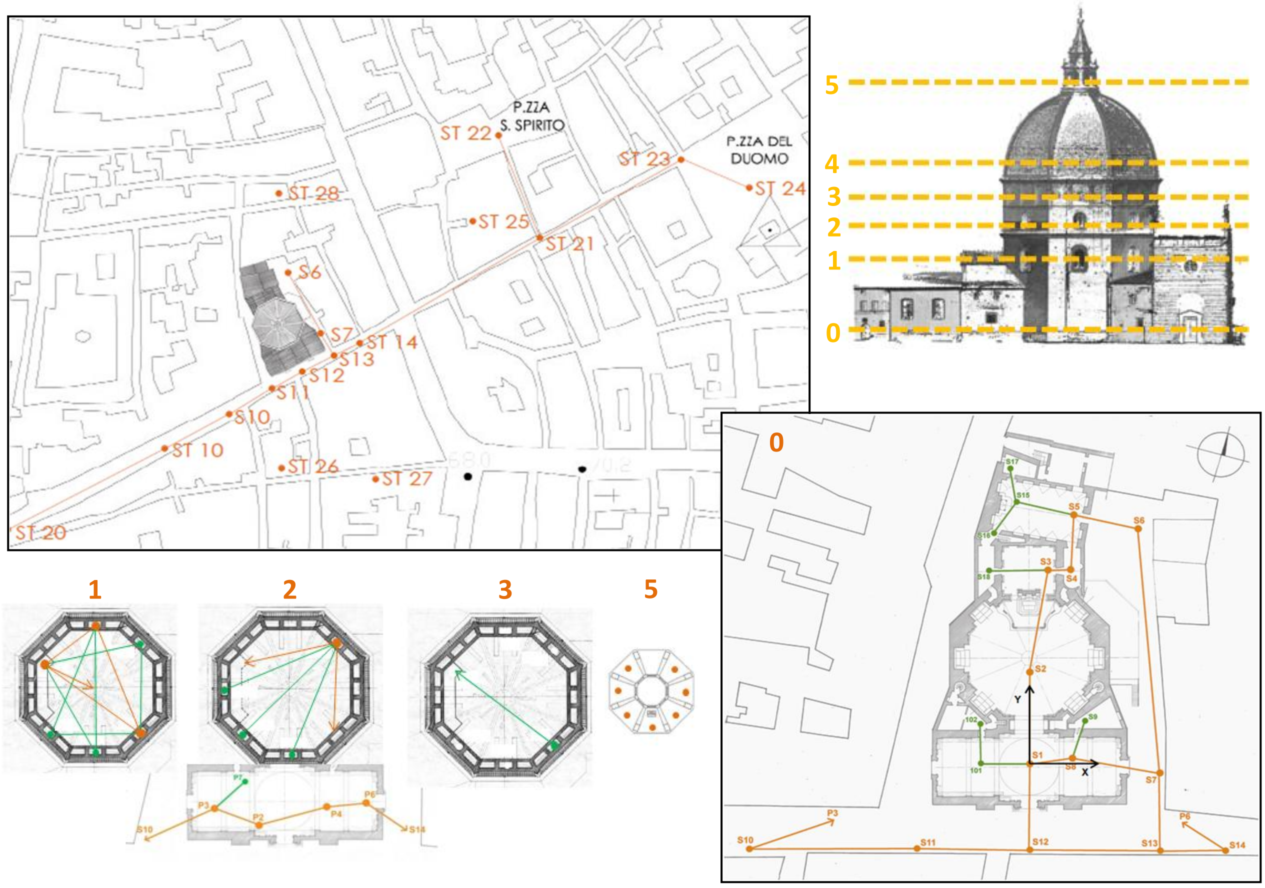

Figure 1 – Internal topographic network, scanned at levels, and the external network.

2.4 3D scanning

The scans resolution has been planned each time for the formal and dimensional characteristics of the investigated spaces. To estimate the acquisition times both the times of the execution of the scansions and the times for the moving and orientation of the sensor have been evaluated. The planning phase of the scans has been fundamental in forecasting the different positions of the scanner, the extensions of the singular acquisitions of the subject and the position and type of target.
The most problematic parts found are:
- the arrangement of the reference frame in order to ensure the correctness of the operations of rototranslation of the points obtained from the different stations;
- the acquisition of the space between the two calottes. In all the survey campaigns a phase shift scanner has been used, except in the fourth campaign where a time of flight scanner (Leica

ScanStation2) has been used, in order to obviate the instrument/subject maximum distance (circa 100 – 150 m).
The high working speed has permitted the realization of a number of significantly important scans. The alignment of the scans has been organized according to projects, each one of which contains the data relative to significant portions of the surveyed spaces:
- *Campaign I:* the internal, external and extrados vestibule;
- *Campaign II:* the octagonal hall (level 0, 1, 2);
- *Campaign III:* manse, external (via Vitoni and interior courtyard);
- *Campaign IV:* the dome-external;
- *Campaign V:* the spiral staircase, tambour and impost of the dome.

2.5. Graphical output

Starting from the complete model of the points, the following elaborated graphics have been extracted:
- for the whole *architectonic complex*, scale 1:50 - four plans, at level 0,1,2,4; the longitudinal section (Figure 2); scale 1:100 - the plan of the roofing; 3 views, one of Via Vitoni, one of via della Madonna and one of the interior courtyard;
- for the *vestibule*, scale 1:50 - two plans of the extrados, one architectonic and one structural; three sections, one longitudinal and two cross-sections; the photo-mosaic view of the main façade; scale 1:20 – the development of the barrel vault;
- for the *octagonal*, scale 1:50 - two sections, one cross-section and one diagonal.
- for the *dome* – a 3D model with the correct geometry of the thirty-nine ribs, the two calottes and the real size of the lantern base.

3. ANALYSIS OF THE DOME

Among the objectives of the research we can find the analysis of the morphological and structural configuration of the Vasarian dome, carried out by matching the results with the instabilities affecting it. This is exactly the field in which the survey method used proved to be very successful. Often it is not so easy and clear to detect the structure of old buildings; in fact, the type of building materials, the purpose of the builder - who could follow, violate or invent building rules - and the concrete result obtained according to the circumstances, originate a somehow enigmatic product from the structural point of view. This product will be further subjected to other variables linked to weather (the age of a historical building is measured in centuries) and external actions (earthquakes or ground settlement can change the loads acting on the structure). We all know that a common morphological reference actually hides different structural solutions, depending on the fusion among design, technique and building methods (Tonietti et al.). Furthermore, the in-situ study is not always able to clearly illustrate the real situation characterising such an important and big building. An example is the continuous sense of disorientation that you can feel walking along the annular dark and narrow corridors, caused by the regular repetition of the building elements and by the complex system of vertical connections among the different levels. In such cases the 3D data bank is very useful: the point cloud, which can be viewed by unusual perspectives (generally impossible in real life), enables a better perception of the total space of the structure by compensating for the physical limitations and the visual hindrances present in the real world. The 3D survey of the Basilica della Madonna dell'Umiltà highlighted (and made it possible) the quantification of the number of ribs (thirty-nine, of which: eight angular, eight at the base of the lantern, seven central and sixteen middle), as well as their correct positioning, form and dimension; the exact placing and size of internal and external chains; the actual thickness of the two calottes; the building materials and techniques; the past interventions of consolidation; the internal connections, both horizontal and vertical; the cracks present on both calottes, highlighting the most damaged awnings; the existing links among geometry, structure and deformations shown over time.

3.1. Materials and building techniques

The first study aiming at investigating the structural typology of the Vasarian dome was carried out by Giovan Battista Nelli at the beginning of the 18th century. In his work "Discorsi di architettura," in the chapter on constructions without centring, he used the Vasarian work as a basis for comparison with

the Brunelleschi's dome, in order to enhance its building technique (which has evidently not been employed in Pistoia, considering the structural problems that instantly occurred). Nelli set the building of the dome of the Umiltà in a wider context: following a wise technical and design path leading to the perfect execution of domes with polygonal plan and two calottes, with or without centring, to avoid any negative consequences (Tonietti et al. 1993).
The ample literature available on the dome of the *duomo* of Florence unveiled its building and structural operation. One of the most important elements is the arrangement of the bricks in the awnings, which develop curvilinearly and draw conical surfaces, forming concave lines to the top, called "corda blanda". According to prof. Di Pasquale, the result is a dome similar to the rotating one, self-bearing during the building phase, as well as complete solidarity of the awnings even next to the corners (Corazzi and Conti 2011). There is little doubt that Giorgio Vasari, while creating the dome of the Umiltà, took Santa Maria del Fiore as a reference, but he adopted another building technique, quite rough and lacking any particular trick, which led to a completely different result (despite the reduced dimensions: 2,800 tons for the Umiltà against 24,000 tons for S. Maria del Fiore) (Tonietti et al. 1993). The Vasarian dome was clearly inspired by S. Maria del Fiore in the two-calotte structure, the chromatic contrast between the stone ribs and the bricks covering the awnings and in the lantern layout. Structurally speaking, however, it looks more like the Florence baptistery than the Brunelleschi's model: the bricklaying on pyramid beds and the middle ribs parallel to the awnings. Vasari's formal reference is Michelangelo and the hemispherical shape of the dome of Saint Peter's Basilica. Actually, they share the same destiny: instant and worrying static problems affected it some years after its completion (Tonietti et al. 1993). The Pistoia dome, divided into eight ribs now covered with copper and framed by chains, stresses the architectural importance of the Basilica of Pistoia (Figure 2). It is set on an octagonal tambour and is composed of two calottes representing the extension of the underlying piers (Figures 2, 3).

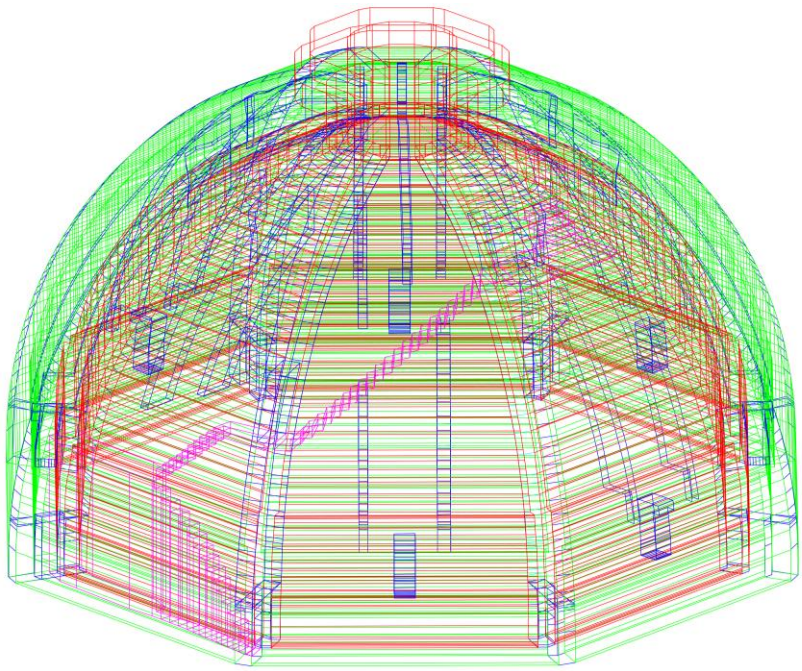

Figure 2 – On the left, External view of the dome.
On the right, Axonometric view of the 3D model of the dome (wireframe 3D).

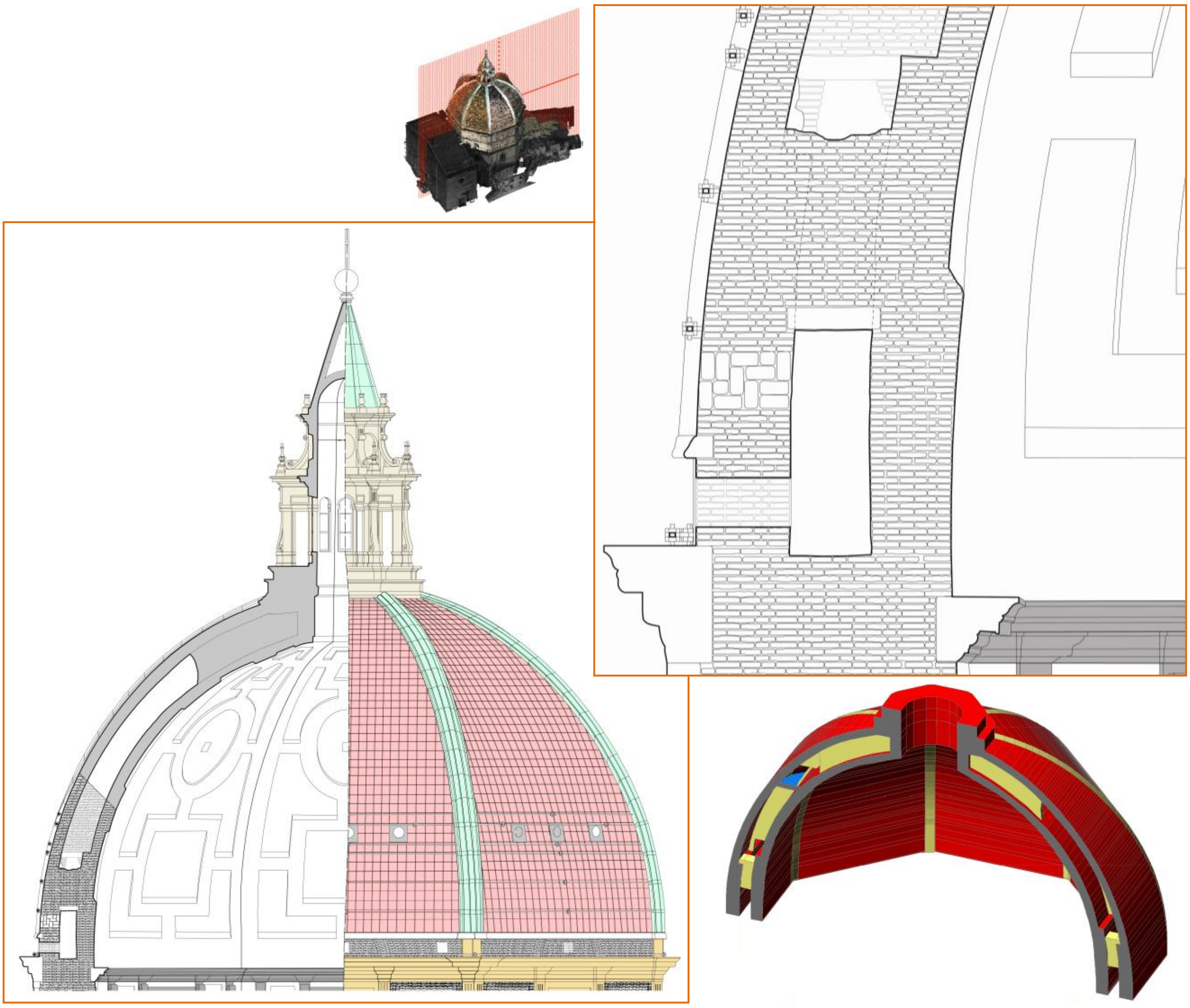

Figure 3 – On the left, Section and elevation of the dome. Upper left, Section plan.
Upper right, Detail of the section providing information on building materials and elements.
Lower right, Cut-away axonometric view of the dome.

The two calottes form an air space whose ground surface is at approx. + 29.60 m from the floor. Starting from the ground surface, they present two tapers: the one of the inner calotte is at + 4.60 m, while the one of the outer calotte is at + 3.50 m. The two bodies have a pretty similar wall section, with a higher thickness under the tapers (approx. 1 m for the outer calotte and 0.80 for the inner one); from this point on the calottes becomes thinner and thinner, reaching 35 cm (the minimum value) under the lantern (Figure 3). The two calottes are linked by thirty-nine ribs, of which: eight angular, sixteen middle, seven central and eight supporting the lantern. They all converge on the centre, even though their development is not regular, and only the middle ones are perpendicular to the two calottes (Figure 4). The eight angular ribs are located at the vertexes of the octagon and they are walled up starting two metres from the impost up to the base of the lantern, with a radius of curvature whose centre is along the starting axis of the ribs. The resulting dome is semi-circular. The ribs have a sandstone base and a brick body; as in the final part they are not flat, in the connection between the dome and the lantern gravel and mortar were poured. The two domes are further linked by sixteen middle ribs, two per each awning, starting from the taper of the inner calotte, where they are placed perpendicularly to the latter and ending at approx. + 13.00 m from the impost. They have a brick body and a sandstone base resting on two brick shelves, while at the centre of each awning there are seven middle ribs starting at the same height compared to the angular ones and ending at the external taper.

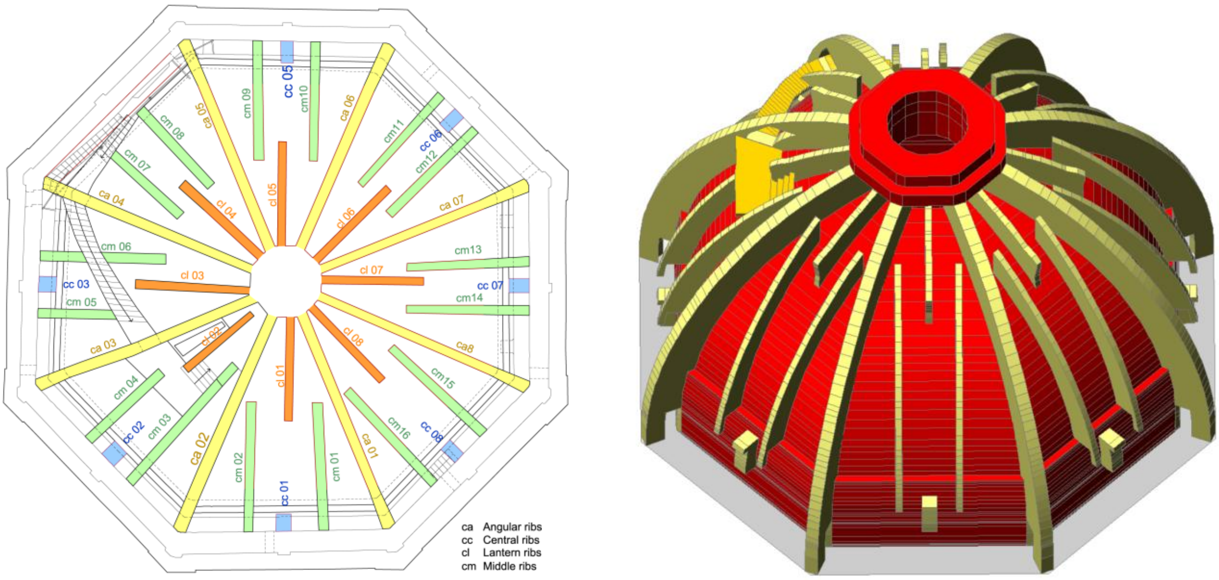

Figure 4 – On the left, Schematic plan of the ribs. On the right, Axonometric view of the 3D model of the dome.

To support the lantern there are eight central ribs, which fall down from the top following an irregular and non-radial planimetric development (as expected) and stop next to the middle ones. Their layout and the different building technique suggest that these are the ribs added afterwards and mentioned by Jacopo Lafri in his report dated 1620. Probably, they were added during the construction of the lantern, when Vasari became aware of its huge mass. The Vasarian dome is entirely made of brick masonry. As it emerged from the documents, low-quality materials were used to build the dome, resulting in very poor masonry compage, highly below the qualitative level required by such an important work. According to Lafri: *le calotte sono male manipulate; perché ora si muovano a terzo auto, ora a semicircolo; poi ritornano a terzo acuto, e così vanno ondeggiando, poi per altro terzo che sono gli angoli dei costoloni della cupola di fuori vanno serpendo in modo che si viene a false intersecazioni (calottes are wrongly manipulated: sometimes their development is at 'terzo acuto,' sometimes semi-circular, then at 'terzo acuto'*[2] *again, like waves; in the corners of the ribs of the dome they move like snakes creating false intersections).* The bricks used for the awnings and ribs vary in thickness and length. The laying is rough and the mortar joints are irregular, more than 1 cm thick. According to Lafri, the bricks of the dome are the ones to blame, because of their poor quality and wrong scarfing.

The occasional presence of Vasari in the building site could be the cause of the poor accuracy in the choice of the materials and the way they were laid down. In fact, he only performed some short inspections, at monthly intervals, while heading towards other places. He considered the Umiltà complex a very important work, but it is easy to understand why the court artist, loaded down with more responsibilities, decided to focus his attention on ducal buildings, such as the Uffizi and above all Palazzo Vecchio. However, if we consider Vasari's artistic career, he prioritized painting. His choice reflected on the way he used to organise more and more demanding work efforts. He entrusted Master Bernardo with the management of the works at the Umiltà; unfortunately, this reliable collaborator was already engaged with the works in Florence, so he could not keep a constant eye on the Pistoia building site. That is why there was also an "assistant master," controlled by the master himself and paid less. Such a delicate challenge suffered technically the absence of his creator and interpreter, who was well aware of this risk. In fact, he published the whole text of the letters in which

[2] TN: a type of lancet arch, where the centres of curvatures are at a distance of 1/6 from the arch axis, i.e. 1/3 from the ends of the span.

an old Michelangelo regretted the serious building error made in the St. Peter's Basilica, caused by his forced absence (Belluzzi 2002).
What is particularly relevant is the building technique of the ribs and awnings. In both cases, the brick groot beds never follow the radius of curvature of the dome. The horizontal angle is no more than 20°-25° (even on the top) (Tonietti et al 1993). The round shape is rough: a row of bricks overhangs compared to the lower ne. This phenomenon is particularly clear next to the top, where bricks were found, forming a 4-5 cm.

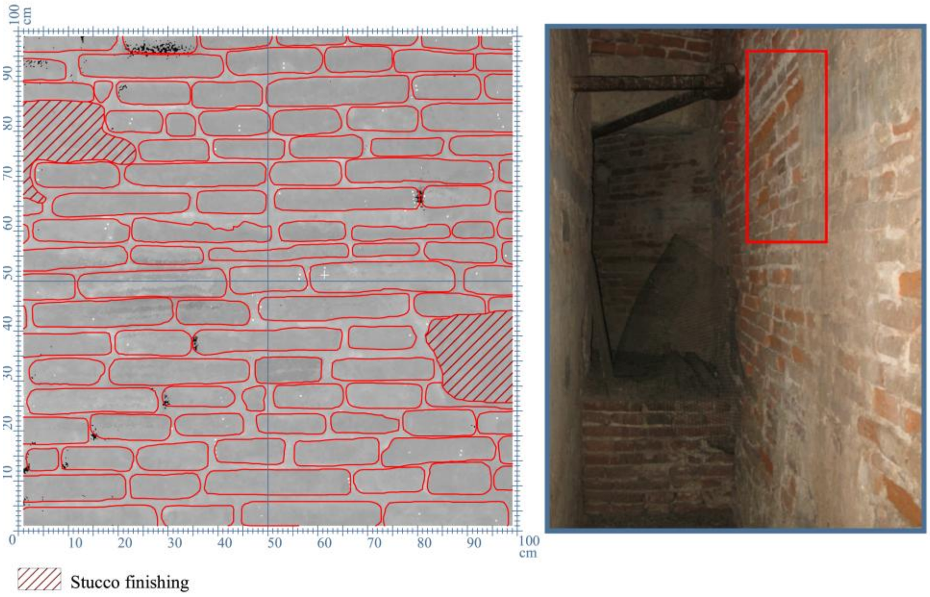

Figure 5 – Detail of the internal masonry of the outer calotte. On the left, Vectorialization of the masonry compage overlapping the orthogonal image of the point cloud.

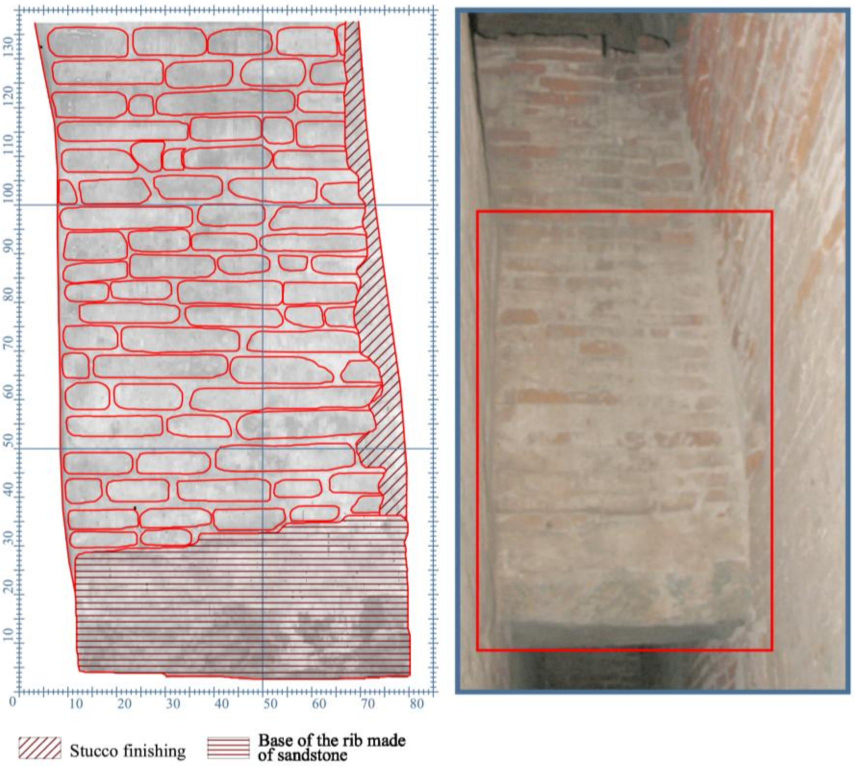

Figure 6 – Detail of the masonry of the middle rib (cc 05). On the left, Vectorialization of the masonry compage overlapping the orthogonal image of the point cloud.

The visible ribs of the brick joints are clearly aligned, as the laying is performed on pyramid beds (Figures 5 and 6). This pretty effective technique for medium-volume roofing, is characterised by unfeasible scarfing among the awnings. The encircling effect of the outer calotte does not occur in the dome of the Umiltà because partial separation joints form next to the angular ribs due to the masonry compage made of perfectly horizontal rows. The result is the lack of structural continuity among the awnings and between them and the ribs. For this reason, orthogonal intermediate spurs were constructed on the octagon sides, in order to ensure a connection between the two calottes. Structurally speaking, the Pistoia dome is far from the one of Santa Maria del Fiore. With the conical bed solution Brunelleschi obtained complete solidarity of the awnings even at the corners. Vasari's idea, taken from the Florence baptistery and not from Brunelleschi's dome, make scarfing of two adjoining awnings impossible, as the bricks that should overlap are on incident inclines. Despite his undisputed genius, he did not understood Brunelleschi's structural lesson. Michelangelo too, while facing the project of the Vatican dome, studied S. Maria del Fiore and surveyed all its measures; after having outlined a stilted dome, he changed its profile and prepare a model provided with hemispherical roofing. The Uffizi's architect did not manage to develop his own constructive thinking, limiting himself to a mere imitation of both solutions.

3.2. Map cracking and deformations due to the passing of time

Map cracking is made of two groups of cracks. The first can be observed directly from the inside of the place of worship and runs symmetrically on vertical plans that converge on the building axis, cutting it into eight segments up to a height corresponding to an approx. 60-degree angle from the level of the impost (Figure 7). The domes are subjected to a double effort system: general compression on the meridians and traction on the parallels next to the impost.

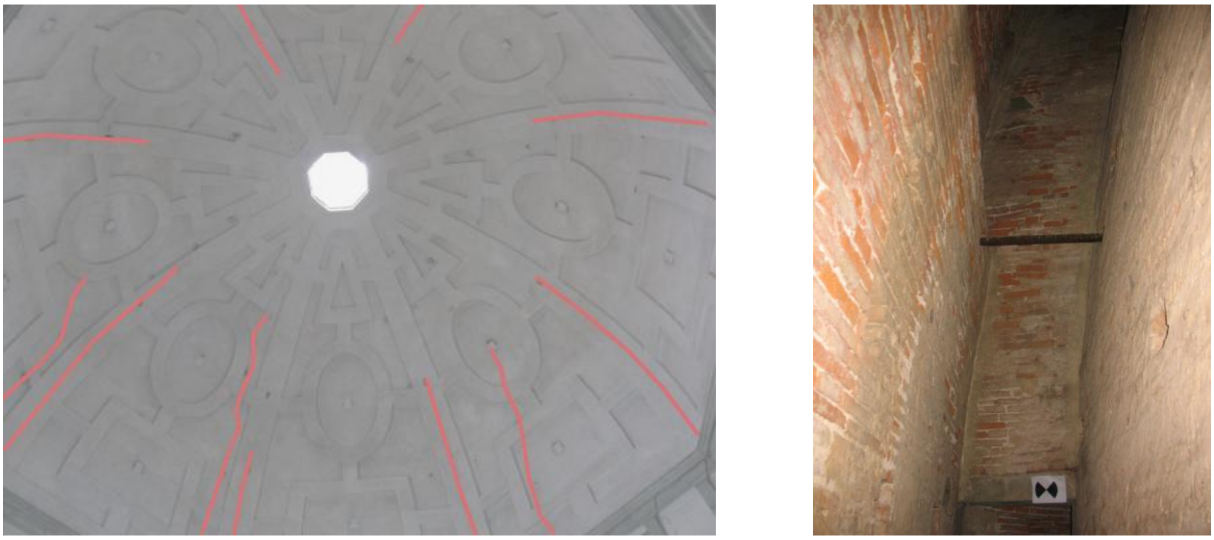

Figure 7 – On the left, View of the dome from inside the Basilica, where the first group of cracks is highlighted. On the right, Image showing the second group of cracks.

These cracks are larger at the base, probably where they first appeared. They occur in the weakest levels of the masonry compage, i.e. the corners between each awning. Over the centuries, encircling chains were used to solve the problem (Tonietti et al. 1993). The majority of them are located outside the dome. Through the 3D model of the point cloud we identified and catalogued all the chains present in the octagonal body and in the dome, detecting their type, planimetric and altimetric position, structural function and possible dating and identification. The chains inside the Vitonian hall (form c 01 to c 33) were added by Vasari to consolidate the structure before vaulting the dome. The chains in the tambour and in the dome (from c 34 to c 78) were added to oppose to the instabilities due to the passing of time (Figure 8, Table 3).

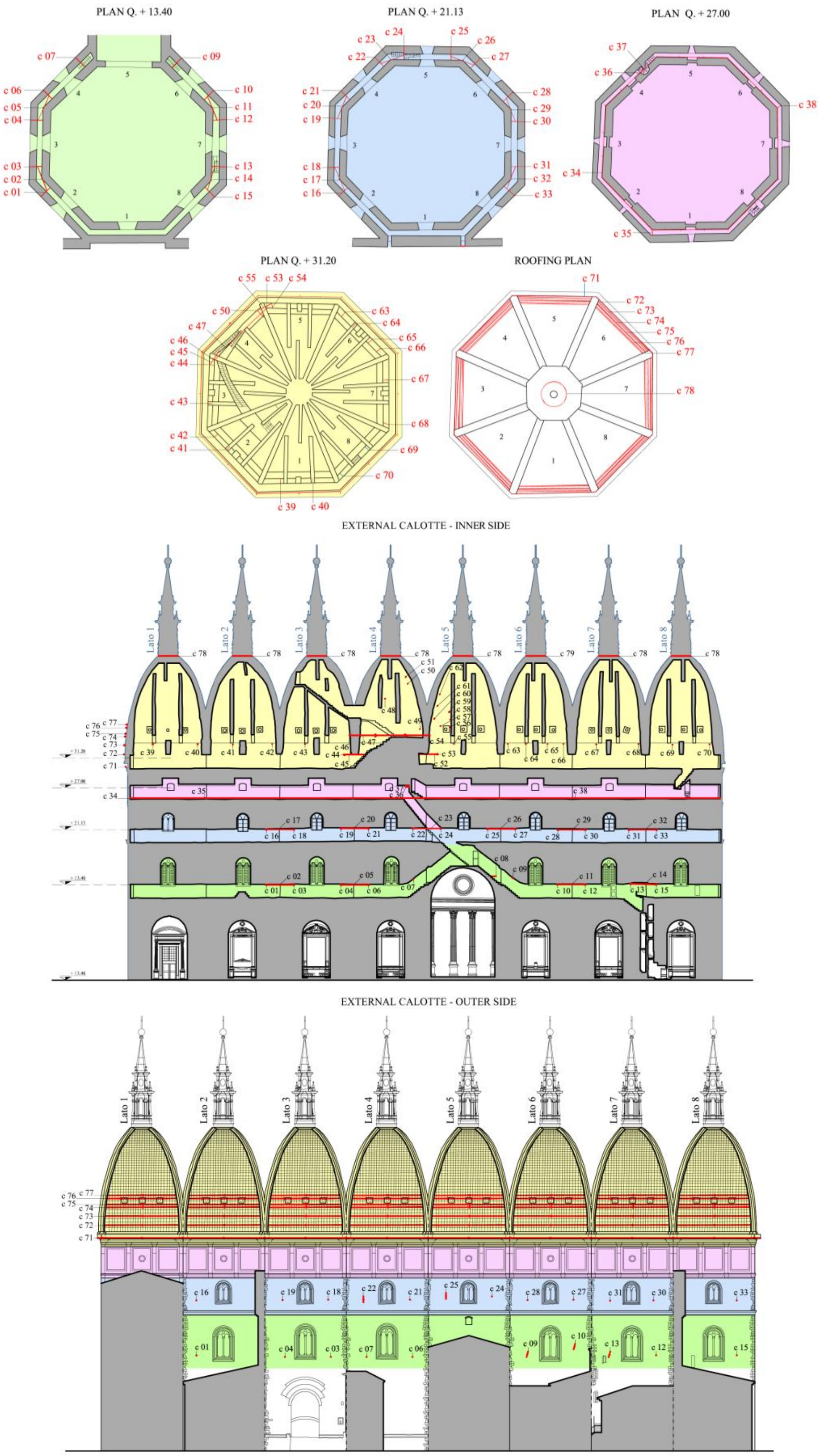

Figure 8 – Identification and cataloguing of the chains in the octagonal hall and in the dome.

Table 3 – Identification and cataloguing of the chains in the dome.

	No. chain	Side	Height (m)	Type	Structural function	Possible dating and identification
DOME	c 39	Side 1	+ 33.15	Metal bar	Shell connection	
	c 40					
	c 41	Side 2				
	c 42					
	c 43	Side 3				
	c 44		+ 31.60			
	c 45	Side 3 - Side 4				
	c 46	Side 3	+ 34.40			
	c 47	Side 4				
	c 48		+ 39.50	Wooden bar		
	c 49		+ 35.50	Metal bar		
	c 50			Wooden bar		
	c 51					
	c 52	Side 4 - Side 3	+ 31.70	Metal bar		
	c 53	Side 5				
	c 54		+34.40			
	c 55		+33.15			
	c 56		+ 35.50	Wooden bar		
	c 57		+ 35.70	Metal bar		
	c 58			Wooden bar		
	c 59					
	c 60					
	c 61					
	c 62					
	c 63	Side 6	+ 33.15	Metal bar		
	c 64					
	c 65					
	c 66					
	c 67	Side 7	+ 33.15			
	c 68					
	c 69	Side 8	+ 33.15			
	c 70					
	c 71	Exterior of the dome	+ 29.88		Circular union of the dome	1572 - 1575 Giorgio Vasari after the first cracks appeared.
	c 72		+ 31.72			
	c 73		+ 32.95			
	c 74		+ 34.25			
	c 75		+ 34.66			1584-1586 Bartolomeo Ammannati
	c 76		+ 35.48			
	c 77		+ 35.90			
	39	**TOTAL OF THE DOME CHAINS**				
LANTERN	c 78	Inside	+ 44.30	Metal bar	Stability of the lantern	1572 - 1575 Giorgio Vasari after the first cracks appeared.
	1	**TOTAL OF THE LANTERN CHAINS**				
	78	**TOTAL OF THE CHAINS OF THE OCTAGONAL BODY AND THE DOME**				

More problematic is the other group of cracks, which occurred in the movement of the two parallel shells, as mentioned by Lafri in 1620 (Figure 7). These phenomena cause remarkable detachments between the intrados curve of the angular ribs and the extrados curve of the internal dome, even though the movement is amplified by the concrete mortar wedge that links the two building elements. Another detachment can be seen on the external side of the staircase, which is completely detached from the superficial shell. The corresponding movement between the two calottes causes cracks that cut the middle ribs as well as those at the base of the lantern, as they cannot follow the two shells at the same time. The key issue is certainly the two-shell structure, as well as the difficulty of creating a true collaboration among the different elements. In Santa Maria del Fiore the compact masonry structure is obtained through the Brunelleschi's solution, and the sharply prevailing structural weight of one of the domes limits or even removes this kind of problem (Tonietti et al.) Since the very beginning the dome showed great weaknesses. The first was surely due to the influence of the heavy lantern (which represents 1/8 of the whole weight, while in S.M. del Fiore the lantern-dome ratio is approx. 1/25), which led to the insertion of ribs on the base in order to distribute the excessive weight of the lantern on the angular ribs. Another weak point is the building technique. Because of the brick layout (horizontal rows), the external dome never creates an encircling effect, as a separation joint forms in these corners. The measures taken in the last years aim at stopping the opening of the octagon corners, through the insertion of chains, but they did not manage to face the other movement (Tonietti et al. 1993).

4. CONCLUSIONS

This report deals with a step of the survey carried out on the monumental complex, which will be finished only after the re-opening of the building site. Thanks to the surveys carried out up to this moment, we can state that the three-dimensional survey of the Basilica della Madonna dell'Umiltà has highlighted and made it possible to quantify the following:
- the number of rib, their correct placing, form and dimension;
- the exact placing and dimension of the internal and external chains;
- the actual thickness of the two calottes; the building materials and techniques;
- the consolidation of the interventions; the internal connections, both horizontal and vertical;
- the cracks present on both calottes, highlighting the most damaged awnings;
- the links among the geometry, structure and deformations shown over time. The new digital technologies both rationalise and streamline the survey procedures while also creating the new infographic representations that can easily adapt to the multiple needs of the scholars and operators (architects, archaeologists, engineers, restorers, historians).

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