GEOMETRIC SURVEY FOR THE STRUCTURAL ASSESSMENT OF THE ARCHITECTURAL HERITAGE: THE CASE OF THE CUPOLA OF THE BAPTISTERY OF S. GIOVANNI E REPARATA IN LUCCA

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ABSTRACT

The present work reports an experimental combined application of laser and photogrammetry techniques. The current research aims to the testing of both innovative (scanning instruments) and classical survey techniques applied and architectural and structural objects, as to evaluate their interoperability for a conjunct usage with static purposes.
The object of the study is the brick masonry Renaissance cupola of the ancient baptistery of S. Giovanni in Lucca, constructed over a square basis of 14 m side at the level of 15 m from the floor. The main features of this cupola reside in its shape, remarkable dimensions and construction technique. Authors have carried out a survey aimed at the study of the shape of the intradox surface as well as at the reconnaissance of the hidden structures (safety arches in the West-facing webs) and of the crackings, each and every one necessary elements for a static check.
Terrestrial laser scanning has enabled fast, smooth surveying of the coordinates of many points of the surface. An accurate choice of the points and their subsequent elaboration with specific software have led to the comprehension of the shape and of the geometrical irregularities as well as the definition of an ad hoc interpolating surface, actually a mesh, for static checks.
The photogrammetric techniques, together with all the information concerning the surface masonry patterns, help to understand the construction phases and to identify, characterise and locate the existing damages. Thus, the combination of different survey techniques has shown its effectiveness in the case of the static assessment of architectural structures.

1. INTRODUCTION

Our country has an immense wealth in the field of cultural goods: there is no city which doesn't contain a patrimony, be it small or great, of architectural, artistic or archaeological interest Without doubt, an essential factor for the exploitation of this patrimony is to hold a certain amount of knowledge both in historical-artistic terms as well as in terms of the characteristics of position, form, geometry and colour.
With this is mind, over the past years, the disciplines of the survey, have improved the techniques of measurement, making them suitable for the situations and the possibilities offered by the technology: from the simplest methodologies of the direct survey to those derived from the descriptive geometry and finally, today, with the tools from the modern geomatic.
It is the sector of civil engineering and particularly the architectural sector which constitutes a relatively recent and particularly interesting filed of application. Its interest lies in the morphological and dimensional characteristics of the objects to be surveyed which often represent insurmountable obstacles when using classical techniques.
This work introduces the survey of the intrados of the dome of the Baptistery of *S Giovanni and Reparata* in Lucca. The work provides an opportunity to apply and experiment with different survey methods using the innovative scanning laser system, combined with photogrammetric techniques and the purpose being to check the problem linked to their integration, but also the potentialities offered by each of them.

2. THE DOME OF THE BAPTISTERY OF *S GIOVANNI AND REPARATA* IN LUCCA

The baptistery of *S Giovanni and Reparata* makes up part of the monumental complex situated in Lucca between Piazza St. Giovanni and Piazza del Duomo (fig.1). The church itself following the Latin cross design with three bays, dates back to the 12th century. Its original structure is an Episcopal-Palaeochristian cathedral with a single bay. An ancient cathedral built on the ruins of an even older Roman thermal structure.

Fig. 1 The monumental complex of *SS Giovanni and Reparata* in Lucca

The first framework of the baptistery, following to the birth of the ancient cathedral, was a square structure with three apses with roof coverage. It was however destroyed and rebuilt and subsequently restructured, according to an unknown chronology, to the Romanesque framework, which can be dated back to the beginning of the 12th century. At the end of the 16th century, the hipped vault which we can still see today was built in brick and to a height of approximately 15 m from the floor on a square lateral base of 14 m, with eight groins and webs in tile (fig.2). The ceiling raises for around 15 m and is surmounted by a lantern. Figure 3 shows a longitudinal section of the church and the baptistery.

On the east webs two unloading arches surmount the vault above to the preexisting apse structure, which was dejected because it seemed to threaten the stability of the dome.

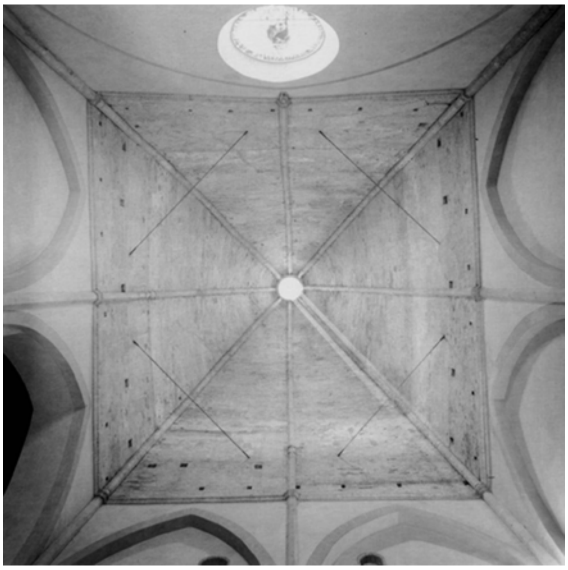

Fig. 2- view of the lower part of the intrados of the dome.

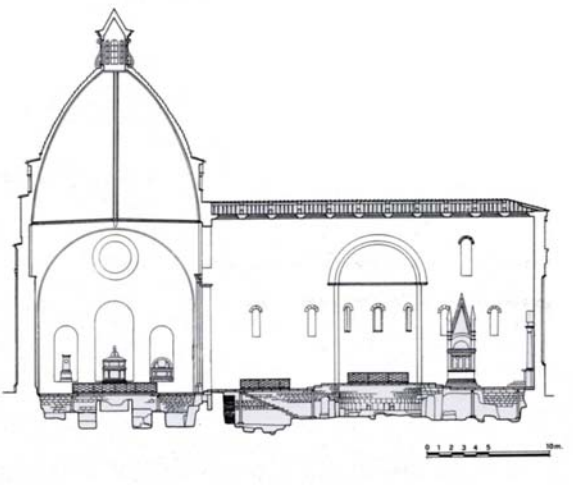

Fig. 3-longitudinal section of the church and baptistery.

Originally plastered, the intrados shows the frame of the webs which emphasizes rows of alignment, rectilinear up to ¾ of the total height of the current vault joined through four pendatives to the terminal portion, characterized by rows with a ring course. You can also notice an interesting fissure on the webs which probably motivated the insertion of four iron chains embedded into the walls whose trace is still recognizable, and another four which are clearly visible and are placed in the corners of the room and date back to the second half of the 10th century.

The spatial charm and the architectural message of the whole dome brings to mind other similar structures of coeval buildings even though the shape may be different and the structure larger. It also allows us to draw a comparison with Brunelleschi's dome in Florence Cathedral built decades later.

3. THE SURVEY OF THE BAPTISTERY

3.1. The project and the phase of acquisition

The survey of the baptistery was performed using the photogrammetric and laser method for the vault's walls and webs, on the basis of a principle web of organization performed topographically. As shown in figure 4, a closed traverse of 4 vertexes, connected at another two points, respectively to the outside of the Baptistery and inside the adjoining church, can be outlined. Subsequently four other points were added to the corners of the baptismal hall in order to bring forward the intersection coinciding with each of the individualized photogrammetric points of support, in the lowest target point and the highest from architectural detail (in order to collimate these a pointer laser was used which reduced the possibility of error during the contemporary collimation of two instruments). Station Point 1000 was identified in the center of the font, inside the small circular hollow, below floor level, in order to be able to frame the structure to the relative underlying archaeological area, the vertexes 2000 and 3000 are identified from details in the brickwork flooring of the loft in the area of the archaeological excavations, while point 4000 is situated in front of the stairs that lead from the church to the baptistery.

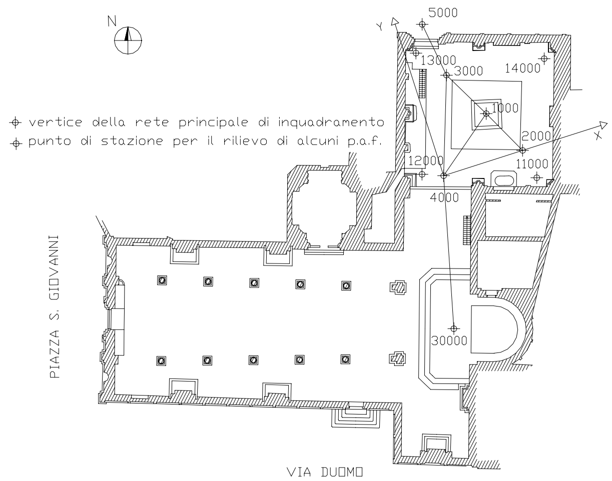

Fig. 4-The topographical web of organization.

Being an architectural article of considerable prestige, the materialization of the inside vertexes with permanent signalings, have been avoided, instead choosing architectural details described by an accurate monograph.

The measuring operations were carried out with a Leica TC1100L station (composed of an electronic theodolite with automatic reading of the angular values, resolution ± 1mgon, and an electronic infra-red diastimeter, precision ± 2 mms + 2 ppms, and with the Geodimeter 412 station, of angular resolution equal to ± 1 mgon and precision on the distance of ± 5mm+5mm/km).

For the photogrammetrical survey Rolleimetric 6006 camera was used with a focal length of 80 mms and for every wall 6 frames were shot without stereoscopic covering, whilst for the vault the photographic acquisition required 8 frames (two for each side). Figures 5 and 6 show the images of the couple of frames related to the East side.

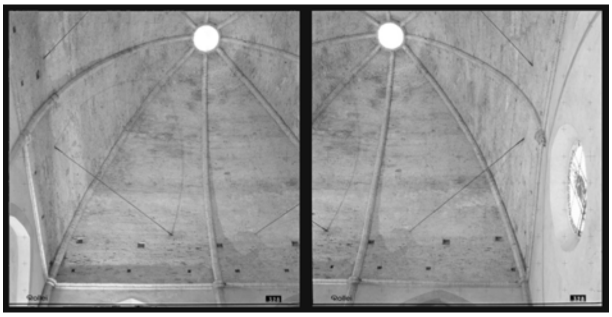

Fig. 5 & 6 - Frames of the East side of the vault.

For the survey of the dome the Riegl LPM-25HA laser was used, with a precision of ± 8 mms in the measurement of distance, of ± 0.01 gons in the angular positioning, able to acquire 100 points per second in a field of measurement of 300° x 360°. The instrument was arranged at station poiont 1000, from which it is possible to detect both the internal face of the dome and, and that of the walls. (fig. 7).

Fig. 7- The laser in position.

In the project phase the best configuration was sought, in order to be able to gain metric and radiometric information of the tile face, in doing so the instrument operates on a mesh system equal at least to the length of the smallest element that is to be surveyed. In this case a mesh of approximately 2cm was chosen, which, seen from a variable distance from a minimum of 17m and a maximum of 30m (fig.8) determined the entity of the middle angular step of the scanning that has been fixed in the order of 0,06 gons. Such a mesh obviously thickens towards the lower part, in virtue of the curved surface of the dome, but it however allows it to gain an acceptable value even in the highest points.
In order to be able to control better the acquisition of data phase, it was decided to proceed with four separate scannings, one for each side, always carried out from the same station point (vertex 1000), for the duration of approximately 30 minutes which produced variable dimension files from 5.08 MB to 12.31 MB up to a total of 4220250 points.
During the acquisition phase the software 3DRISCAN allowed the definition of general parameters, as the step and the area of scanning and the visualization in real time of the results with distance-measuring and radiometric representation. The final product of the scanning is a spatial model made up of points whose three-dimensional coordinates are known, and is exportable through interface dxf and easily legible with any graphic software.

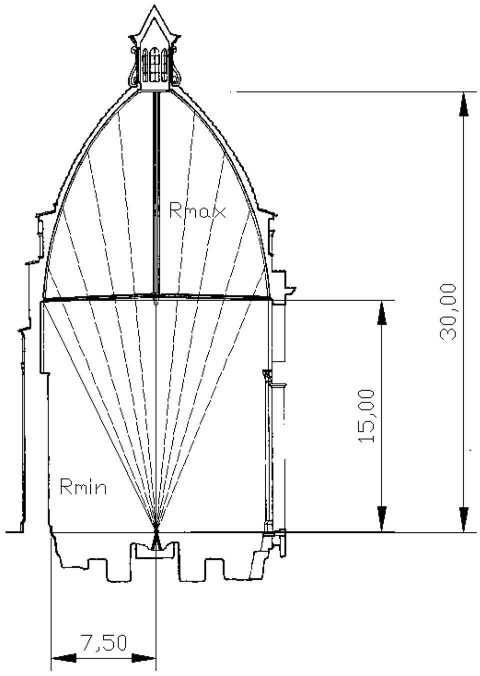

Fig. 8-outline of the survey project.

3.2. The elaboration of the acquired data

The data, recorded in the form of dense clouds of 3D points has been recorded in a single reference system and elaborated with a specific software which is capable of lining up the scannings, gathering them together in a single group of points. (fig.9).

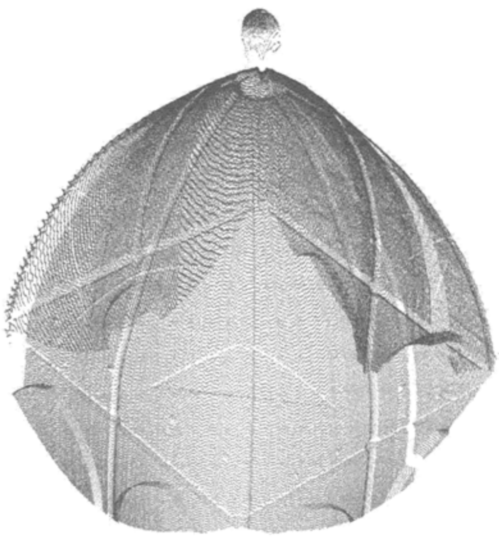

Fig. 9-The global cloud of points.

In order to be able to recreate a surface upon which the extraction operation of sections, and contour lines could be carried out, a specific software was used which allowed the execution of polygonal mesh through the aggregation of the previously lined up data. (fig. 10).

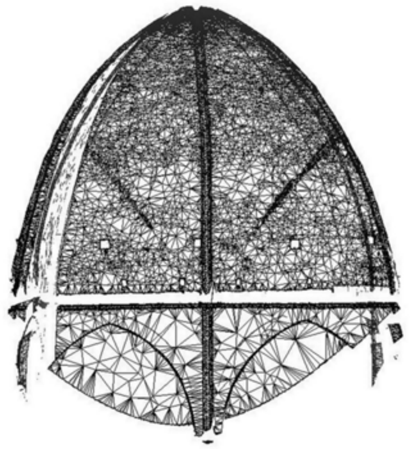

Fig. 10-The mesh created by the aggregation of the points.

4. THE EXAMINATION OF THE RESULTS

On the basis of the information obtained from the survey it has been possible to understand the structure of the dome, making some considerations into the shape of the surface of the intrados and on the building techniques used.

4.1. The shape of the surface of intrados

The mesh obtained by the treatment of the filtered data, after the reconstruction of the lacking parts, was used to draw the contour lines and vertical sections.
The vertical sections of the only web were obtained using vertical plans not passing them through the “center” of the dome since the irregularity of the groins, a vertical section could have intercepted groin and web at alternate stages.
The sections and level curves obtained were exported in “dxf” format for the following elaborations and the comparison with the noted equation, through the use of graphic programs with and ample diffusion.
The horizontal sections of the web have shown a rectilinear course in the overlapping sections of the adjoining groins, emphasizing the possibility of bringing the score surfaces closer. (fig. 11). Furthermore, every contour line shows itself to be made up of a broken line with the vertexes corresponding with the angles and with the middle points of the side of the base perimeter. Such a conformation, statically favorable, allows the formation of mechanisms which resist the arch in a horizontal level on the inside of the thickness of the brickwork.

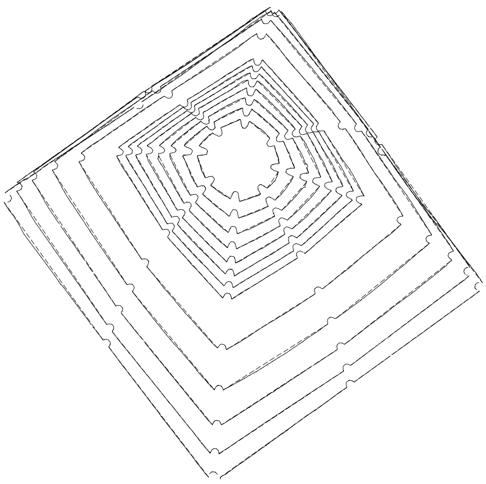

Fig.11-Comparison of the contour lines and broken lines.

From the contour lines it was possible to obtain the performance of the profile of the groins, connecting the edges to following lines with 3D polylines (fig. 12).

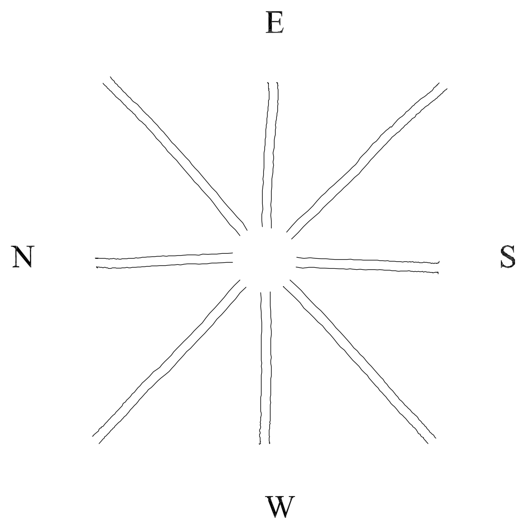

Fig.12-Individualization of the groins

The vertical sections of the web have been compared with known curves.
The section carried out in a North-Southerly direction, in correspondence with the connection between the web and the median groin, and compared with a tricentric curve (fig. 13). The contour was marked out taking into consideration the correspondence point of which the change of the frame of the rows of bricks can be checked, individualized by the survey. Note the good arrangement with the tricentric curve which shows movements up to a maximum of 3 cm. Besides the bigger arch which continues as far as the axle of the transversal section, it has the property to intercept a segment of length exactly equal to twice the semi-length of the vault.

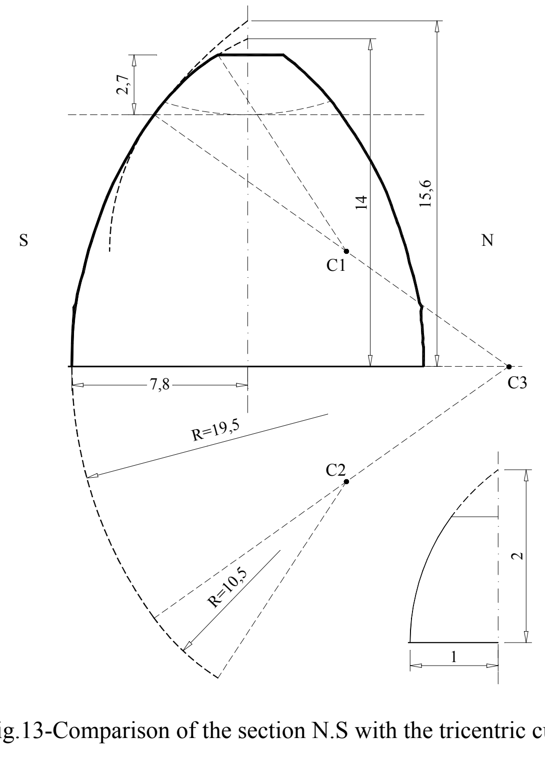

Fig.13-Comparison of the section N.S with the tricentric curve

The comparison of the section with a catenary arch and horizontal axle, with a ratio 1:2 semi-width and arrow, shows however bigger movements in the protruding contour.
The two vertical sections carried out along the opening between the webs and the diagonal groins were compared with the circular arches with a radius of 18.6 m and 18.4 m respectively. (fig. 14).

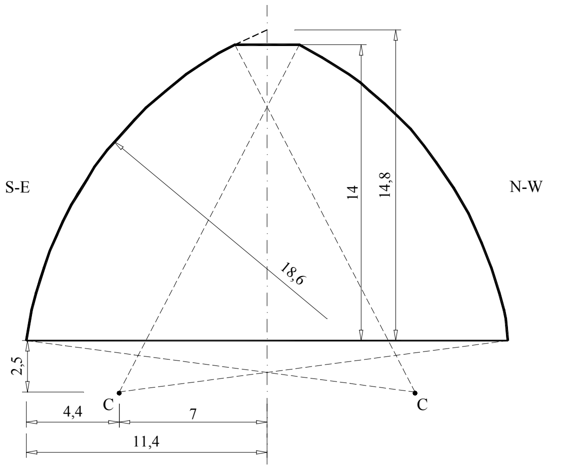

Fig.14-Section S.E - N.W.

In both cases, the center of the circular arch is approximately on the inside of the perimeter of the base and at the level of approximately 2.5 m above the impost line. To be noted is the good correlation between the protruding profile and the arch which diverges locally by a few centimeters.

4.2. The building structure

From the raw data it was possible to recognize the profile of the two arches in the thickness of the wall of the web on the East side (fig. 15). The recognition of the fissure was possible only in the case of particularly deep lesions, and with the aid of photographical images, also the change in the frame of the bricks and the holes caused during construction. The reference of the position from the opening point of the diagonal chain was extremely simple, whilst that of the traces of the old chains required the use of a photographic image.

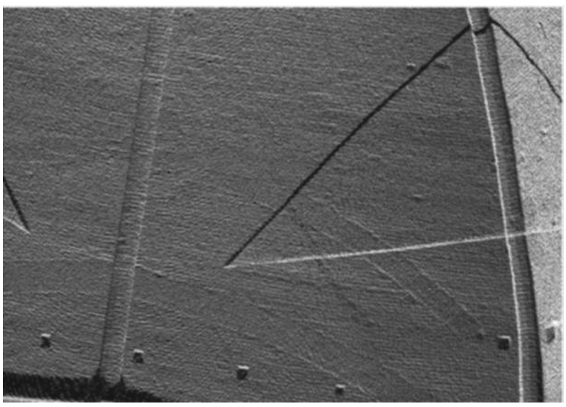

Fig.15- Details of the raw data of the East web.

Figure 16 shows the representation of the vectorial restitution of the webs on the East side, with the contour line and the signs of protruding architectural elements.

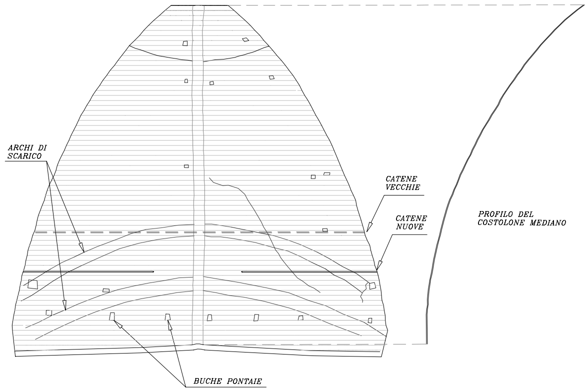

Fig.16-vectorial restitution of the sails on the East side.

The observations made allow us to formulate certain hypotheses on the building techniques: the angle of inclination of the row of approximately 60° in correspondence to the change of plot leads us to think of a construction without the aid of arched fixations up to that level. The lay-out of the following rows could have happened with the help of a taught rope of a variable length, bound around the center of protruding wooden joists and made to turn around the vertical axel. (fig. 17)

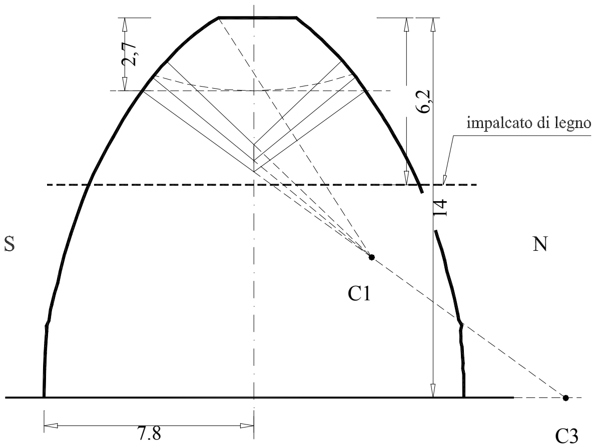

Fig.17- Vertical section with indication of the possible building technique.

4.3. The calculus model

By reconstructing the surface of the intrados with lined surfaces and exporting the model between the interface dxf in Sap2000, a calculus program of finished elements of ample diffusion, it was possible to construct a true and proper mesh in order to be able to valuate the current statical conditions and the wealth of the intervening reinforcements. The mesh shows to be composed of 4352 shell elements and 4488 knots. (fig. 18).

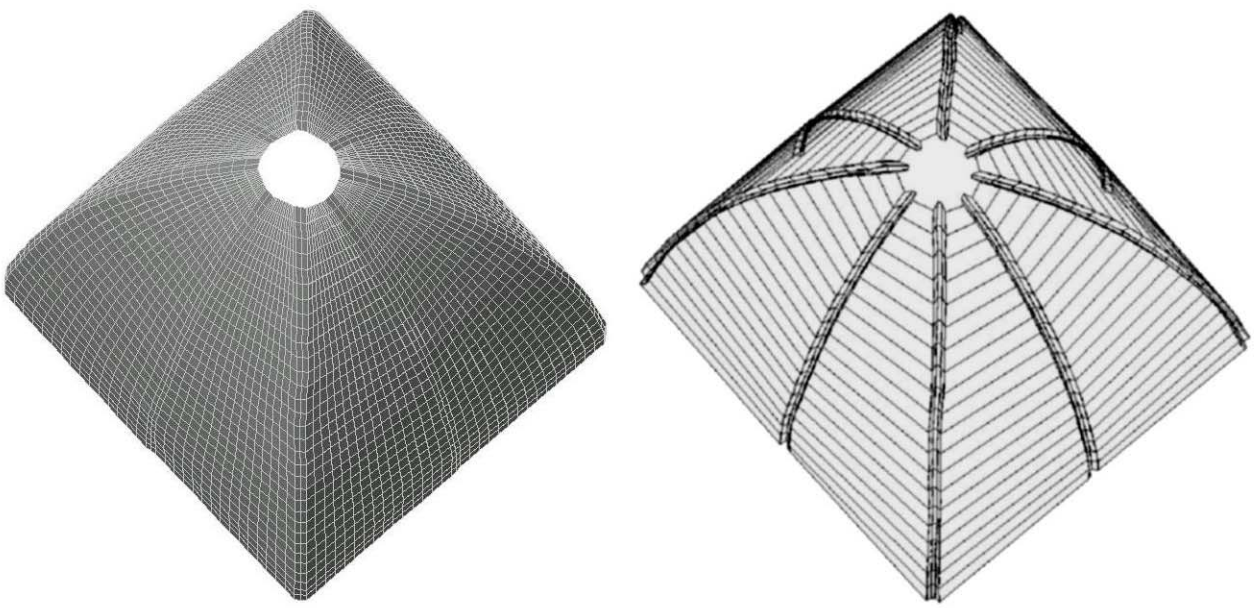

Fig.18-geometric Model and mesh for the calculation.

5. CONCLUSIONS AND POSSIBLE DEVELOPMENTS OF THE RESEARCH

The use of a laser allowed the surveying of a great amount of points that allowed us to study very closely the surface of the intrados of the dome. The combined use of the survey with the laser scanner and the photographical and indispensable techniques, was necessary to carry out a precise acknowledgment of details such as the fissure, the frame of the breaking and the crashed openings, in addition to the hidden structures such as the arches and the traces of following interventions of reinforcement. The advantage of an elevated precision in the measurements added to the quality of information easily obtained from the photographical images.
The possibility to carry out a calculus model, united to the relative information of the fissure and to the hidden structures allows us to interpret the symptoms of instability and to evaluate the wealth of the reinforcements carried out through the centuries which increase the current level of safety.
Until now the work carried out constitutes the base of a starting point for other studies and in-depth studies on the application of survey techniques carried out, on the study of the form of the surface of the dome and of the ancient building techniques used and on the statical valuations.

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