TOPOGRAPHIC AND PHOTOGRAMMETRIC STUDIES OF THE BEARING STRUCTURES OF THE CAPPELLA DEI PRINCIPI OF FLORENCE

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ABSTRACT

For the conservative restoration of historical buildings and cultural Heritage, it is crucial to compose a complete registration of structural data to verify many interdisciplinary and complex problems that involve different scaled parameters. For an extensive monitoring pattern, direct transducers and high precision levelling on structural nodes may detect any variations expressed in fractions of millimeters, but these data have to be correlated with other parameters expressed in centimeters or meters and spread on large surfaces (i.e a complete crack map of a building). A critical reading of structural data needs 3D restitutions and other graphical representations, as well as mathematical routine elaborations. Nowadays specific softwares offer a concrete possibility to make use of many different data sets in a single environment. Graphical and numerical data could interact at different model scales so that resulting 3D plotting elaborations may show several complex structural correlations. Similar guide-lines previously experienced for the *Cupola di S. Maria del Fiore* and for the *Battistero di S.Giovanni* in Florence were employed since the first phase of the study planned for the restauration works of the *Cappella dei Principi di San Lorenzo*. The acquisition process of technical data was carried out to obtain a complete integration among photogrammetric surveys and other consolidate structural investigations. Graphical elaborations derived by this approach show a kind of crowding of interesting pieces of information on some critical structural nodes in concordance to specific boundary elements of the SAP building model.

1. INTRODUCTION

No doubt the *Cappella dei Principi di San Lorenzo* is an interesting theme for architectural studies, but surveying operations here introduced were not planned to extract any styling or formal data. This study, carried out by the Department of Civil Engineering on request of the Soprintendenza ai beni Culturali e Architettonici di Firenze, Prato e Pistoia, was planned for the project of a complete structural monitoring system implemented with various diagnostic methodologies. The construction of the *Mausoleo Mediceo di San Lorenzo* was carried out in long time, in part for the complex inner decoration, in part for the floating economic situation of the Medici family. The work began in 1604 with the first stone of the cripta, and continued until 1740. The last part of the work was the inner paving decoration begun in 1882 and definitively concluded in the sixties. Equally articulated appears the structural composition of the monument. The building complexity was investigated since the seventies with detailed photogrammetric surveys and, as the time goes by, with any other kind of new measurement systems, creating a useful 2d, 3d data base of the main structural elements: *crypt*, *chapel*, *drum* and *dome*.

Figure . *Cappella dei Principi di San Lorenzo*

Figure . *Venceslao Spinazzi drawing (1797)*

Before any important restoration work, and in presence of a complex operative problem, it is crucial to obtain a complete set of technical data. This knowledge needs some routine studies about the definition of the historical picture, construction techniques, materials, structural characteristics, photogrammetric surveys, structural studies, crack map plot, and many other different technical data. The perspective adopted in this work was the correct understanding of the structural phenomena in action in the bearing structures, for a better individuation of the structural behavior of the building, and finally verify some structural hypotheses for the operative consolidation works. For that technical premises and for correlate multiple sequences of data and different hypotheses, a data base structure configuration open to relational encoding software was planned. In this way it is possible to verify in qualitative terms some structural hypotheses and emphasize elements acquired with various methodologies.

Figure . *External window and a rectified image*

2. ELEMENTS OF THE MONITORING SYSTEM

The project of a structural monitoring system generally depends on the building peculiarities and on the record data limits request. A preliminary phase of study is the identification of the main structural parameters, and subsequently the operative monitor system definition, involving the choice of technical instruments and their correct position on the structures for the best description of the phenomena trend. A monitoring system set-up for structural studies normally includes various kinds of instruments as barometer and thermometer stations for the measurement of temperature and atmospheric pressure, piezometer stations for aquifer level, and deformeters on the main lesions. In our area of study, in addition to these conventional instruments, a complex control system composed by four telecoordinometers for the measurement of planimetric movements and a topographic monitoring system was added for the measurement of vertical movements, in order to capture the "breath" of the bearing structure of the Cupola. On the base of specific structural hypotheses and with the aid of topographic and photogrammetric surveys, was then projected and carried out the structural monitoring system here described.

Records	Instrument	Label
Pression	1 Barometer	BA-1
External and internal temperature	3 Termometers	TA 1.1, TA 4.1 TA 7.1
Aquifer height variation	3 Piezometers	PZ 3.1, PZ 3.2, PZ 7.1
Crack enlargement variation	12 Deformeters	DEF 1.1, DEF 1.2, DEF 1.3, DEF 3.1, DEF 3.2, DEF 3.3., DEF 3.4, DEF 3.5, DEF 5.1, DEF 5.2 , DEF 7.1, DEF 7.2
Wall verticality variation	4 Telecoordinometers	TEL 2.1, TEL 4.1, TEL 6.1, TEL 8.1

Figure . *Installed instruments and their telemetry labels*

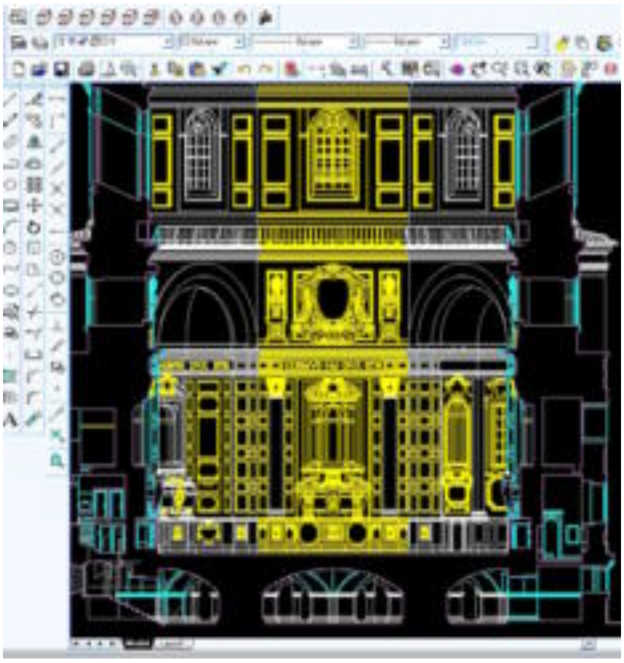

Figure . *Inner section*

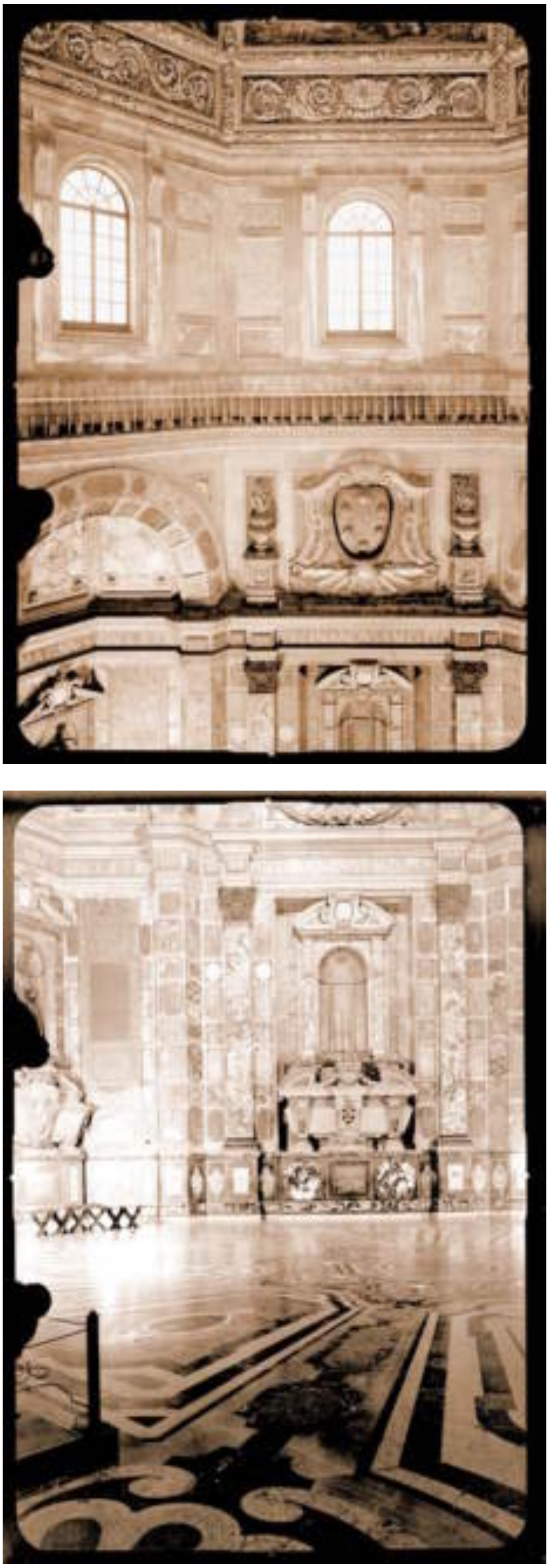

Figure . *Photogrammetric pictures from the seventies*

2.1 Monitoring of the planimetric movements of the bearing structure of the Cupola.

The recording system of the horizontal movements of the *dome* is made up with the mentioned telecoordinometer installed on the four walls main structural septa of the *chapel*. For an effective recording of the planimetric movements the telecordinometer thread suspension bars are strongly fixed to the mass of the building near the balcony. The impulse reading of the relative free movements is time to time electronically acquired and recorded by an external high precision photoelectric cell. A computerized system shows the evaluation data in real time and offers the possibility to set up reading, registration and transmission data rate in telemetry. Periodically, in winter and summer, accordingly to the season thermic records, planimetric movements are correlated with vertical movements recorded around these sensitive structural nodes at various levels of the structure. Final variation evaluation passes through the aquifer level stratum reading recorded from the piezometer installations in the immediate surround of the mausoleum foundations area.

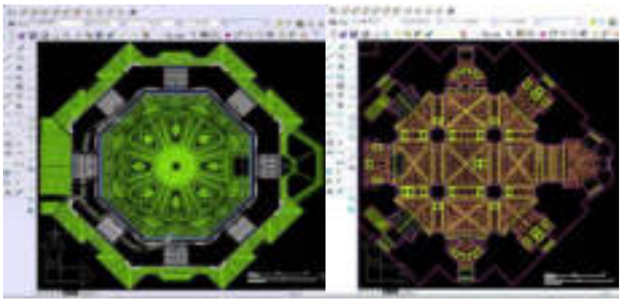

Figure . *Balcony and crypt plan view*

Figure . *Crypt key stone monitoring with a modified 3 meters bar code levelling rod for the reading from the top.*

2.2 Monitoring of the vertical movements

Surveying system methodology that employs high precision levelling lines offers an easy and accurate method for an effective support of a structural monitoring systems. Choosing an opportune monitoring time period, levelling lines are useful to complete the structural image of a building; in particular a regular monitoring could show some interacting elements in the structure-foundation-land system affected by bad-land phenomena. In subsequent times this methodology offers the c)

opportunity to control any corrective actions introduced by consolidation and restoration works. As planned in agreement with the structural and restoration experts, a kind of this monitoring system was then carried out. This method utilizes a high precision network of level lines and another series of bench marks acquired at short equidistance around the main line, as predisposed for the key stones of the *crypt* arches. Differential vertical data are recorded with a high precision Leica 2002 digital level instrument and with invar bar code levelling rod and elaborated data show an average ± 0.15 milimeter of standard deviation. Bench mark installation was obviously defined in agreement with the *Soprintendenza ai beni Culturali e Architettonici di Firenze, Prato e Pistoia* in order to obtain the minimal invasivity and a good stability for a correct differential trend reading. This part of the project result as an interconnection of level lines networks with more than 60 bench mark points on the main structural nodes at the foundations level, on the key stones of the *crypt* arches, on the paving of the *chapel*, and on the balcony under the *dome*. Other strategic check point bench marks were also installed near the piezometric stations and in correspondence to particular crack zones where the vertical data trend seems to be useful to verify and integrate the deformeter stations records. Vertical relative variations between the *chapel* paving and the balcony under the dome were checked with four small bar code invar signals mounted on each telecordinometer thread.

a)

b)

c)

Figure . a *Chapel telecoordinometers with small bar code levelling rods* c) *balcony levelling instruments*

In corrispondence to these four points and around the balcony ring, other 20 bench marks control points were also installed (fig.9c); differential records between summer and winter on these bench marks offer a good reference point of the total vertical lengthening caused by thermal expansion. These specific acquisition data have been correlated to the temperature range of the invar telecoordinometer thread; not a negligible data for about 30 linear meters Recently, the crypt arches zones seem to be interested by an additional load added on the upper floor for the restoration works and for some stone materials coming from the lateral *apses* actually lying on the paving of the *chapel.*

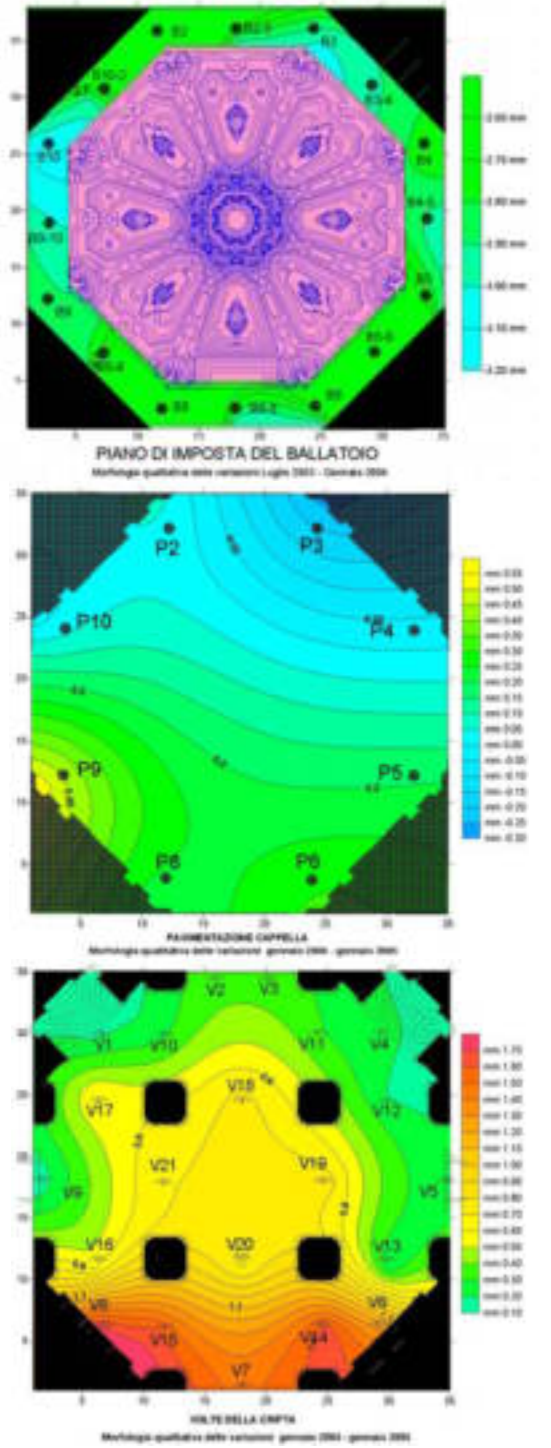

Figure . *Vertical variation elaboration on three different levels*

Figure . Scaffolding installations

2.3 Stabilization of the monitoring system

Experience acquired for the monitoring system of the *Cupola di Santa Maria del Fiore* shows that for assestment local factors, the measurement instrument set need at least 2-3 years in order to correctly estimate the acquisition of an evolving phenomenon. The monitoring system of the *Mausoleo* is now active in telemetry since june 2002, but anyway it seems possible to draw some principle indications on the operation modality of the system and report some notes about the evolving structural phenomena. The deformeter stations have recorded in the examined period an amplitude variation of the cracks between 0.5 and 1.6 mm; an order of magnitude compatible with the normal temperature variations of the air inside the dome (approximately estimated 18° C in the period in examination). Variations in the horizontal position of the balcony, recorded by the telecoordinometer stations, turn out to be in the range between 0.3 and 1.2 mm, also compatible with the thermal phenomena that have interested the monument. Similar appears the record data coming from the monitoring system of the vertical movements, except for the total vertical lengthening paving-drum-dome that is in the range between 2.8 and 3.5 mm, a record data not far from the conventional concrete lengthening coefficient.

3. MONITORING OF THE CRACK MAP

Before the shape modification works and the opening of new windows on the dome drum, (by *Ruggeri* Architect in 1740), *Alessandro Cecchini* architect in a comparative technical note about the *Cupola di Santa Maria del Fiore* and the *Cupola di San Lorenzo,* gives some interesting historical information: *" le diverse lesioni della Cupola Laurenziana son larghe il doppio più, che non son quelle della Cupola del Duomo"* and he also talks about an important crack (*"larga un sesto di braccio"* a sixth of arm approximately 10 cm) repaired by Torricelli. (*"Secondo dei due discorsi sopra la Cupola di Santa Maria del Fiore"* - 1690 *).*

These simple notes seem to agree with the hypothesis scenario of a main *catenario* structural system, probably planned in the old original project (by Nigetti Architect).

The plan view at the paving level shows a series of *maschi* alternated to empty zones in correspondence of the small lateral *altars* under the octagonal drum of the *dome.*

These sides are closed by four *arconi* (large arches*)* causing alternation between empty and full zones.

Recent inspections about the actual crack system status were focused to verify the *drum* and the *dome* situation; the fissures system appears regular and quite symmetric on the surfaces.

In the main structural septa of the *chapel* the fissures begin in the middle of the *gable roof* and stops on the *drum;* on the other empty structural zones the fissures on the gable roof are longer and continue just to the key of the *arconi*.

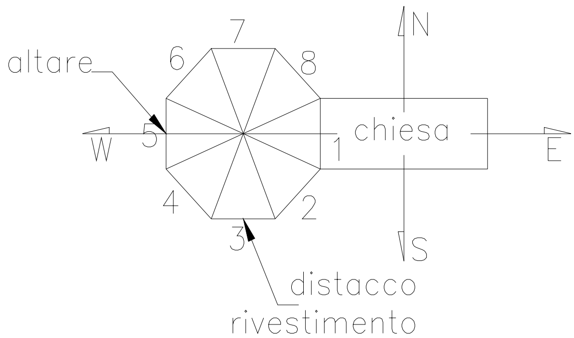

Figure . The dome sector identification num ers.

3.1 Survey of the fissurative picture

In sector 3, after some new direct and photogrammetric surveys, the marble covering surface was removed from the wall septa to prevent possible stone material landslide dangers.

The same operation was then planned in sector 5 for other problems caused by structural geometric changes in this specific area.

For circumstantial elements, fissurative picture survey was not an immediate reading; in our case this kind of data was often masked by the marble covering tables supported by long iron bars plugged sometimes at 50 or 80 centimeters away from the real masonry body.

In this sectors a new cognitive analysis was planned to analyze in deep the construction modalities and some other specific elements of the particular static degradation here encountered.

Of course this part of the study was growing in the time with the progressive necessity of taking apart new portions of marble tables for revealing the type of lesions and subsequently deduce the kind of structural behavior of the *arconi*.

The fixurative picture survey was carried out with the aid of any old and new measuring systems, but for some critical situations only direct measurements from the scaffoldings were possible. As a result from the surveys a sliding of the key stone arches was discovered in sector 3 and 5.

This sliding has been emphasized by a constructive error of an incorrect wedge shape of the key stone.

Figure . A sliding of the ey stone arches as discovered in sector and

Figure . A ind of large crac on mar le covering

A kind of similar data was acquired during the *Cupola di Santa Maria del Fiore* studies; in this case the elaboration data and other specific test correlate the structural behavior to the deviation of the isostatic lines compression along the meridians. With this background a multi purpose instrument set location able to detect a local monitoring on the critical zones, and also to get a qualitative global structural picture, was then planned. Thanks to this approach a preliminary hypothesis about the bearing structure behavior is now under study with a specific numerical model elaboration.

Figure . Tthe Triumphant Christ fresco sector

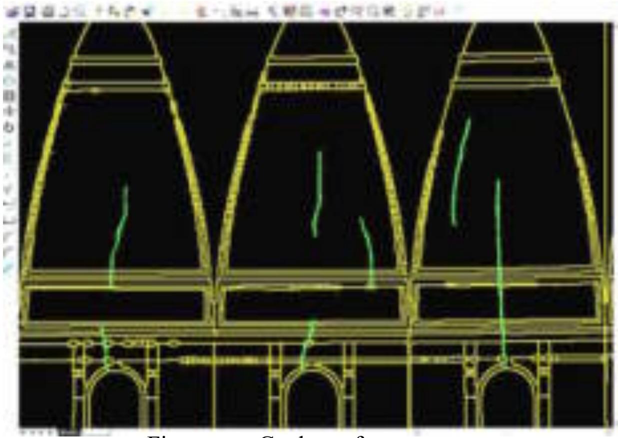

Figure . Ga le roof crac map

To investigate other structural hypotheses a specific stereophotogrammetric close range survey was then planned in order to acquire the geometric cylindrical shape of the *gable roof* of the dome in the Triumphant Christ fresco sector. Resulting 3D data show only slight irregularity; no structural concavities or convexities were found. (fig.17)
Digital photogrammetric techniques were also applied on crack maps for some qualitative elaboration of structural interactions.

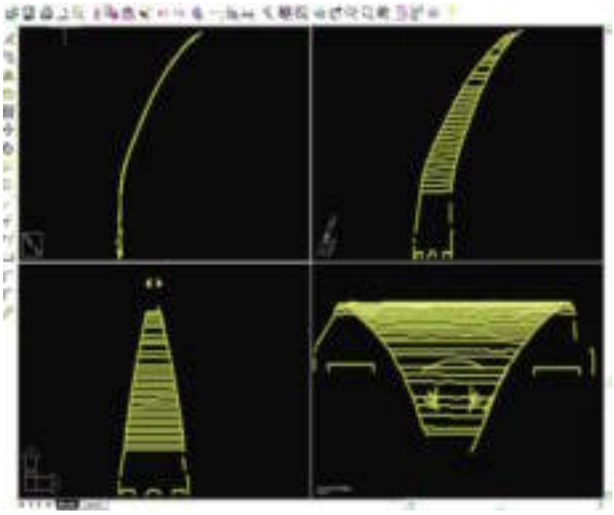

Figure . Photogrammetric survey of ga le roof

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