Static monitoring system for the Brunelleschi Dome in Florence

Autor(en): **Castoldi, A. / Chiarugi, A. / Giuseppetti, G.**

Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

Band (Jahr): **56 (1987)**

PDF erstellt am: **17.05.2024**

Persistenter Link: https://doi.org/10.5169/seals-43551

Static Monitoring System for the Brunelleschi Dome in Florence

Système de contrôle statique pour le Dôme de Brunelleschi à Florence

Statischen Kontrollsystems für die Brunelleschi Kuppel in Florenz

A. Castoldi, ISMES S.p.A., Bergamo
A. Chiarugi, Università di Firenze
G. Giuseppetti - A. Fanelli, ENEL-CRIS, Milano
G. Petrini, Sovrintendenza per i Beni Ambientali e
Architettonici di Firenze

SUMMARY
A structural control system is important when a global and simultaneous analysis and comparison of the process is required. The diagnostics of the structural safety based on the ensemble of the quantities — and not on single or group of variables — is a main requirement of the Brunelleschi Dome and basement control system. The article describes the purpose and requirements involved in the project, together with the measurement instrumentation used and its functions.

RESUME
L'application d'un système pour le contrôle structurel est essentiel là où il faut considérer en même temps et entièrement tous les processus d'analyse et de comparaison des observations. La prévision de la sécurite structurelle fondée sur l'ensemble des grandeurs relevées et non pas sur chaque variable ou groupes de celles-ci - représente la condition fondamentale du système pour le contrôle du Dôme de Brunelleschi et de ses fondations. L'article présente les objectifs et les conditions du système, les instruments de mesure employés et les fonctions effectuées pas le système.

ZUSAMMENFASSUNG
Die Hilfe eines Strukturpruefungsystem ist wesentlich für eine Gesamtbeurteilung die ganze Analyse- und Vergleichsverfahren zu berücksichtigen hat. Die Diagnose der strukturellen Sicherheit, die nicht auf einzelnen oder Gruppenvariablen, sondern auf die Gesamtheit der entnommenen Grössen abgestützt ist, bestimmt die Grundlage des Kontrollsystems der Brunelleschi Kuppel und ihre Fundationen. Der Artikel beschreibt die Ziele und Forderungen die zum Systementwurf führten, sowie Art und Funktion der gewählten Instrumentierung.

1. INTRODUCTION

The dome of the Santa Maria del Fiore in Florence presents a complex crack pattern that has the significant aspect in the four through lesions involving the even sectors of the structure.

The wealth of existing historical documentation on the monument confirms the assumption that the first lesions had already commenced in the early years after the building of the dome and that, subsequently, the process of deformation underwent a constant evolution up to the present time.

The large number of studies undertaken over the centuries make it possible to reconstruct this evolution in broad terms.

The construction of the Cathedral began in 1295, starting out with the facade and proceeding slowly through diverse vicissitudes over the span of a whole century, with the transept with pulpits and the chapels being completed only at the beginning of the 15th Century.

The first signs of failure in the lateral walls of the building can be traced back to 1434, that is to say, with the completion of the building of the dome.

For what concerns this latter, the oldest document - which clearly refers to small cracks that however provide a passageway for "air and the wind" - is a report dating from 1639, some two hundred years after the construction of the dome [1].

The first scientifically valid document however is dated 1757 and is the work of the astronomer Leonardo Ximenes, who in his studies for the sun dial of the Cathedral set out an exact description of the existing failures via observation of no less than 13 cracking phenomena [2]. Ximenes also carried out the first geometric measurements that indicated that both the church as well as the bell-tower were slightly out-of-plumb towards the south in the direction of the river.

No other significant document was issued until 1895, a year that witnessed a violent earthquake. That same year, however, saw the execution of maintenance operations, that reasonably lead to the conclusion that perhaps new cracks had shown up [3].

The Commission appointed by the Opera del Duomo in 1934 verified a condition of cracking that was similar to the one at present [4]. The Commission laboured for three years, studying with great care the relationships existing between the air temperature and the opening/closure of the cracks, and was able to show how the cracks undergo variations of amplitude linked not only with seasonal thermal cycle but also with the daily ones.

Recently the "Superintendence of the Beni Ambientali ed Architettonici" of Florence has carried out a new and detailed study of the state of cracking, that sets out in a reference document a series of tables giving the position and the number of all the main cracks in the structure [5].

The present Commission with the task of studying the renewal of the Santa Maria del Fiore structural complex, with special reference to the static problems of the dome, issued in 1985 a document [6], that puts forward a number of assumptions on the structural behaviour of the monument that, supposedly, underly the formation of the cracks. Considerable assistence towards the interpretation of the mechanical phenomenon has been provided in recent years by the analysis carried out by ENEL-CRIS with the employment of finite element mathematical models that have facilitated in examining various causes of the damage [7].

In view of the complexity of the problem, the Study Commission has deemed it necessary to check for a suitable period of time all the quantities that are held to be the most significant in terms of the structural behaviour of the monument. As such, in 1986 the Superintendence of the Beni Ambientali assigned ISMES the task of supplying and installing a system for the control of the dome, the start-up of the system being scheduled for September, 1987.

The article refers to the most important design aspects and describes the technical choices adopted for what concerns both the measurement instrumentation as also the data acquisition system.

2. DESIGN OF THE CONTROL SYSTEM

2.1 Aims of the System

Two essential objectives were aimed at with the decision to install a monitoring system on the dome.

The first and the more immediate one was that of keeping under control the evolution of the deformation process of the dome by means of measurements of both the variations of amplitude of the main cracks as also of the movements of the structure, and thereby to be able to issue a warning in the event of these quantities exceeding a pre-established threshold.

In these terms, the system represents the mean for the safeguarding of the Cathedral.

The system was entrusted with a further task as well: that of identifying the correlations between the quantities that describes the deformation process and the quantities that may be considered to be the causes - thermal variations, foundation settlements, etc.

Such correlations can be of great help in interpreting the on-going phenomenon, thus facilitating the setting up and calibration of mathematical interpretative models.

2.2 System Requirements

From the definition of the objectives of the system are derived a series of requirements connected partly with the structural problems and partly with the functional aspects that have involved a precise design and the adoption of particular technical solutions.

The main considerations that have characterized the design of the system are as follows:

- Type, number and position of the sensors are defined by the need to gather in a comprehensive manner the on-going phenomenon, while at the same time, containing the cost of the system within acceptable limits and therefore the number of sensors. The choice was made on the basis of a preliminary survey of the deformation condition and a entirely qualitative model of the structural behaviour.

- Sensitivity, accuracy and stability over time, full scale of the various measurement networks are obviously established on the basis of the expected variations in the values of the quantities under observation, thus involving the choice of sensors with high characteristics.

- Measurements process must be completely automatic, making it possible to gather data with the desired periodicity and their transfer to mass memory: the autonomy of the system must be in the order of several months.

- System to offer highly flexible and expandable characteristics, to enable enlargement or at any rate modification, subsequently and on the basis of the initial indications, of the sensor network and of the data gathering mode.

- The reliability of the system to receive special attention via choice of special components and adoption of a madular construction. These criteria facilitate in reducing not only the number of breakdowns but also maintenance time.

3. MEASUREMENT INSTRUMENTATION

3.1 The Structure and The Deformation Condition

As already emphasized, the choice of the quantities to be monitored was made with the aim to ensuring a reliable interpretation of the on-going deformation phenomenon.

In this choice, the knowledge of the structural scheme and the crack condition is of fundamental importance.

3.1.1 The Structure

Examining the structure of the dome-base complex, it is possible to recognize three abses and the nave of the Cathedral, which though not called on to act as a real support of the vertical forces transmitted by the structural masses above it nevertheless play a determinant role of buttress of the complex (Figs. 1 and 2).

The structural elements making up the base of the dome consist of four polygonal cross-section supporting pillars. The inner side coincides with that of the sides of the inner octagon of the base (sides 2, 4, 6, 8).

The load-bearing capability of these massive supports, some 30 metres in height, is weakened by reductions of resistent cross-sections. In fact, the two sacristies are located in the apse supports (sides 4 and 6), while those in adjacent to the body of the Cathedral are traversed by accesses to the side naves that lead to the octagonal space under the dome (sides 2 and 8).

From the height of the first inner gallery, a structural element - drum - in the shape of an octagonal parallelepipedon joins the supports with the springer of the dome. While found to be weighted above on every side of the dome, the lower part presents the edge alternatively supported by the pillars or free with curved soffit. In the upper part of the drum, that is, between the second and third inner gallery, the circular windows at the centre of each side weaken the resistent cross-section.

The octagonal dome made up of two inter-connected canopies is set on the upper cross-section of the drum, coinciding with the third inner gallery.

The skylight completes the construction.

3.1.2 The Deformation Condition

The main phenomenon involving the dome, the drum and the supporting pillars is to be met with, though with varying amplitude of the cracks, on all four even sides of the octagon of the base (Fig. 3).

Starting out from the top, the cracks are to be found in the dome at a height between the last inner walkway and the base of the skylight. They then run downwards almost vertically to the centre of the gables and are found to pass through both the inner and outer canopy; extending to the drum, where they present the maximum amplitude, they cut through its entire thickness and involve the cornices of the circular windows. Still proceeding downwards, they take in the outer structures of the semicircular chapels. Finally, they are still identifiable in the pillars inside the Cathedral, below the first gallery.

Quantitatively, the phenomenon is more emphasized in sides 4 and 6; while in side 2 rather than concentrating in one or more branches the cracking is more spread out, so much so that it is difficult to recognize it in the canopies of the dome.

In the drum, corresponding to the odd sides, the cracks start out from the circular windows at an angle of about 60 degrees vis-a-vis the horizontal, then reaching down to the second gallery they proceed towards the soffit of the arch that defines the free edge of the drum.

Inside the construction, in the eight angle areas, cracks are encountered that with essentially vertical progression involve the drum and the dome up to an intermediate height between the second and third inner walkways. They are identifiable in the drum areas also in the stretch of the inner helicoidal stairs that rise up in the vicinity of the corner.

In the dome springer area they involve the corner ribs and are found to pass through inasmuch that they are visible also on the inner and outer walls of the opening that the first inner walkway produces in the corner ribs.

Again in correspondence to the odd gables at the soffit of the inner canopy of the dome, systematic crack formation is identifiable at the centre of the gable itself, with an essentially vertical progression, from a height of the second inner walkway to the third.

The inclined symmetrical crack systems are identifiable on both sides of the walls of the main nave adjacent to the base of the dome and cut downnwards through the first gallery. In this strecht a vertical relative settlement of the pillars of the dome respect to the pillars of the nave is to be noted.

In the area of contact between the side chapels and the pillars, marked inclined cracks are identifiable.

3.2 Monitoring of the Deformation Condition

3.2.1 Monitoring of the Cracks (Fig. 3)

The main attention was focused on the through-cracks that have developed vertically in the event sectors of the dome. For these cracks it was deemed important to measure the opening and closing movements - in the circumferential direction - at five different heights. The radial components of the movement were instead neglected, since notwithstanding their presence, they are limited in magnitude.

The control of the behaviour of the cracking on the dome was then completed by measuring the opening and closing movements of the cracks in the lower edge of the circular windows - in the uneven sectors - in as much that these are of particular interest for clarifying the behaviour of the drum and those of the cracks corresponding to the corners.

The sensor adopted for these measurements was an inductive type transducer that, mounted astride the two opposite edges of the cracks, ensures an accuracy in the order of +/- 0.02 mm.

3.2.2 Monitoring of the Displacements of the Structure

The measurement of the displacements of some of the structural elements is of particular significance in view aboveall of the setting up and calibration of a mathematical model capable of explaining the behaviour of the structure.

For this standpoint it was deemed essential to measure displacements - vertical and horizontal - of the drum and the pillars, which could provide an indication of the manner in which the vertical loads and the thrust of the dome are transferred to the ground.

a. Horizontal displacement of the drum and the pillars below it (Fig. 4):

   The measurements were effected via a system made up of a plumb-line and a telecoordinometer.
   The plumb-line, whose point of fixture is located in correspondence to the third gallery, represents the line of vertical reference for the measurement. The telecoordinometer, connected to the structure via a rigid support, measures the position of the line by means of a system of optical interception, and thus provides the measurement of the horizontal components of the displacement of the mounting point vis-a-vis the point of fixture of the plumb-line.
   Eight plumb-lines were installed in proximity of the corners of the dome and three telecoordinometers were mounted for each of these, respectively at heights below the drum, of the first gallery and at floor level.
   It is obvious that the indication provided by the telecoordinometer at floor level coincides with the measurement of the displacement of the point of fixture of the plumb-line.

b. Vertical settlements of the drum and pillars (Fig. 4):

   For these measurements, a hydraulic levelling system was resorted to, this being made up of 8 levellometric tanks positioned at the height of the second gallery and approximately at the centre of each sector.
   This arrangement facilitates the gathering of two fundamental aspects for the analysis of the structural behaviour: on the one hand, the relative settlements of the 4 pillars - and therefore a possible overall rotation of the dome; on the other, the settlements of the centre line of the "beam-wall", to which may be ideally similarized the side (uneven) of the drum above the arch of the lateral naves.
   In view of the press in the field of electronic instrumentation - in the present case the measurement of the level of the liquid in the tank is of the capacitive type -

the levellometric measurements achieve high sensitivity and optimal accuracy, in the order of +/- 0.04 mm.

3.3 Temperature Monitoring

Owing to the essential role placed by the variation in temperature in the context of the possible evolution of the cracking condition, it was thought important to acquire detailed knowledge on temperature distribution in the structure over the annual cycle.

As such, a network of sensors was installed, the numbers and position of the latter being chosen with the aim of both identifying the value of the temperature in some of the significant positions, as well as of gathering a series of data against which to set up a "thermal" model of the dome (Fig. 5).

The measurements - a total of 60 points - were carried out:

- along the octagonal perimetre in correspondence to the second walkway;

- along two meridians in the sectors facing North and South-West, which obviously are subjected to conditions of minimum and maximum sunlight, respectively.

For each position along the directions cited above temperature measurements were effected of the inner and outer surfaces and in several points along the masonry of the inner canopy, the air space in between and the masonry of the outer canopy.

The thermometers employed for the measurement of the temperature of the air and the masonry mass were of the electrical resistance type, with platinum sensitive element and capable of offering an accuracy of measurement equal to +/- 0.1 degrees C.

4. MONITORING SYSTEM

The number and the distribution of the sensors, especially the considerable distance separating the various measurement points, obliged the choice of a monitoring system based on the concept of distributed measurement. This system is composed mainly of two types of physically and functionally separate units linked with digital data transmission lines for the exchange of information: one or more peripheral units and the central control unit (Fig. 6).

The peripheral measurement units (Fig. 7), deployed centrally vis-a-vis a group of measurement points, carry out the task of electrical conditioning of the sensors, scanning of the measurement channels, analog/digital conversion of the signals, temporary memorization of the values measured and, finally, of transferring the data to the central control unit.

Based on the use of a microcomputer, this latter unit (Fig. 8) is instead entrusted - via suitable programmes - with all the control functions of the system.

As against a centralized type traditional system, this conception facilitates in limiting the lengths of the connecting cables of the sensors, thereby reducing costs, bettering measurement accuracy, increasing signal/disturbance ratio, and providing immunity from the overvoltages induced by electrical discharges.

The control software of the system was realized on the basis of previous experience and facilitated the carrying out of periodical type measurement cycles, as also of the manual type and of those meant to updated the measurements, and of controlling the instrumentation.

The periodical cycles can be effected at well-defined times of the day or else uniformly distributed over the span of the day, with regular time intervals.

As such, the system provides for the execution of a complete measurement cycle, which involves the acquisition of all the pre-established quantities within four minutes, the recording of the data on magnetic cassette with a maximum capacity of 90 cycles, and the print-out of the information related to the acquired values.

The execution of a cycle of manual measurement is provided for, which is similar to that described above and offers various possibilities of visualization: on video-monitor, with print-out and recording on magnetic support.

Moreover, updating measurement cycles are executed hourly, the acquired data being used for the possible identification of irregularities vis-a-vis the components of the system.

5. CONCLUSIONS

The automatic system of monitoring of the dome and its base is expected to provide a response that can offer the interpretation of the on-going structural phenomena and facilitate the setting up of a reference mathematical model.

This model will subsequently represent the basis for designing interventions of structural consolidation of the monument and for the verification of their effectiveness.

In any event, the activity will bear precise historical witness of the life of the monument and should provide an useful reference for future studies.

6. REFERENCES

[1] GUASTI C., "La Cupola di Santa Maria del Fiore", Florence 1857

[2] XIMENES L., "Del vecchio gnomone fiorentino ......", Stamperia Imperiale, Florence 1757

[3] DEL MORO L., "Relazione sui danni arrecati ....", Atti per la conservazione dei monumenti della Toscana compiuti dal 1 luglio 1834 al 30 giugno 1895, Florence 1896

[4] "Rilievi e studi sulla Cupola del Brunelleschi eseguiti dalla Commissione nominata il 12 gennaio 1934", Opera di Santa Maria del Fiore, Florence 1939

[5] "Catalogo dei plessi fessurativi della Cattedrale di Santa Maria del Fiore in Firenze", Ministero per i Beni Culturali ed Ambientali di Firenze, July 1984

[6] "Rapporto sulla situazione del complesso strutturale Cupola - basamento della Cattedrale di Santa Maria de Fiore in Firenze", Ministero per i Beni Culturali ed Ambientali - Commissione di studio per la salvaguardia del monumentale complesso della Cattedrale, con particolare riguardo a problemi di statica della Cupola (DD.MM. 1.2.1983, 10.3.1983, 9.3.1984), Florence, March 1985

[7] CHIARUGI A., FANELLI M., GIUSEPPETTI G., "Analysis of Brunelleschi - Type Dome Including Thermal Loads", IABSE Symposium: Strengthening of Building Structures, Venice, September 1983.

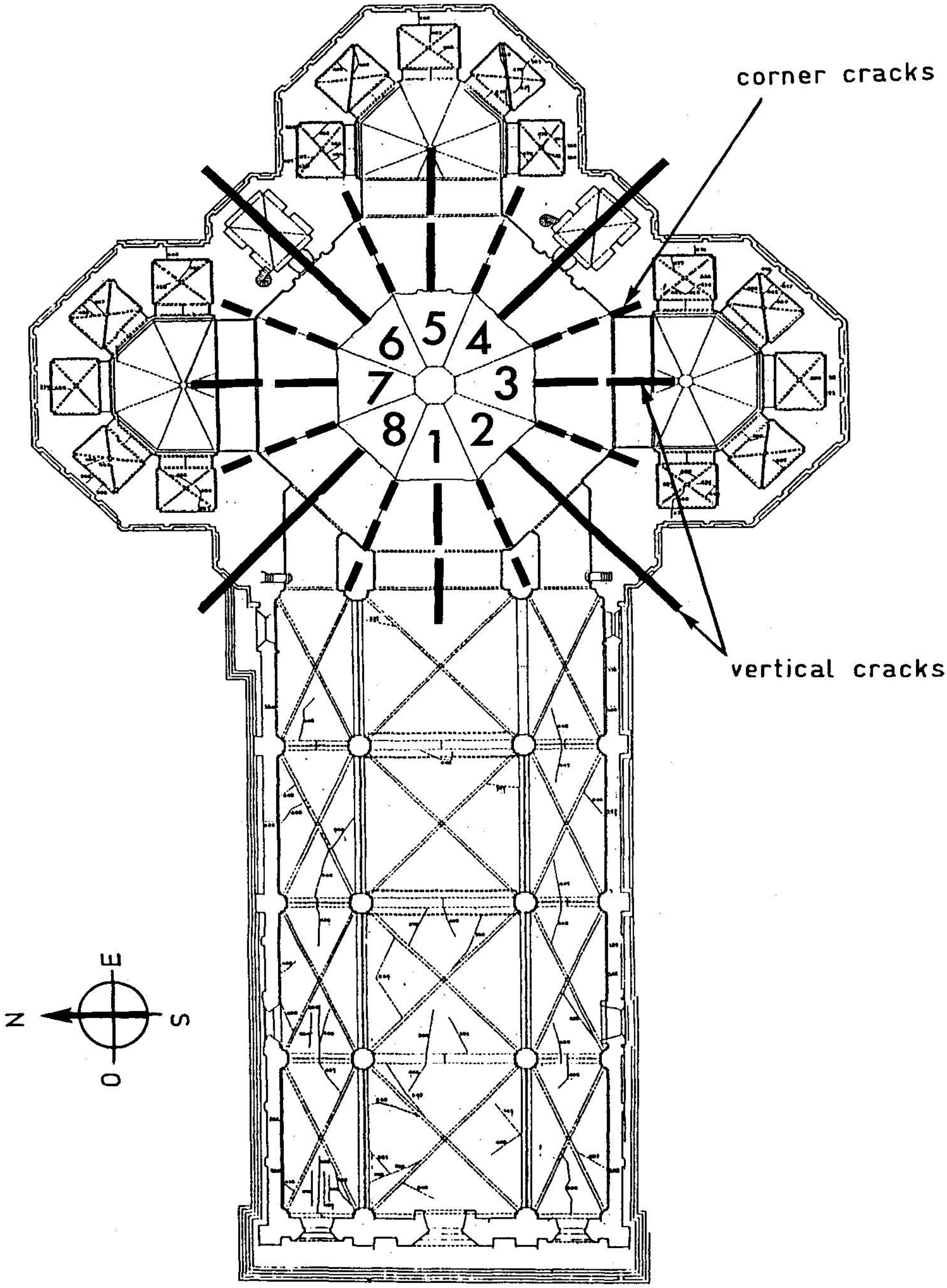

Fig. 1 Plan of the cathedral basement : crack location

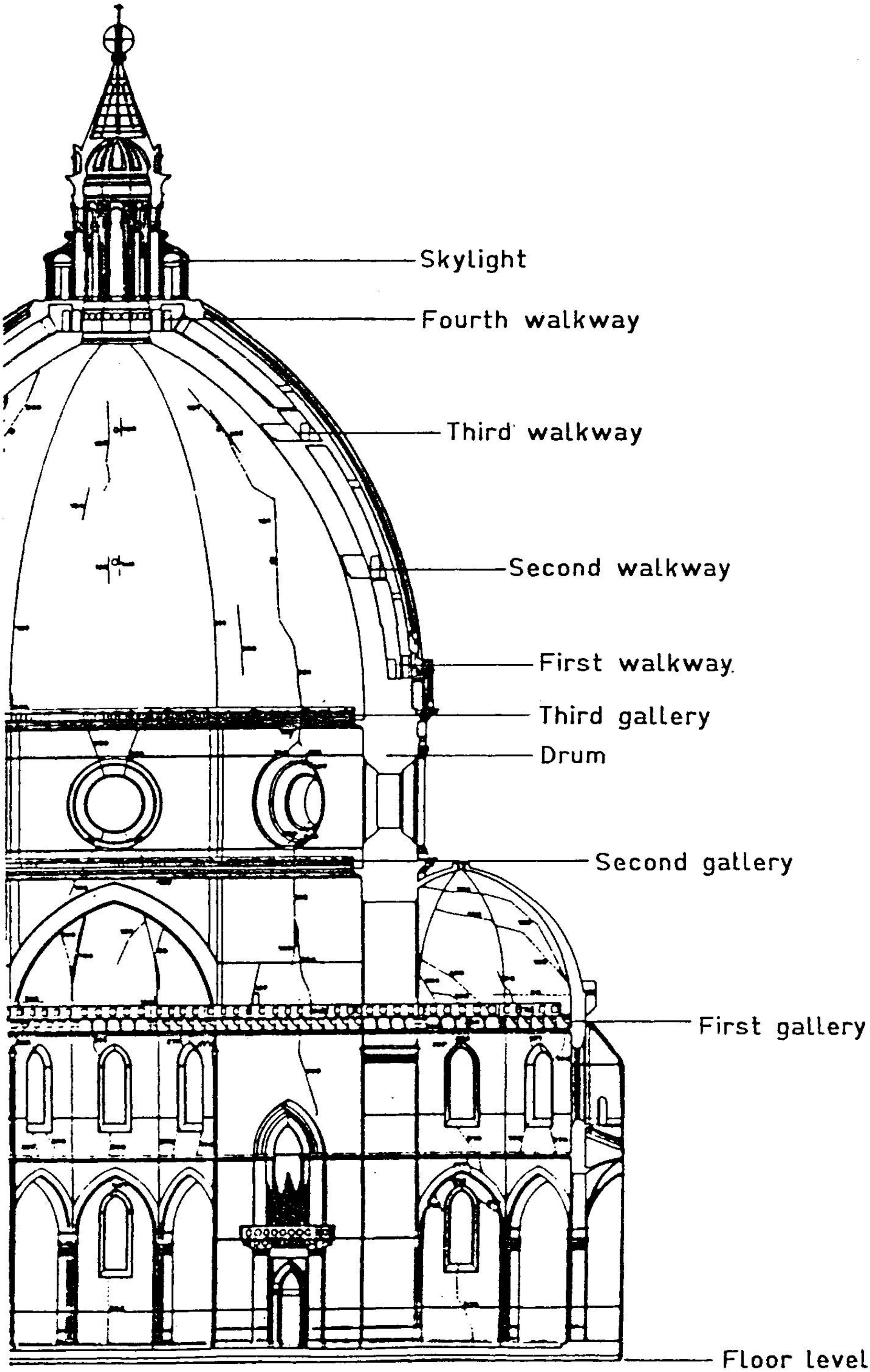

Fig 2 Dome and basement transversal section

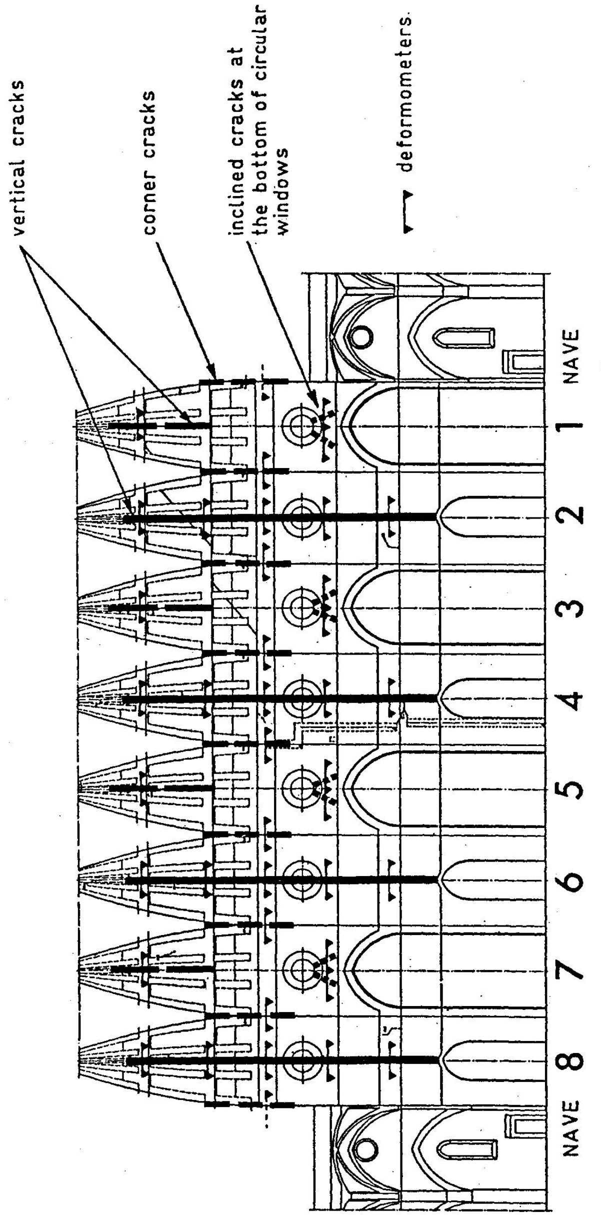

Fig. 3 Crack and deformometer location

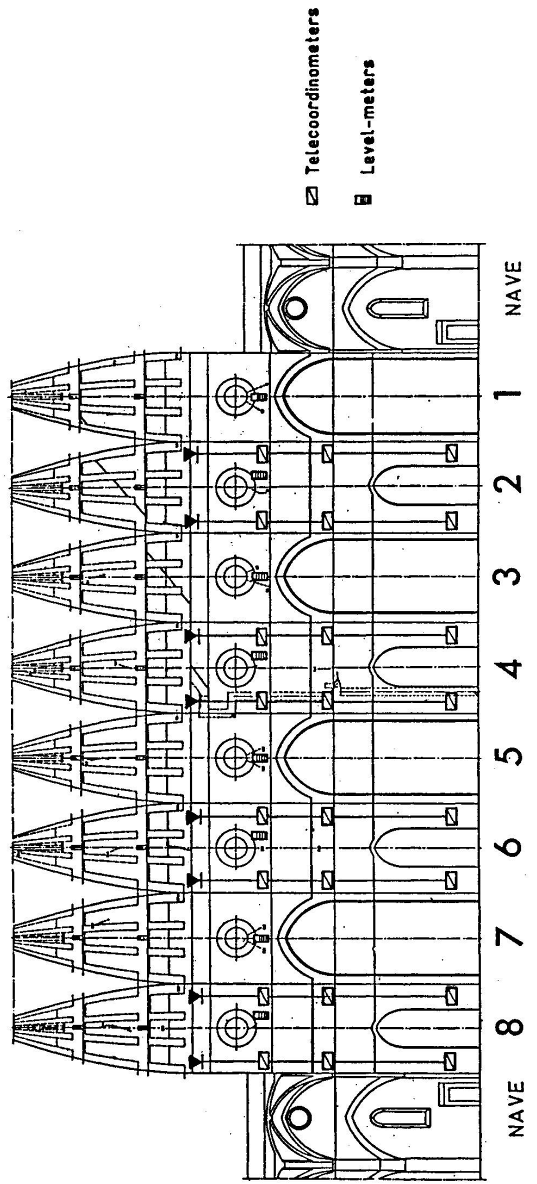

Fig. 4 Telecoordinometer and level- meter position

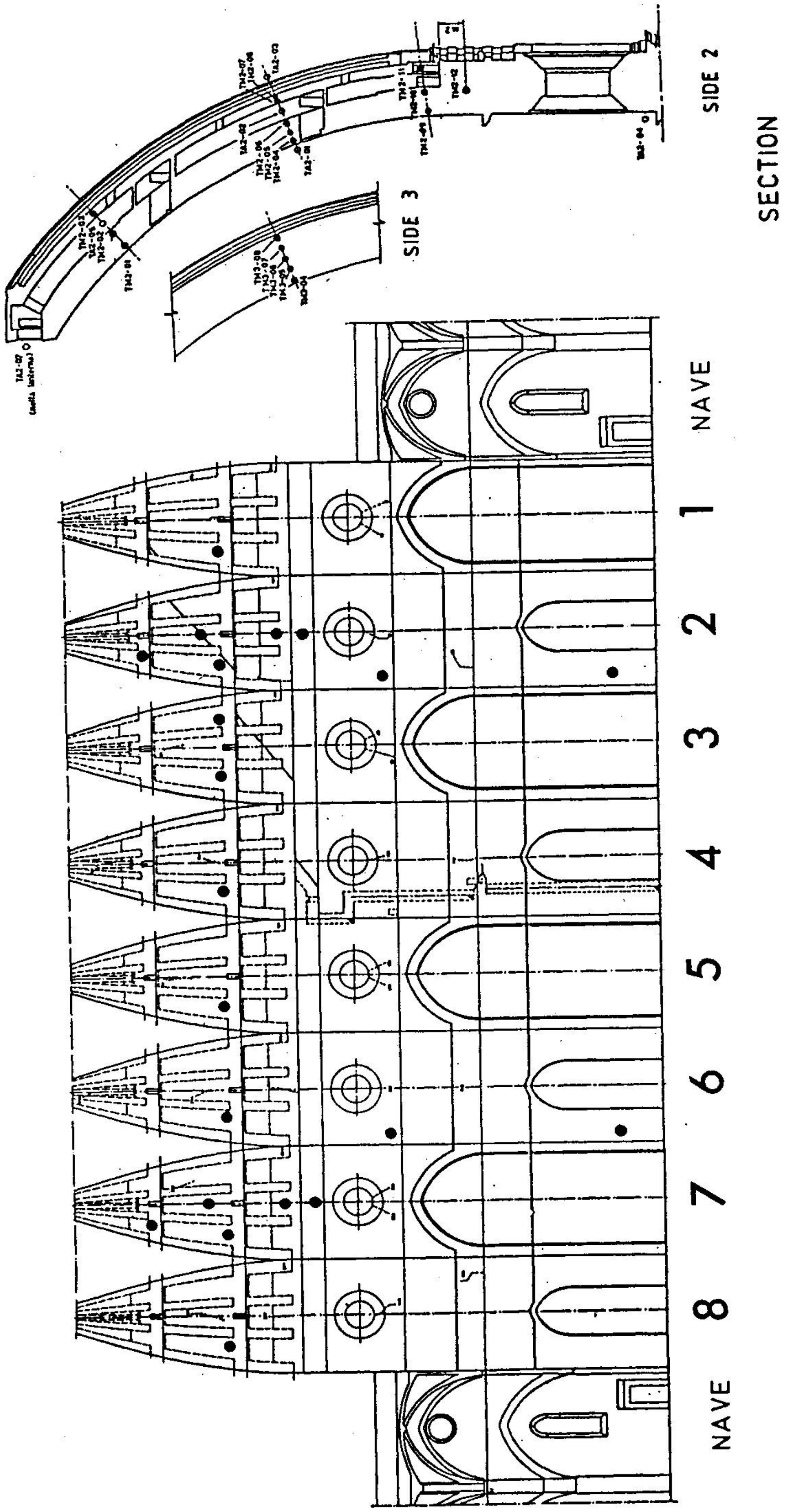

Fig. 5 Thermometer position

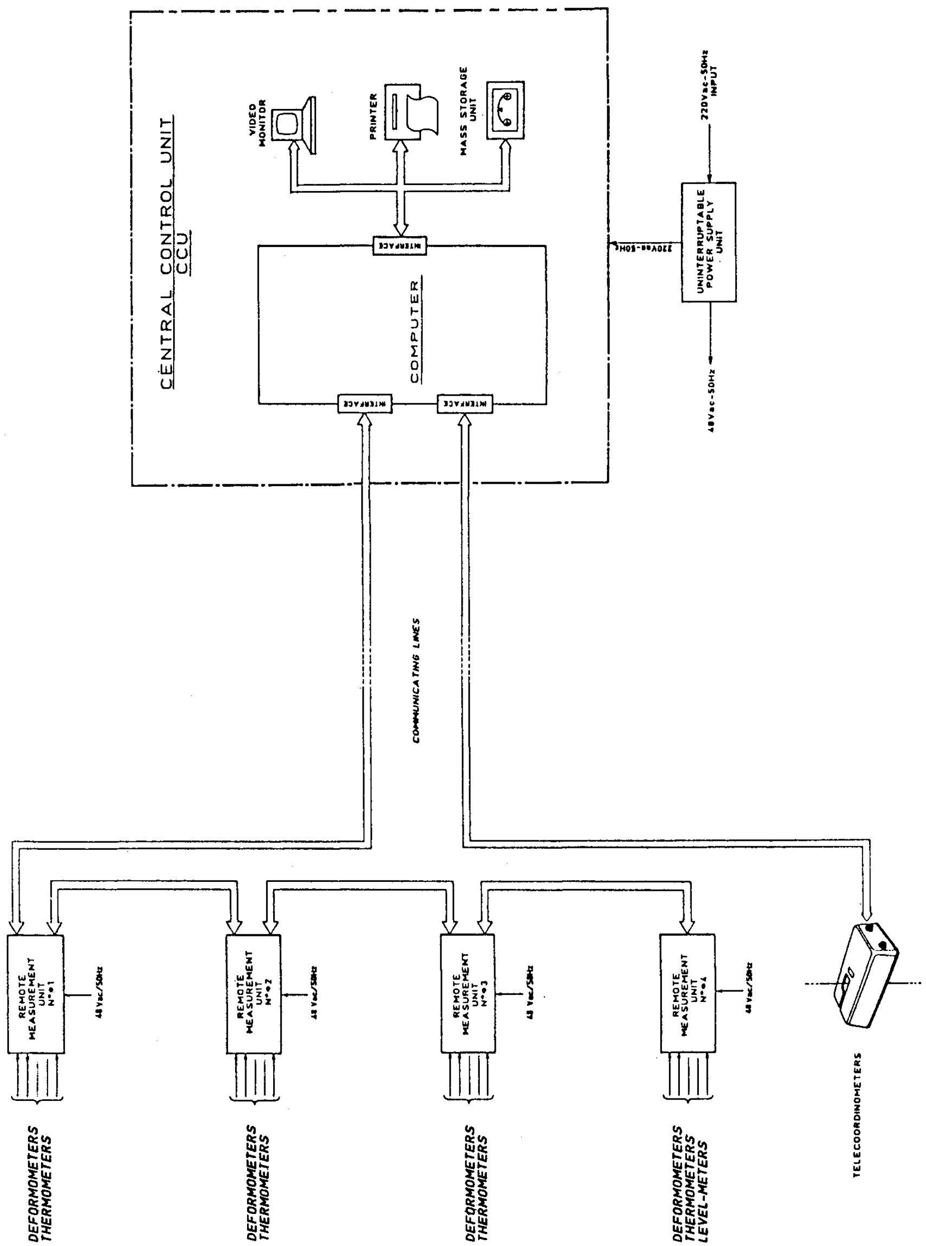

Fig. 6 Static monitoring system - block diagram

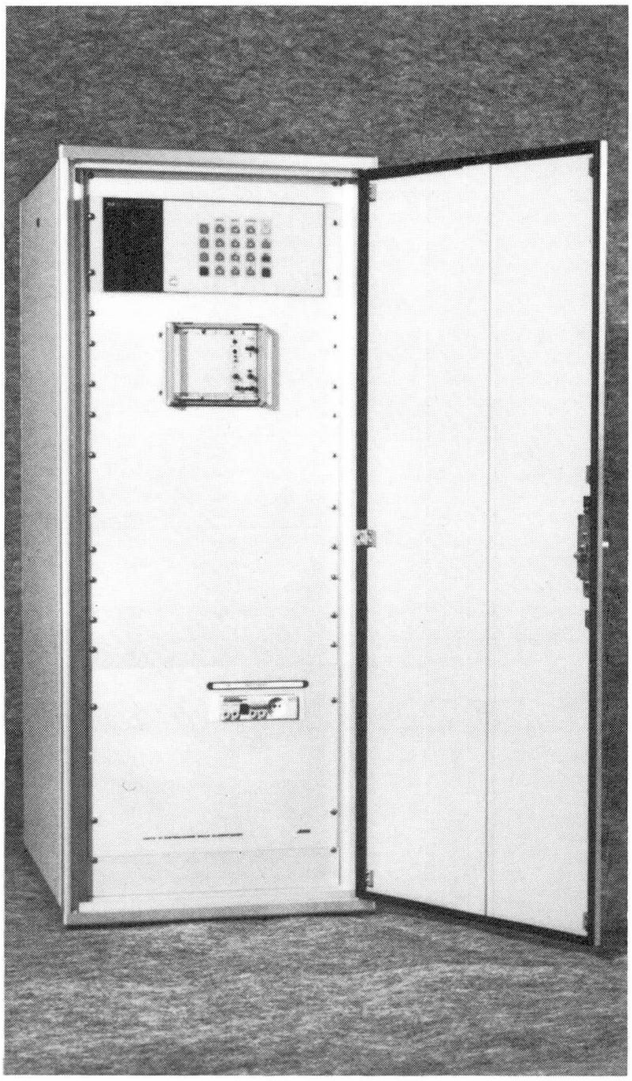

Fig. 7 Remote measurement unit

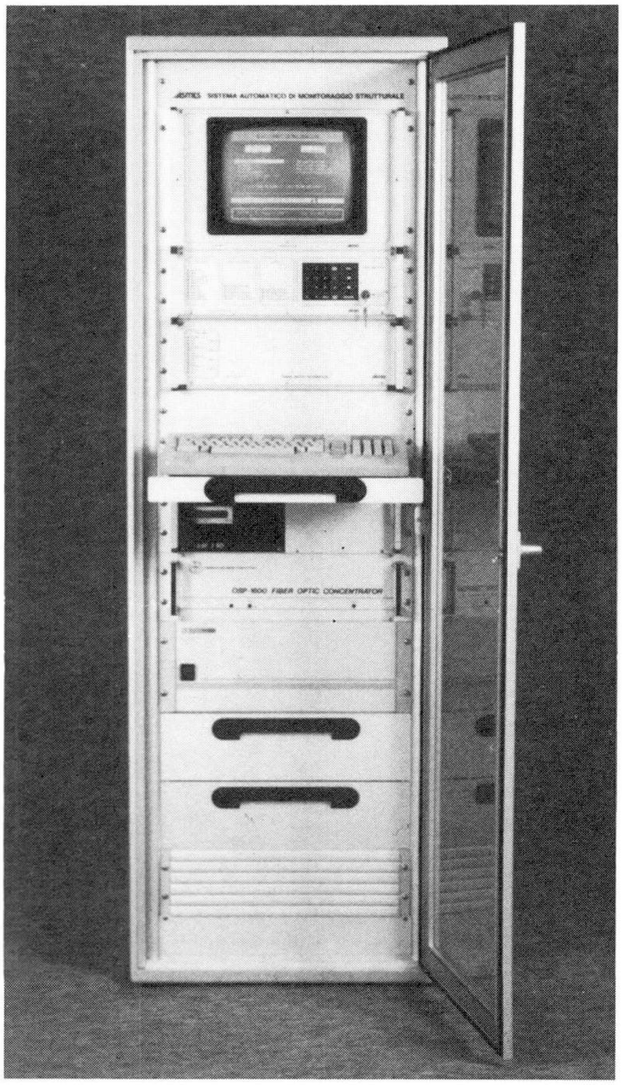

Fig. 8 Central control unit

Leere Seite
Blank page
Page vide