STRUCTURAL ANALYSIS OF HISTORICAL CONSTRUCTIONS II
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SURVEILLANCE AND MONITORING OF ANCIENT STRUCTURES: RECENT DEVELOPMENTS.

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Summary

The general criteria for the design of a monitoring system to assess the static behaviour of a structure are presented as well as the different types of instruments which are used. Special emphasis is devoted to automatic monitoring, but manual reading techniques are also examined.
Some important examples are then presented which illustrate the use of monitoring for the analysis of long-term behaviour of a structure (St. Mark's Basilica in Venice), for the control of restoration works (Metropolitan Cathedral in Mexico City) and for the surveillance of the safety conditios of an important structure affected by a catastrofic event (Chapel of the Holy "Sindone" in Turin).

1. Introduction

Monitoring plays a very important role in the diagnostic process of an historical building because it significantly contributes to a better understanding of the structural behaviour. This information is particularly important in the case of the rehabilitation of an older building because the restoration project should be well-defined and executed only after a period of observation of the behaviour of the structure as a function of time and of environmental conditions changes.

A monitoring system installed in a building for a suitable period of time leads to the following main results:

- evaluation of structural behaviour through correlation between environmental actions (temperature, radiation, wind, earthquake, new forces applied to the structure, foundation settlements, boundary conditions changes) and structural response (opening of the cracks, displacements and tilting of the supporting structures, differential movements of the foundation structures, etc.)
- study of long-term behaviour by means of a trend analysis
- definition of a procedure to promptly check anomalous behaviour or exceeding of warning levels

Depending on site conditions, the design of a monitoring system can be based on two different approaches:

a) use of electrical transducer and automatic continuous data acquisition and recording system;

b) use of removable instruments and manual reading taken at fixed intervals of time.

The first approach is certainly more interesting and attractive because of the real time monitoring of the behaviour of the structure without the aid of technical operators and the ready long distance transfer of data. The manual reading approach requires, on the contrary, the periodic presence of technical operators at the site and is not capable of continuous monitoring in real time of the structural behaviour. Nevertheless, the manual approach must not be neglected because it economically provides information in cases where environmental conditions are so difficult that it is impossible to guarantee protection for the sensors and automatic data acquisition.

The following aspects must be taken into account for the design of an automatic monitoring system.

- Environmental conditions.

- The choice of a measuring system and the cable route locations must be decided after a detailed analysis of environmental conditions in order to guarantee reasonable protection of the system, a stable and continuous power supply, the prevention for electrical noise, and accessibility for wiring and assembling works.

- Accuracy:

  the accuracy of the system can be defined by analysing all types of errors (systematic or random) which can affect the instruments. For automatic monitoring systems it is important to pay attention not only to the accuracy of the individual components (such as instruments, data logger and computers) but also to the accuracy of the whole system.

- Reliability

  A monitoring system is generally used for long-term observation of the behaviour of a structure, therefore it must sufficiently ensure long-term reliability. For this reason, special attention should be devoted to ensure long-term reliability in each phase: design, installation and operation. Also the concept of redundancy for system design is regarded as very effective in ensuring higher reliability of the system. The system should be capable of periodic inspection and self-diagnosis to detect malfunction caused by internal disconnection, defective contact and other accidents. Some automated monitoring system defects could be detected by comparison of measured values with predicted ones, in addition to comparing measured values trends with control standard values.

- Flexibility

  Great flexibility is desirable because the measuring system is expected to operate in the long-term and some changes or substitution of components could be necessary during the life of the system. Some instruments may become useless due to their decreasing importance in measurement or different types of instruments may need to be installed. Recalibration of functioning instruments may be necessary and malfunctioning instruments will need to be replaced. It is thus advisable to design data acquisition and analysis systems with functions that enable adjustment of calibration constants and initial values, the number of measuring points and items, and the frequency of measurement.

- Maintenance

  Periodic inspection of system components for overall operational functioning and for checking eventual deviation of measured values from expected and historical trends, should be readily performable in order to secure the long-term system reliability. Emergency inspection may become necessary in certain cases.

2. Instruments and data processing systems

In order to analyse the static behaviour of a structure, the following main phenomena are measured. Each measure can be taken by using either permanent electrical instruments, connected to an automatic data acquisition system, or removable instruments for manual reading only.

An intermediate solution is also possible by using electrical transducers and a small electrical removable unit for manual reading.

2.1 Crack movements

For the design of a monitoring system, a detailed crack-pattern survey must be carried out in order to check the most important cracks which may affect the structural behaviour. Measuring the relative movements of the cracks (opening and sliding) is by far the most simple and frequently applied method. When an automatic system is required, fixed electrical crack-gauges are used. These instruments are connected to the masonry by using special spherical devices that eliminate bending effects on the sensor. Fig. 1 shows one of the fixed electrical crack-gauges installed by R teknos on the main cracks opened on the supporting structures of the Hanging Church in Cairo (Egypt) by a recent earthquake. This automatic monitorig equipment, including more than 95 crack-gauges and 10 temperature-gauges, has been installed on the coptic monuments (Hanging Church, Coptic Museum, Roman Church and Babilon Fortress) in order to control the deformation behaviour of the monuments during the restoration works. When a solution based on manual instruments is preferred, the movements of the cracks can be measured by using a hand held mechanical deformation-gauge which is positioned on two small metal plates glued at opposite sides of the cracks. By using a triangular set of steel plates, the sliding movement can also be measured. The reliability of the instrument is very high and the accuracy is about 0.005 mm. In Fig. 2 the removable mechanical strain-gauge for measuring crack movements, is shown. In the same figure, the measurements taken in a period of about 8 years on the vertical cracks in one of the towers of San Leo’s Fortress, are shown. The measurements, taken every 3 months, are reported in Fig. 2 together with the diagram of temperature. It can be observed that some cracks (mainly the cracks 5 and 6) are opening with a trend of about 0.15 – 0.19 mm/year corrected for temperature trend.

Fig. 1 – Measurements of crack movements by means of electrical crack-gauge: Monitoring System installed on the supporting structures of the Hanging Church (Cairo, Egypt) which were damaged by a recent hearthquake.

2.2 Relative movements of vertical structures

Long-base extensometers are used to measure the relative horizontal movement of vertical structures (walls and columns). The instrument is equipped with invar wire, kept in tension by a weight, and an electrical transducer connected to the data acquisition system. These instruments are very reliable and the installation is very easy due to their high flexibility.

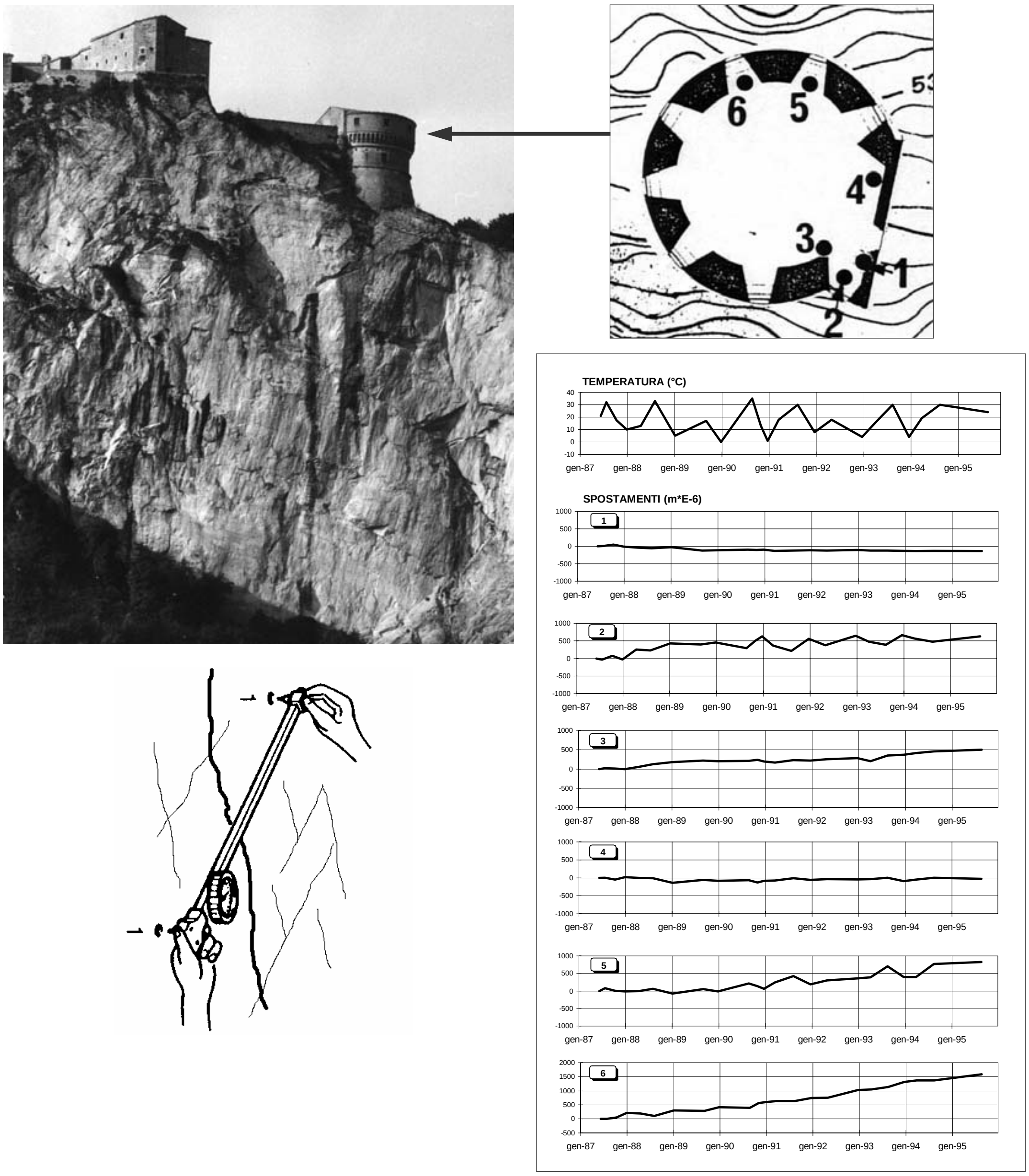


Fig. 2 – Measurements of crack movements (manual system) by means of a removable mechanical strain-gauge. Diagrams of the crack movements on a tower of the fortress in San Leo (Pesaro, Italy) during a period of observation of 8 years are shown. The diagram of temperature is also shown.

This type of instrument has also been installed by Ismes inside the Leaning Tower of Pisa to measure the deformations of the cylindrical structure in radial and longitudinal directions (Fig. 3).

The relative movements of the structures can be also measured by using a removable long-base extensometer connected to anchors fixed on the surface of the masonry wall. Fig. 4 shows the use of this removable extensometer for the measuring of the relative displacements of the columns of Luxor Temple (Egypt) during the restoration phases.

2.3 Absolute horizontal movements

The absolute horizontal movements of the vertical structures are measured by using a direct pendulum. A small cantilever is installed in the upper part of the structure in order to hang the pendulum wire while, at the bottom, a reading unit, equipped with a telecoordinometer, measures the two displacement components of the wire.

Fig. 3 – Measurements of relative displacement (automatic system). Long base extensometers with electrical trasducers installed in the inner walls of the Leaning Tower of Pisa to measure the diametral and longitudinal deformations

Fig. 4 – Measurements of relative displacements (manual system). Long base removable mechanical extensometer for measuring of relative displacements between the columns of Luxor Temple (Egypt), during the restoration phases.

The direct pendulum is particularly interesting for monitoring high structures (towers, bell towers). Fig. 5 shows the scheme of the direct pendulum installed by Ismes on the Tower “Zuccaro” in Mantova and the diagrams of the absolute horizontal movements of the tower during the first four years of observation after the end of the restoration works including the consolidation of the foundations.

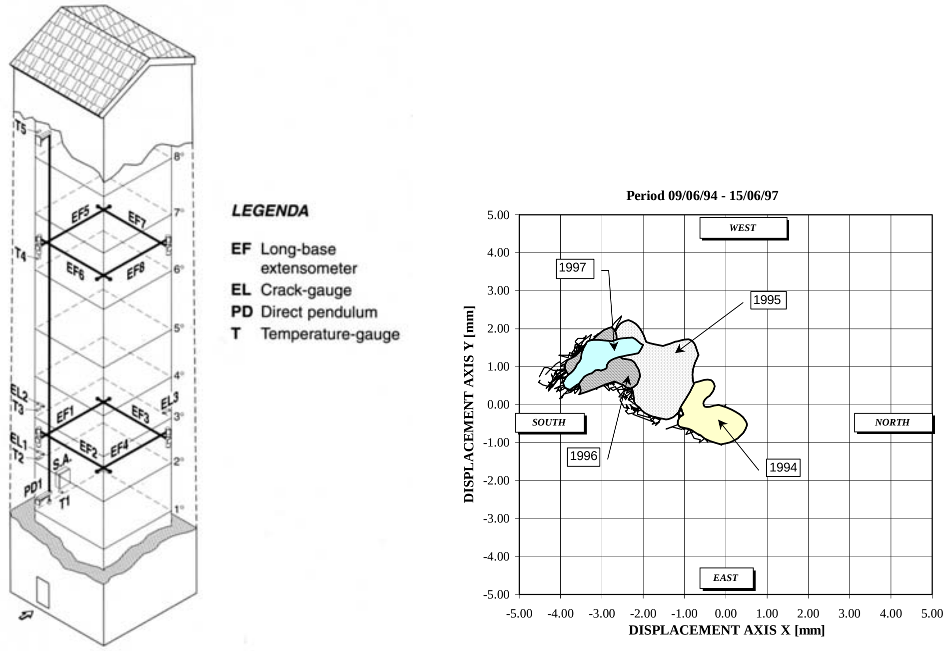


Fig. 5 – Measurements of absolute horizontal displacements (automatic system). Direct pendulum with telecoordinometer installed in the Tower “Zuccaro” and diagrams of the movements observed by the automatic data acquisition system during the first four years of observation. On the left side the typical lay-out of the instrument for monitoring a tall structure is shown.

A progressive movement of the tower during the first 3 years can be observed, while in the fourth year the settlement processes seem to be finished and the movements of the tower are only related to thermal effect. In the same Fig. 5, the typical lay-out of the instruments for monitoring a tall structure, is shown; the direct pendulum is combined with transversal deformation measurements in different sections by using long-base extensometers. Crack-gauges are also installed on the main cracks as well as temperature gauges. When a permanent direct pendulum cannot be installed, a simple and reliable removable pendulum can be used with an optical measuring unit which is positioned on a fixed steel plate only during the reading and then removed. Fig. 6 shows the removable pendulum installed by Ismes in a pillar of the Cathedral in Bitonto to check the deformation behaviour of the Cathedral during the restoration works.

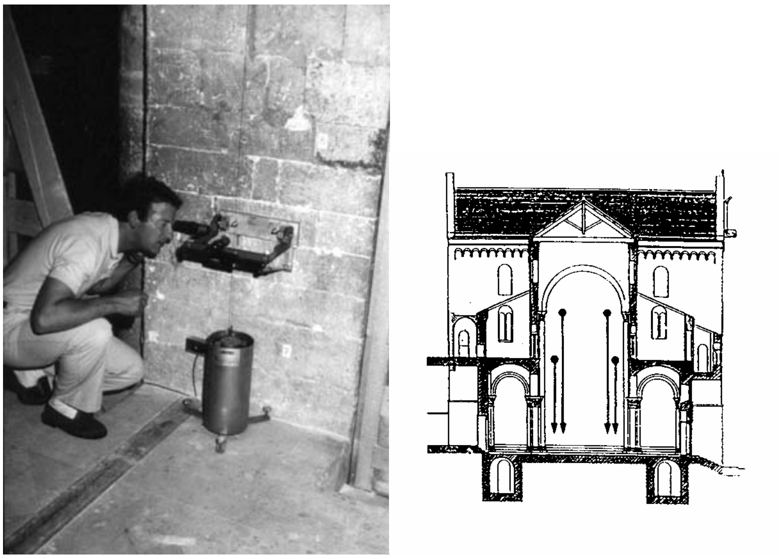


Fig. 6 – Measurements of absolute horizontal displacements (manual system). Removable direct pendulum installed in a pillar of the Bitonto Cathedral during the restoration works. The removable optic unit used for the reading of the two displacements components is shown.

2.4 Differential settlements

The differential settlements of the foundation structures are measured by using levelometric vessels, containing liquid and communicating each other. Inside each vessel, an electrical transducer measures the level of the liquid.

When the structure is affected by differential settlements, it is also necessary to install a geotechnical monitoring system including settlement gauges and piezometers in order to analyse the deformation of the different layers of the soil foundation in relation to the variations of the water table level.

2.5 Tilting

Fixed or removable inclinometers are used to measure the tilting of vertical or horizontal surfaces. This technique gives a local measurement which in some cases can be affected by local anomalies in the behaviour of the masonry. For this reason the tilting measure is less interesting than the aforementioned measures of the global absolute or relative movements.

2.6 Environmental conditions

The deformation of the structure must be correlated with environmental conditions which are mainly: temperature, radiation levels and wind velocity and direction. Temperature measurements are by far the most important because of their effect on the deformation behaviour of the structure. Both air temperature and temperature gradient with respect to wall thickness, which can be measured by installing thermal-gauges inside small diameter boreholes drilled in the thickness of the walls, are very important.

2.7 Data acquisition and processing system

The instruments installed in the different points of the structure are firstly connected to peripheral units that convert the analogic signals into digital information which are then processed by the acquisition computer. Peripheral units, recommended in order to greatly reduce the length of the cable of each instrument, are connected to a central data acquisition and processing computer with the following functions:

- periodic acquisition of the data at fixed intervals
- special acquisition on request of the operator
- data recording
- data elaboration and checking of anomalies or when warning levels have been exceeding
- graphic representation of data in the desired format

The data can be easily transferred over long distances by using modems lines.

Fig. 7 schematically shows the monitoring system installed by Ismes at the Noto Cathedral (Siracusa). The instruments installed on the supporting structures, remaining after the collapse which occurred in March 1996, are connected to three peripheral units which collect data from instruments installed in three different zones of the Cathedral. The three peripheral units are then connected to a central unit installed in the bell tower. Modem and telephone line connections permit the data transfer to the ISMES laboratories in Bergamo and to the Office of “Soprintendenza” in Siracusa.

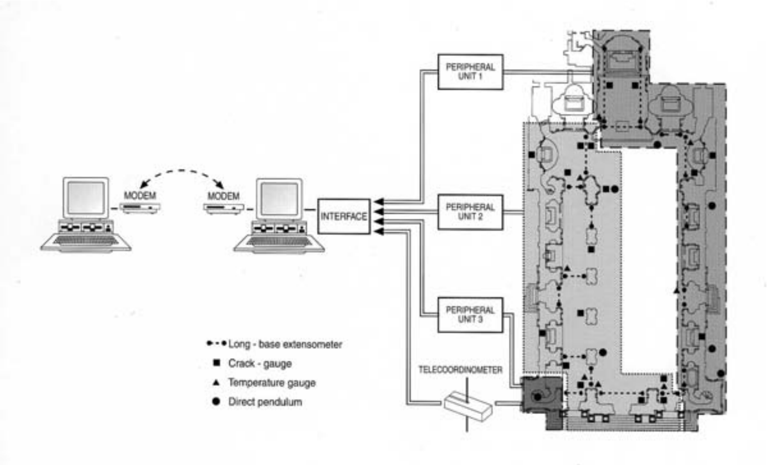


Fig. 7 – Automatic data acquisition and processing system. Scheme of the system installed on the Noto Cathedral to control the deformation behaviour of the remainig structures of the Cathedral after the destructive earthquake of March 1996.

3. The role of monitoring for the control of restoration works - Metropolitan Cathedral in Mexico City (automatic monitoring system)

The Metropolitan Cathedral is a basilical building 115 m long and 66 m wide, with two 62 m-tall towers and a 17 m-diameter dome in the transept.

The very soft clay deposits on which the Cathedral is founded induced high settlements during the early stages of construction, as evidenced by the many significant adjustments made to the dimensions and shape of the construction elements. The span and rise of the arches and vaults were adjusted in order to achieve an almost flat roof. After the completion of the roof, the structure acquired a greater stiffness thus the differential settling proceeded at a lower rate. Nevertheless, the large cracks and the inclination of the upper parts of the columns reflect the very large distortions suffered by the structure following its completion. Some time prior to the beginning of the rehabilitation work (late 1989), the maximum value of the differential settlements at this point in time was about 2.40 m.

To reduce the rate of differential settlement it was decided to use the underexcavation method in the clay layer, below the backfills. In this manner settlement would be increased at those points where sinking is now slower because of the greater degree of consolidation in those zones. For this purpose, small diameter radial boreholes have been drilled at the base of 30 shafts at a depth of about 20 m. The closing of the boreholes due to the weight of the overlying soil and structure produces a settlement at the surface. The induced movements have been monitored in order to confirm that the effects of the underexcavation met the expectations of the project.

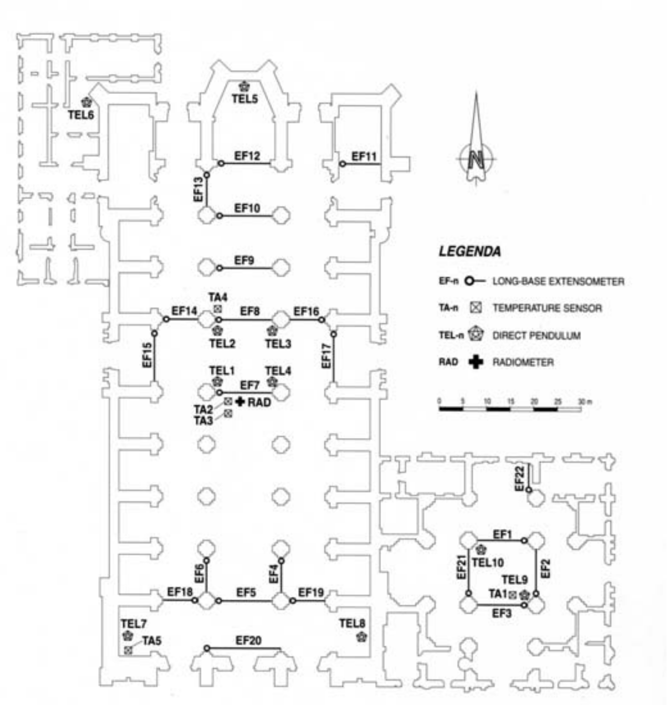


Fig. 8 – Metropolitan Cathedral in Mexico City. General lay-out of the instruments installed at the supporting structures and connected to the automatic monitoring system.

At first a manual system was designed consisting of surveying operations by traditional direct pendulum, convergence measurements with optical instruments, measurement of the opening of the cracks by removable dial-gauges and levelling of the ground floor and vaults.

In light of the complexity of the soil-structure interaction and the continual need to adjust the motion of the two buildings (the Cathedral and El Sagrario) to cause them to settle harmoniously, it was necessary to get immediate information about induced movements. For this reason, an automatic monitoring system was installed in order to have, in real time, the response of the supporting structures of the Cathedral to the underexcavation works. An automatic monitoring system was installed by ISMES in 1994 with the financial support of ENEL. The system was enhanced at the beginning of 1996 with the contribution of the General Direction of SEP. The general lay-out of the instruments is shown in Fig. 8.

The first phase of the monitoring system, installed in June 1994, consisted in:

- 4 direct pendulums on the supporting columns of the central dome
- 8 long-base extensometer in the arches of the central nave of the cathedral at the level of the capitals
- 3 long-base extensometers on the central columns of the "Sacrario"
- 4 temperature gauges
- 1 radiometer.

In February 1996 the monitoring system was completed by adding:

- 6 direct pendulums (2 in each of the towers of the facade, two in the central columns of the "Sacrario" and 2 in the zone of the apse)
- 11 long-base extensometers (on the naves of the Cathedral and on the "Sacrario").

The results obtained by the measuring equipment during the first period of observation have been completely satisfactory. The instruments precisely followed all phases of underexcavation now in progress and provided prompt information for correction of local anomalies in the structural behaviour induced by the underexcavation process. Fig. 9 shows the absolute displacements measured by the telecoordinometers at the top of the four central columns of the cathedral in the period

July 1994 - December 1996. All columns appear to be moving in the desired direction and the deviation from verticality that they exhibited at the beginning of the underexcavation is progressively decreasing. The behaviour of the other instruments installed on February 1996 is also very satisfactory, indicating that the supporting structures are moving as foreseen by the designers. The displacements measured by all the pendulums in the period March 1996 - December 1996 is also indicated in Fig. 9.

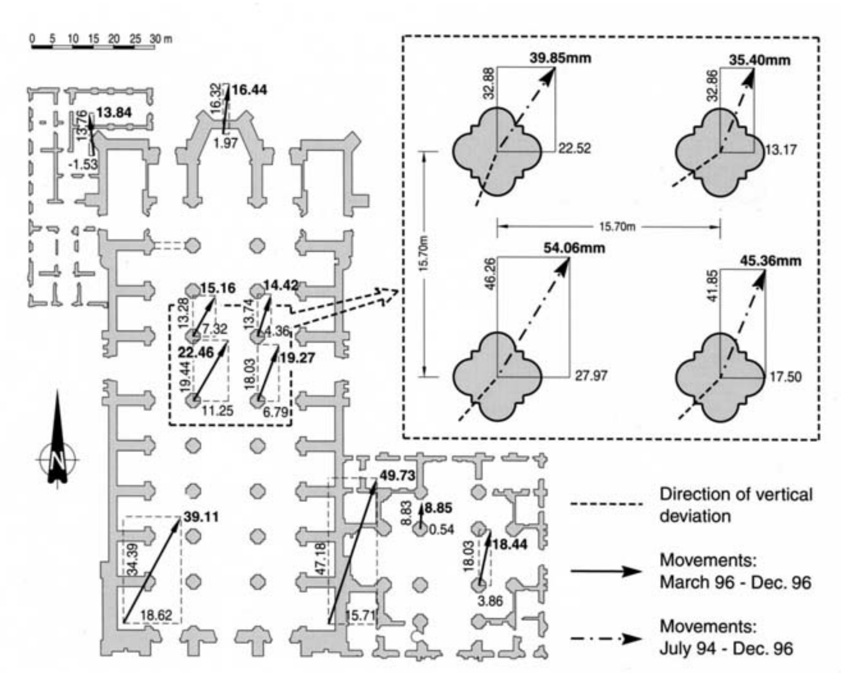


Fig. 9 – Metropolitan Cathedral in Mexico City. Absolute displacements measured by the pendulums in the period March 1996 – December 1996, with detail of the displacements measured at the four central columns in the period July 1994 – December 1996.

The analysis of displacements versus time recorded by the telecoordinometers is also very interesting. Fig. 10 shows the two displacement components (x, y) measured by the direct pendulum (TEL 1). An initial phase, characterized by progressive movement (with a constant rate of deformation) in the desired direction, can be observed. On the 31st of March 1995, when the underexcavation was stopped, the four columns were observed to commence movement in the same direction they had followed prior to underexcavation. When underexcavation was again resumed (July 24th, 1995), the movement of the columns was again in the desired direction.

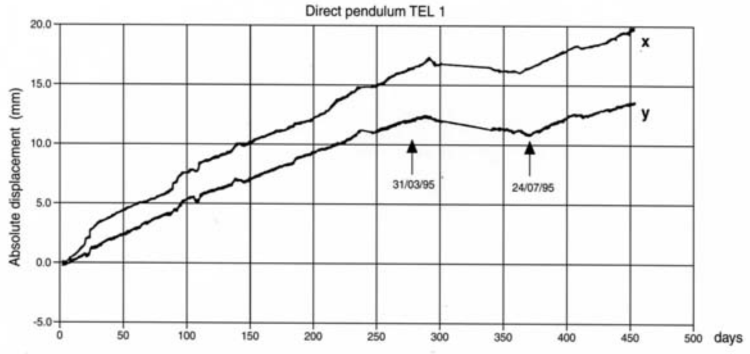


Fig. 10 – Metropolitan Cathedral in Mexico City. Plot of the two components of the absolute horizontal movement of one of the central columns of the Cathedral measured by direct pendulum (TEL1). On the 31st of March 1995 underexcavation was stopped and on the 24th of July 1995 it was recommenced.

A similar effect can be observed by examining the long-base extensometer results. Fig. 11 shows plots of the movements recorded by extensometer FE 8 which is installed on the central nave of the Cathedral. The diagram shows a progressive closure of cracks in the first phase, then a reopening after the cessation of underexcavation and finally, when the works started again, a new closure of the cracks at a rate similar to that of the first phase. These two examples clearly show the great sensitivity of the measuring instruments which permit to follow and guide very carefully, in real time, the rehabilitation works.

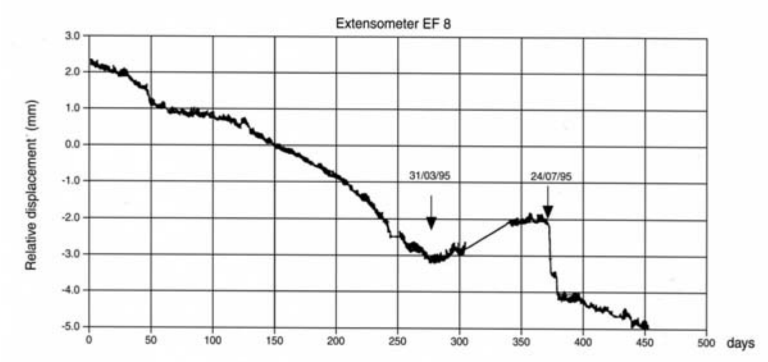


Fig. 11 – Metropolitan Cathedral in Mexico City. Plot of the relative movements between two central columns of the Cathedral measured by long-base extensometer (EF8). On the 31st of March 1995 underexcavation was stopped and on the 24th of July 1995 it was recommenced.

4. The role of monitoring for the analysis of long-term structural behaviour - St. Mark's Basilica in Venice

The installation of an automatic system is without doubt the only way to continuously monitor the structural behaviour of a monument. The period of observation must be long enough (several years) in order to clearly analyse the deformation induced by temperature variations and to separate thermal effects from deformation due to other causes (foundation settlements, structural modification, new forces on the structure and aging of the materials).

Special processing criteria of the data obtained by the monitoring system must be used in order to evaluate the signal trend. Only when the thermal behaviour is clearly known, it is possible to define warning levels to be introduced in the computer program. In this way it is possible to check in real-time eventual anomalies in the structural behaviour and to promptly decide the necessary remedial measures.

The monitoring system installed on St. Mark's Basilica in Venice, which is a monument of great importance, is considered as an example. In 1991 a structural monitoring system was installed by ISMES in order to continuously monitor the static behaviour of the structure.

The principal features monitored are the followings:

- opening of the main cracks in the pillars (8 crack-gauges)
- relative horizontal movements of pillars (11 long-base extensometers)
- tilting of the vertical structure (4 inclinometers)
- internal and external temperature (5 temperature gauges)
- vertical settlements of the soil (3 long-base settlement gauges)
- water-table variations (3 piezometers)

All the instruments are connected to an automatic data acquisition and recording unit which systematically collects and stores the data every 2 hours. Fig. 12 shows the general lay-out of the instruments installed in St. Mark's Basilica.

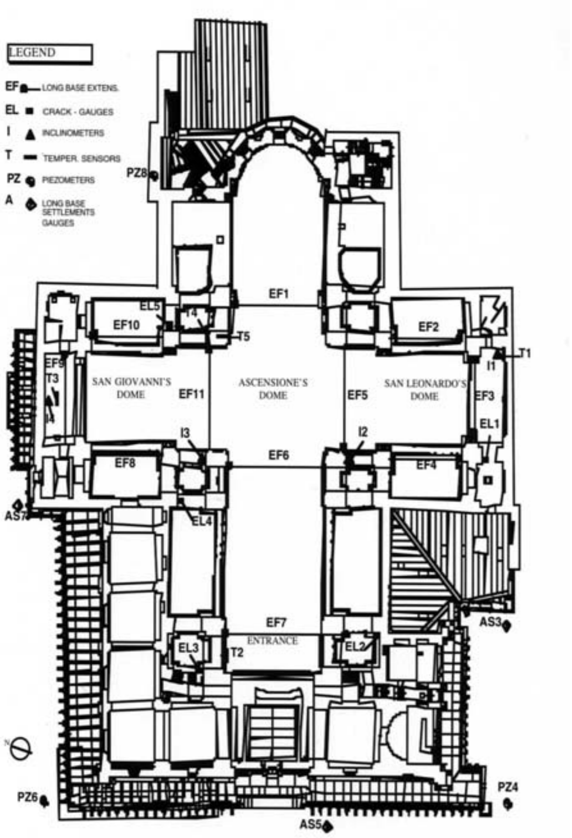


Fig. 12 – Lay-out of the instruments installed on the supporting structures of St. Mark's Basilica in Venice.

The methodological approach for the analysis of the structural monitoring system data aimed at highlighting the strain behaviour of the supporting structures of the Basilica by evaluating the trend of deformations and the correlation between the quantities measured by the instruments. Direct analysis of the time-history diagrams of each instrument permits an evaluation of the main characteristics of the phenomena involved, such as the main periodicities, the amplitude variations of the signal recorded, correlation with temperature measurements, possible significant strain trends, signal irregularities and interruptions. For example, Fig. 13 shows the diagrams of the temperature variations measured by a temperature sensor and the relative horizontal movements between two pillars

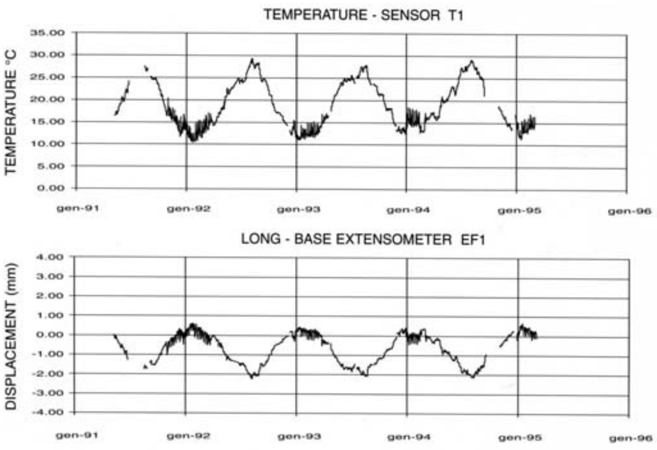


Fig. 13 – St. Mark's Basilica in Venice. Time histories of the temperature gauge (T1) and of the relative horizontal movements between two pillars (long- base extensometer EF1).

measured by a long-base extensometer. This direct analysis is also important for planning numerical elaborations.

The mathematical approach which is used in the analysis of the time series provided by the monitoring systems is as follows:

- Analysis of correlations between the quantities measured by the various instruments
- Signal analysis
    - evaluation of signal's harmonic component
    - evaluation of the signal trend.

The analysis of correlation functions is the preliminary basis for the evaluation of the deformational trend of the structure and possible anomalies in the structural behaviour.
Correlation function analysis was carried out by first correlating the signals coming from instruments measuring the same quantities, and then analysing the correlation between measurements of different

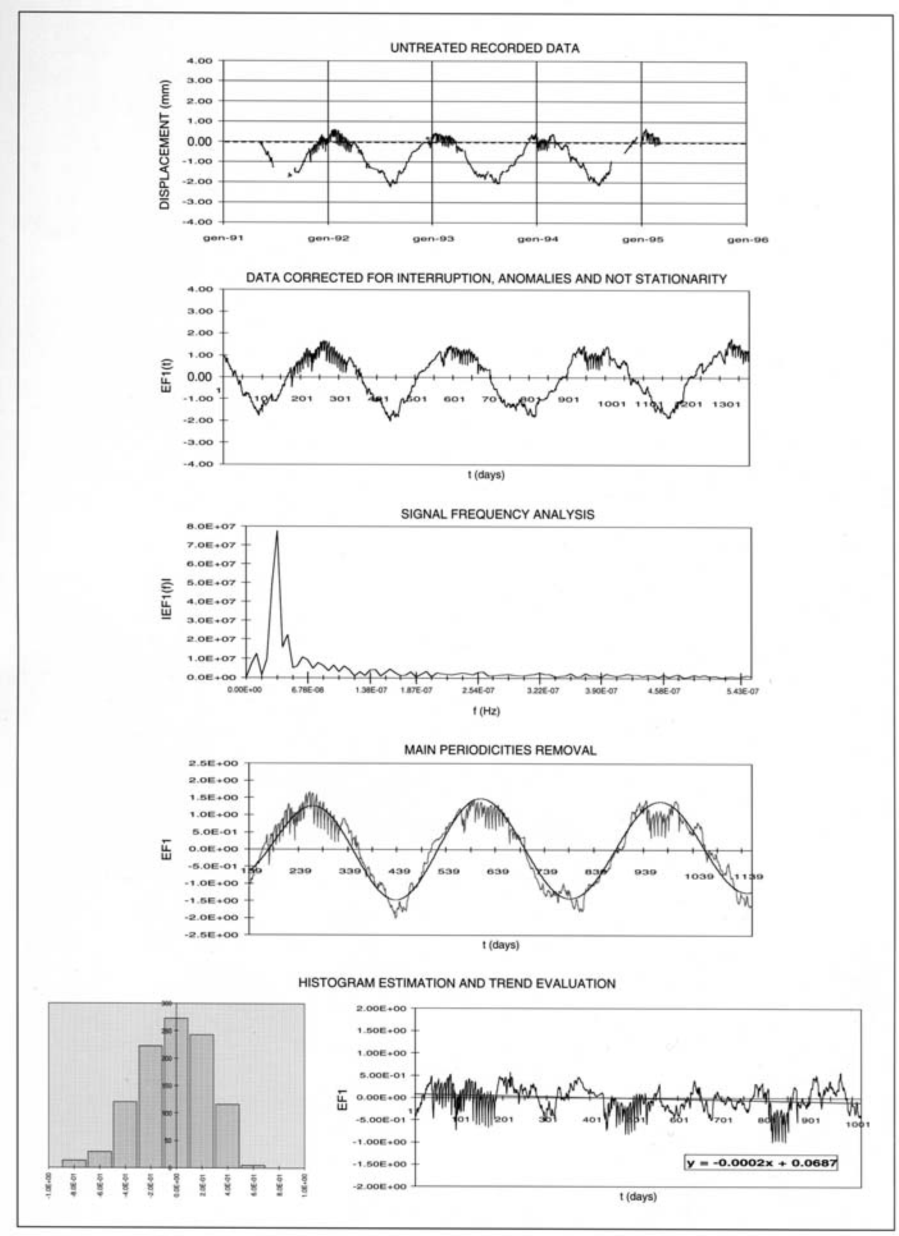


Fig. 14 – Methodological approach for signal analysis.

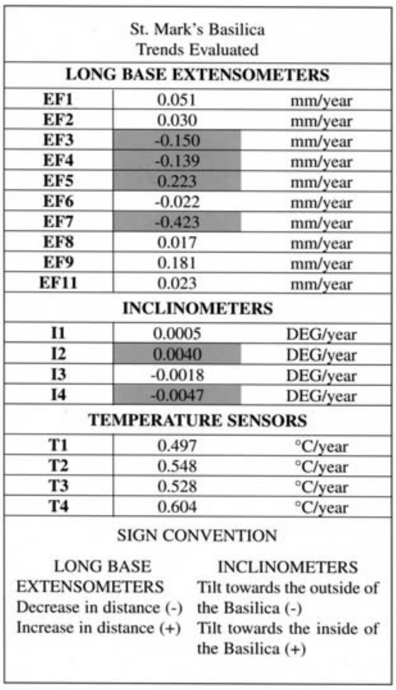
quantities.

The methodological approach proposed for signal analysis of the static monitoring system data, illustrated in Fig. 14, includes:

- Removal of signal irregularities
- Treatment of signal for non stationarity
- Signal frequency analysis
- Removal of main periodicities
- Estimation of the signal probability density distribution
- Deformation trend estimation from filtered signal

The values of the annual trend estimated for the static monitoring system signals are presented in Fig. 15 after the correction for temperature effects. It can be observed that the long-base extensometers EF3, EF4, EF5, EF7, EF9 and the inclinometers I2, I4 demonstrate deformation trends that are significant with respect to the accuracy of the transducers. The maximum trend value is observed on EF7 which is located near the entrance of the Basilica and which can be affected by local anomalies.

It is not possible at the moment to definitively interpret these deformation trends because the observation period is not considered long enough for such a complex structure. It is advisable to repeat this analysis after longer periods of observation so as to verify the validity of these trends.



St. Mark's Basilica
Trends Evaluated

LONG BASE EXTENSOMETERS		
EF1	0.051	mm/year
EF2	0.030	mm/year
EF3	-0.150	mm/year
EF4	-0.139	mm/year
EF5	0.223	mm/year
EF6	-0.022	mm/year
EF7	-0.423	mm/year
EF8	0.017	mm/year
EF9	0.181	mm/year
EF11	0.023	mm/year
INCLINOMETERS		
I1	0.0005	DEG/year
I2	0.0040	DEG/year
I3	-0.0018	DEG/year
I4	-0.0047	DEG/year
TEMPERATURE SENSORS		
T1	0.497	°C/year
T2	0.548	°C/year
T3	0.528	°C/year
T4	0.604	°C/year

SIGN CONVENTION

LONG BASE EXTENSOMETERS	INCLINOMETERS
Decrease in distance (-)	Tilt towards the outside of the Basilica (-)
Increase in distance (+)	Tilt towards the inside of the Basilica (+)

Fig. 15 – St. Mark's Basilica in Venice. Final annual deformation trends of long-base extensometers and inclinometers corrected for temperature trend. Shaded boxes indicate values which are signicant with respect to the accuracy of the trasducers (0.075 mm for the long-base extensometer and 0.0029 DEG for inclinometers).

5. The role of monitoring in the case of a catastrophic event

When a monumental building is affected by a sudden catastrophic event (fire, earthquake, landslide….), the problem of the safety of the whole structure becomes of primary importance.

The survey of the cracks and damages suffered by the structure is extremely important but it is not sufficient because precise information on the deformation rate as a function of time, is necessary.

Only a monitoring system installed very urgently, just after the disaster, is the only way to solve the problem.

In this case there is no time to install an automatic monitoring system; on the other hand, the use of manual removable instruments would be too dangerous for the safety of the people involved in the periodical readings. In the case of a catastrophic event it is advisable to install electrical sensors to be controlled by means of a portable electric reading unit in a safe zone far enough from the dangerous area.

Fig. 16 – View of the Chapel of the Holy Sindone in Turin after the fire which occurred in April 1997.

In April 1997 a tremendous fire induced very great damages to a masterpiece of Baroc Architecture designed by the architect G. Guarini in the second half of the 17th Century: the Chapel of the Holy Sindone in Turin (Fig. 16). Many significant cracks appeared on the arches over the windows and on the upper part of the vault (buttresses and cantilevers) and the steel chain, which was lining the external surface of the Chapel, was broken in two points. The structural conditions of the Chapel appeared very critical and a sudden collapse of the whole structure was feared.

For this reason Ismes was asked to install very quickly a monitoring system able to analyse the deformation behaviour of the structure. With the aid of some firemen, in the period of eight hours, 10 electrical crack-gauges were installed on the main cracks; the sensors were connected by means of electrical cables (length about 200 m) to a connecting unit located in a safe area where it was easy to read the instruments by means of a portable electric equipment. In Fig. 17 the installation of the transducers on some typical cracks is shown. With this simple solution, only few hours after the beginning of the installation, it was possible to start the control of the structure by reading every 4 hours. In this way it was possible to check the cracks which were progressively closing after the initial opening induced by the fire and those which showed a progressive opening during the first days of observation. The opening effect was observed on the cracks of the buttresses which represent very critical points for the safety of the whole dome.

With the aid of this monitoring system it was possible to control the installation of the temporary reinforcing structures (stell cables to confine the upper part of the Chapel, stell plates to reiforce the buttresses).

Some days after the first installation, the number of the instruments was increased and two weeks later all the sensors were connected to an automatic data acquisition system.

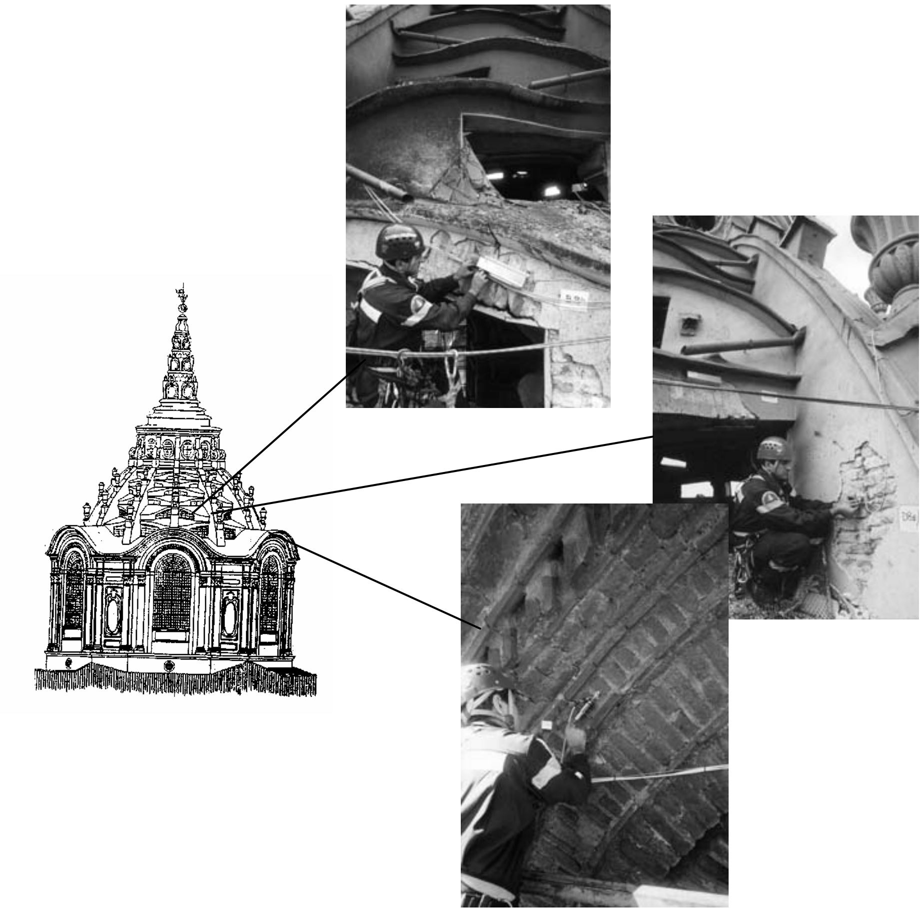


Fig. 17 – Installation of the electrical sensors on the main cracks.

6. Conclusions

The design of a monitoring system for an existing structure of monumental or societal significance, depends primarily on the purpose of the system. It is necessary to identify whether the measurements are needed to better understand the current structural behaviour of the building (e.g. the monitoring of St. Mark’s Basilica in Venice) or to help direct and monitor remedial or restoration work (e.g. the monitoring of the remedial work for the Metropolitan Cathedral in Mexico).

Once the purpose of the measurement system has been defined, the details relative to the specific type of instruments to be employed, the nature of the data acquisition system and the method of data interpretation can be rationally identified. The importance of the flexibility of the initial system and the continuity of system maintenance must be emphasized particularly for the understanding of structural behaviour over the long term.

Interpretation of measurements obtained in conjunction with restoration works is often readily and immediately related to specific remedial actions or events.

On the other hand, measurements obtained during long-term monitoring, in order to understand the structural behaviour of a given monument, can be more susceptible due to environmental and seasonal effects. Thus, such data should be filtered and treated statistically in addition to being considered over a sufficiently long term, commonly several years.

Without doubt, rational conservation efforts particularly for historical monuments are best made with the aid of specific measurements selected bearing in mind the structure and its potential problems.

7. References

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