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Monitoring system of St. Mark's Basilica in Venice. Analysis and Interpretation of the data

MONITORING SYSTEM OF ST. MARK'S BASILICA IN VENICE. ANALYSIS AND INTERPRETATION OF THE DATA

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SUMMARY

A diagnostic analysis to check the static conditions of the supporting structures of St. Mark's Basilica in Venice is presented. The investigation program, commissioned to ISMES by the Venice Water Board of the Ministry of Public Works, includes: historical analysis, topographic and photogrammetric surveys, detailed crack pattern survey, geotechnical investigation and foundation surveys, analysis of the mechanical characteristics of the masonry structures by laboratory tests, sonic tomograph, radar, coring, video camera survey and flat jack tests for the measurement of the state of stress and the determination of the deformability characteristics. The parameters determined by means of this investigation program were used in mathematical modelling of the whole structure.
Special emphasis is devoted to presentation of the automatic monitoring system installed on the major supporting structural elements of the Basilica. The criteria used for processing the data recorded by the structural monitoring system during a period of more than 3 years are then presented.

1. INTRODUCTION

The Basilica of St. Mark is a structurally complex monument in which three major construction phases can be identified. The first phase dates from 828 A.D. when the Ducal Chapel was founded to house the body of St. Mark Evangelist which the Venetians had recovered from Alexandria in Egypt. The second phase began in 976 A.D. when the Ducal Palace and the Church were burnt by the populace to kill Doge Candiano IV; the structure was rebuilt with new decorations by Doge Pietro Orsolo the Saint. The third phase began in 1063, when Venice gave the world a fine example of its power with the construction of the grandiose building designed by the most important Byzantine architects. Built over many centuries utilising pre-existing structures as far as possible, the Basilica shows clear signs of deformation and damage to its walls, arches, vaults and domes, as well as the flooring. Numerous earthquakes exacerbated this situation, especially those in the XII century which shook Venice and the Basilica to their foundations, as well as several devastating fires requiring the rebuilding of entire sections of the monument. Stylistic modifications and the increased structural weight of the domes, joined, in turn, by all the other additions made over the centuries also contributed to the building stress. The longitudinal section of the Basilica in Fig. 1 shows the original masonry domes and the overhanging lead domes built in the middle of the XIII century. It was only in the early XIX century following the fall of the

Venetian Republic, that the Austrian government enacted systematic restoration works. Above all, attempts were made to restore the walls, vaults and arches, and to consolidate the centuries-old structure which, under the thrust of the weight of the lead domes, was literally splitting the Basilica lengthwise in two.

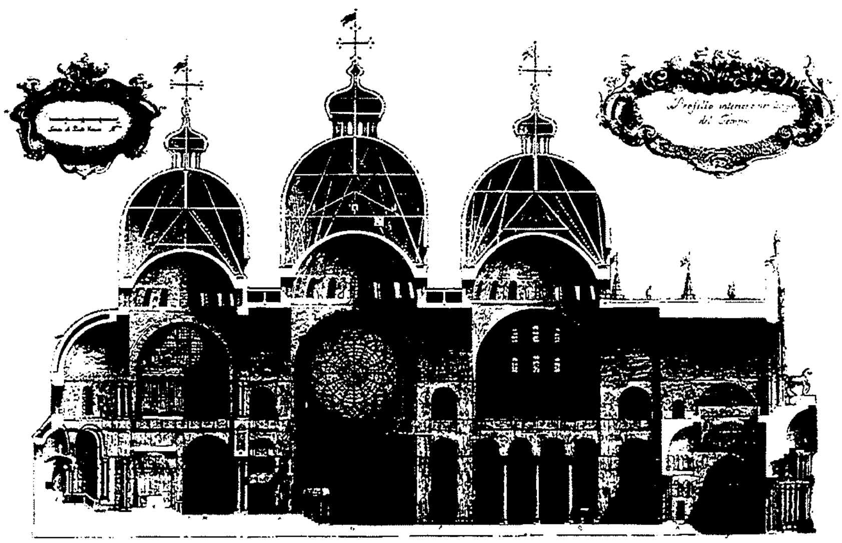


Fig. 1 - Longitudinal section (A. Visentini, XVIII century.

Thanks to the admirable attention of the "Procuratoria" (ancient name of the Surveyor Board of the Basilica) in the eighties a scientifically advanced restoration programme was planned by the Technical Department of the Basilica. A first programme of structural investigations, including the monitoring system, was financed by ISMES and ENEL in 1990. Then ISMES was commissioned by the Venice Water Board of the Ministry of Public Works to carry out a wide-ranging programme of surveys for the evaluation of the static conditions of the Basilica. This research programme is based on a combined experimental numerical procedure consisting of the following major steps:

- topographic and photogrammetric survey;
- historical analysis;
- detailed crack pattern survey;
- geotechnical investigation and foundation survey;
- analysis of the mechanical characteristics of the masonry structures by sonic tomography, radar, coring and video camera survey and flat-jack tests;
- monitoring system;
- numerical modelling

2. PRELIMINARY INVESTIGATIONS

The works performed on the Basilica in the past are documented up to the fall of the Venetian Republic in the Venice State Archives and subsequently through documents filed for the most part in the Historical Archives of the "Procuratoria" of St. Mark. These documents comprise texts, drawings and photographs. This material is extremely important and provides the essential basis for properly targeted restoration work. Moreover, the Technical Department of the Basilica is well-informed of the works performed over the last 20-30 years. This material is organised in a manner which integrates knowledge of written documents with graphics and photographs and it is coordinated in order to provide rapid access, with the aid of computers, to the information concerning the various fields of intervention. Work therefore involves cataloguing these documents, in order to prepare report cards detailing the major restoration tasks implemented in the past.

Unfortunately, no full-scale geometric survey of St. Mark's Basilica presently exists. Various attempts to survey the Basilica are extant, some of considerable prestige, such as those carried out by Antonio Visentini in the mid-1700s and later by the Surveyor - Architect Scattolin. The structure of the Basilica, however, is of such spatial complexity, dominated by curved surfaces embellished by figurative and decorative low reliefs and mosaics, that it cannot be reproduced faithfully without a careful survey of forms, dimensions, measurements and alignments, such a survey would make it possible to evaluate static conditions and verify historical hypotheses in order to target restoration work and conservation methods appropriately. In the case of St. Mark's Basilica, architectural photogrammetry is especially meaningful and pertinent since it is the only means of ensuring absolute correspondence between graphic reproduction and actual architectural-spatial placement. The photogrammetric study, begun in 1983, was completed in order to obtain a complete graphical and numerical restitution. The photogrammetrical survey was very important for planning the diagnostic analysis program and for carrying out the finite element modelling.

3. SUBSURFACE AND FOUNDATION SURVEY

A detailed survey of the soil underlying the Cathedral was carried out in order to define the stratigraphy as well as the mechanical characteristics of the different soil layers. Seven boreholes (30 m deep) were drilled around the perimeter of the Basilica and many undisturbed samples were taken for carrying out physical and mechanical laboratory tests. Static cone penetration tests using a digital cone were also carried out in three testing points, in order to identify the mechanical characteristics of the different layers of soil. An example of the stratigraphy obtained by correlating the in situ and laboratory tests results of three boreholes drilled on the North side of the Cathedral is presented in Fig. 2. Under a surface layer of fill material, a silty-clay layer (about 5 m thick) was observed. A silty-sand layer with stronger mechanical characteristics is also present with a thickness varying between 5 and 10 m. Under the sand layer, silty-clay material was found. The presence of local lenses of sand inside the silty-clay material is considered typical of lagoon-side environments. Three boreholes were equipped with electric piezometers and three with long base settlement-gauges connected to an automatic reading unit. This monitoring system will allow the settlement of the perimeter of the Cathedral to be monitored as a function of time and water-table variations.

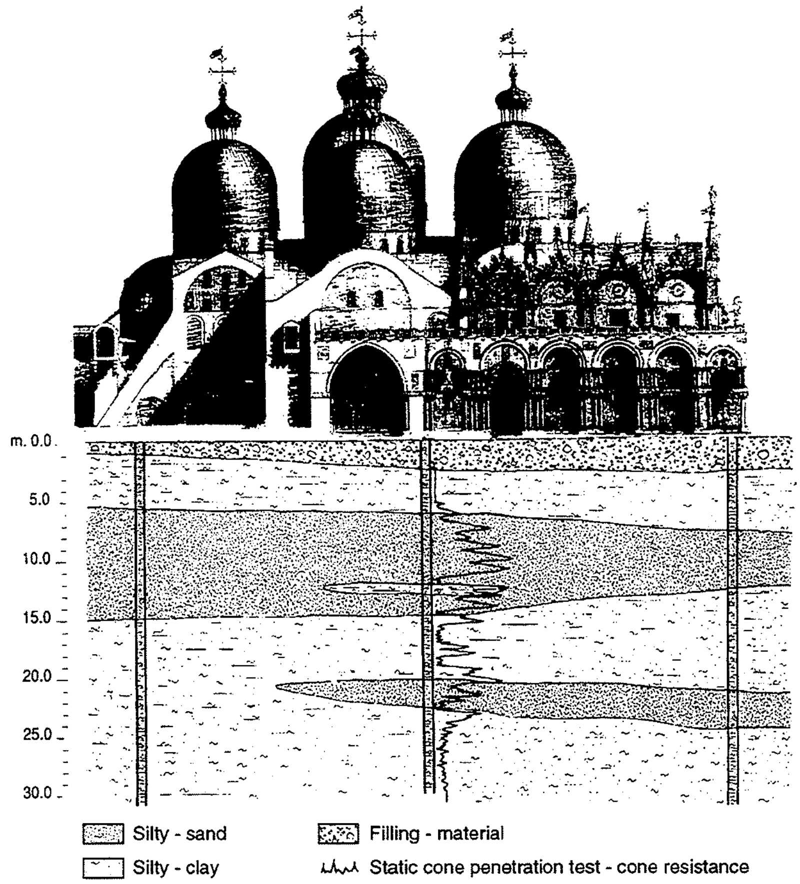


Fig. 2 - Stratigraphic profile along the North side of the Basilica. The results of static cone penetration tests are presented.

An in-depth investigation was also carried out to analyze the geometric and structural characteristics of the foundation masonry of the perimeter walls and of the pillars. Several small boreholes (diameter 62 mm) were cored by using a light diamond saw and the lateral surface of the boreholes was surveyed by means of a colour video camera. More than 50 sub-vertical boreholes were drilled to investigate the structural characteristics of the foundation masonries. In order to obtain qualitative information concerning the mechanical characteristics of the masonry structures, a sonic-log survey was carried out as well as cross-hole velocity measurements by using two parallel boreholes. As a result of the coring and video camera survey, the typical structural scheme of the foundation masonry was determined. At a depth of about 70-90 cm from floor level, a stone basement made with large blocks of sandstone is present with a thickness of about 2 m. Underneath this stone basement there is a wood plate (10 cm thick) which is about 3.0 m below the floor. This wood plate rests on short wood piles which are very poorly preserved.

4. ANALYSIS OF THE MECHANICAL CHARACTERISTICS OF THE MASONRY STRUCTURES

The pillars and the perimeter walls of the Basilica were intensively investigated with both non-destructive and slightly-destructive tests. Special attention was devoted to the pillars that were investigated in the only unlined portion (about 1 m high) along the "matronei". Below this portion, the pillars are lined with marble and above it the surfaces are covered by mosaics.

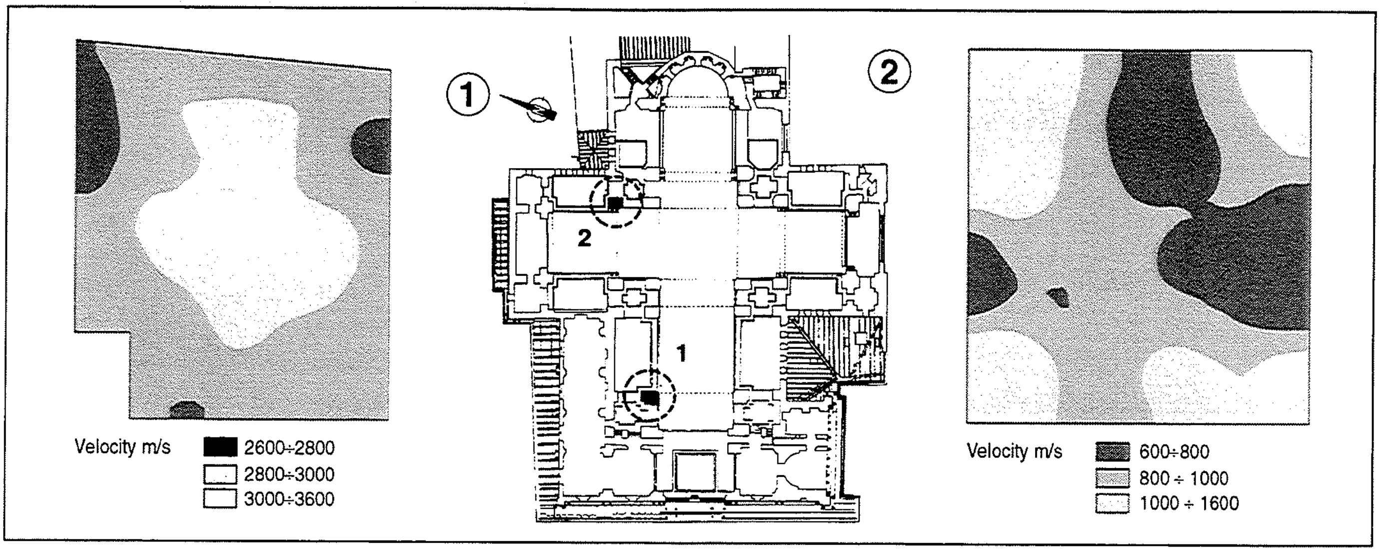


Fig. 3 - Results of tomographic survey in two pillars with different mechanical characteristics.

Sonic tomography and radar survey

First, a non-destructive sonic tomography and radar survey investigation was carried in order to identify possible anomalies. The most significant results were obtained from the sonic tomography survey which provided a clear mapping of the different velocity zones, as exemplified by the results for pillars 1 and 2 in Fig. 3. It can be clearly observed that pillar 1, consolidated by grouting about 30 years ago, shows high velocity values, especially in the internal zone which was involved in the grouting operation. On the contrary, the velocity values obtained for pillar 2 show that the mechanical characteristics of this pillar are very poor (in fact no consolidation work was performed on this pillar in the past).

Coring and borehole video camera survey

Horizontal and vertical boreholes (more than 60) were drilled in each pillar with light drilling equipment. A video camera survey was then performed with a detailed description of the borehole surfaces. By drilling subvertical boreholes (about 4 m long) starting from the level of "matronei", it was possible to investigate the lower part of the pillars lined with marble plates. Several boreholes were also carried out along the perimeter walls of the Basilica.

Measurement of the state of stress and analysis of the deformability characteristics

For the evaluation of the static conditions of the Basilica it seemed advisable to measure the actual state of stress on the main supporting structures with special attention to the pillars. For this purpose the well-known flat-jack test was used.

This non-destructive test, developed by ISMES about 17 years ago, is based on the release of the state of stress by making a small slot in a mortar layer and then reloading by means of a thin flat-jack inserted into the slot Fig. 4. This test is very simple and reliable as proven by calibration tests carried out

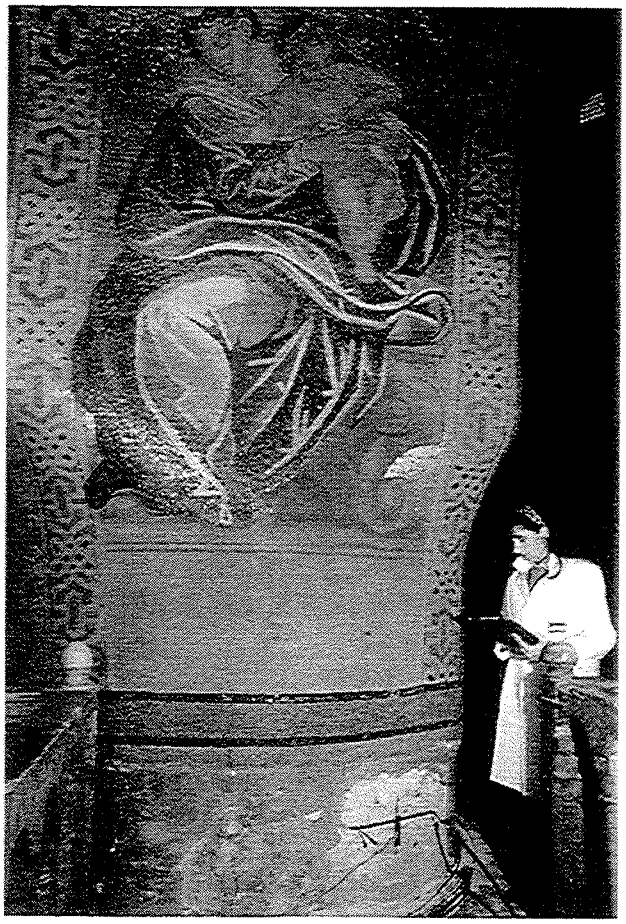


Fig. 4 - Measurement of the state of stress in a pillar by means of the flat-jack technique.

in the laboratory. More than 80 flat-jack tests were carried out (about 65 on the pillars and 20 on the perimeter walls). The stress values measured on the pillars, shown in Fig. 5, demonstrate a certain heterogeneity of the state of stress, which is related not only to the position and size of the pillars but also to the type and extent of the consolidation works which some pillars have undergone in the past. High stress values (up to 1.1 MPa) were measured in some pillars. Furthermore, in the above-mentioned pillar 2 (the south-east pillar of the St. John's Dome), a state of stress of 0.95 MPa was measured. This value was considered very high in relation to the results obtained by sonic tomography, coring and video camera survey.

By using two parallel flat-jacks the deformability characteristics of the masonry were determined for the pillars and along the perimeter walls. Two flat-jacks were inserted in the masonry in order to involve a specimen of appreciable size (40 x 50 cm) on which a uniaxial state of stress was applied. During the loading phase, the axial and transversal deformation of the specimen was plotted as a function of the applied load. This simple testing technique allowed the deformability moduli of the different types of masonries analyzed to be determined. These values have been used as input data for the finite element model.

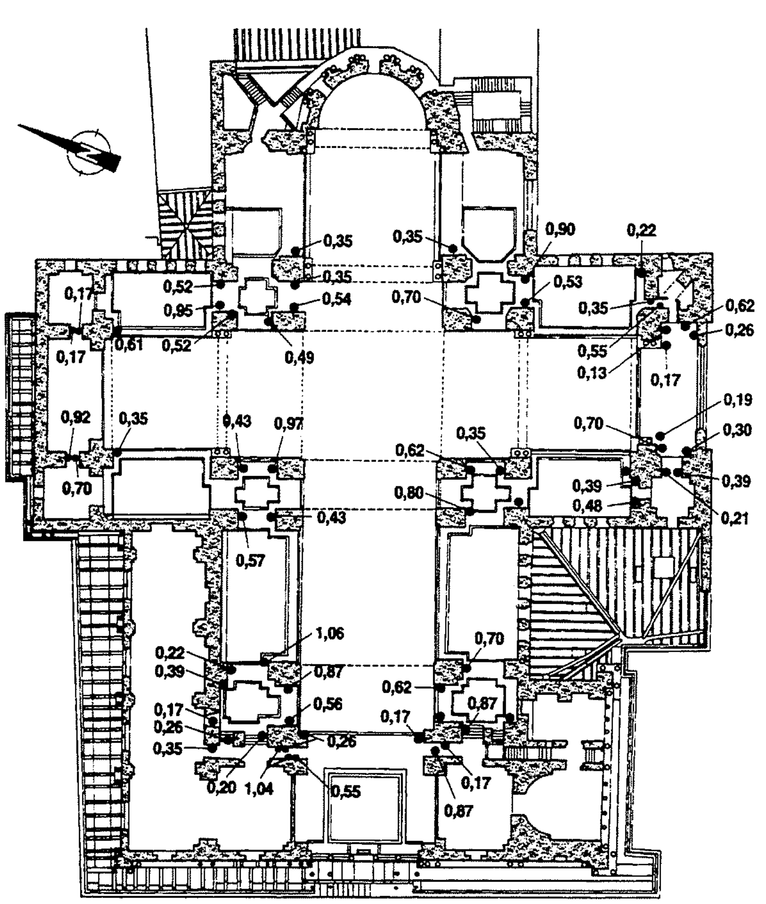


Fig. 5 - General lay-out of the flat-jack testing point with the indication of the measured states of stress.

The deformability characteristics of the pillars are a function of the type of consolidation works performed on the masonry. The tests carried out on the original unconsolidated masonry show values for Young's modulus varying between 800 and 2000 MPa (for a stress range of 0.4 ÷ 0.8 MPa). The values determined in the same applied stress range on the masonry previously consolidated by grouting are higher (between 1600 and 4000 MPa). In some pillars, where the masonry was completely rebuilt about 30 years ago, Young's modulus has an average value of about 5000 MPa.

Supplementary investigation on the south-east pillar of St. John's Dome

The combined analysis of the results obtained by flat-jack test, sonic tomography, coring and video camera survey clearly shows that pillar 2 (south-east pillar of St. John's Dome) must withstand very severe loading conditions with poor mechanical characteristics of the masonry. For this reason it was decided to carry out a more detailed investigation in the lower part of the pillar after removing the marble lining. First, a detailed crack pattern survey was carried out which showed the presence of several vertical small cracks, especially near the corners. Sonic tomography was performed at three sections of the pillar at different heights from the floor and the results confirmed the low velocity values presented in Fig. 3. In several points of the pillar, the state of stress was measured by flat-jack test and an average value of 0.85 MPa was found. Then the deformability characteristics were determined in two points by two parallel flat-jacks. A typical stress-strain curve of the masonry is shown in Fig. 6 where axial and transversal strain values are presented as functions of axial stress. The average value of the measured state of stress is also indicated. It can be observed that the masonry presents a linear behaviour up to a stress level of about 0.8 MPa with a value of Young's modulus of about 2000 MPa. For higher stress levels, up to 1.2 MPa, Young's modulus decreases to a value of about 900 MPa and for the stress range between 1.2 and 1.5 MPa the modulus is less than 300 MPa. It can be observed that the average state of stress measured in the pillar exceeds the limit between elastic and plastic behaviour. This supplementary investigation clearly confirmed that the static conditions of the pillar are not satisfactory and it was decided to carry out urgent consolidation works that now have been completed.

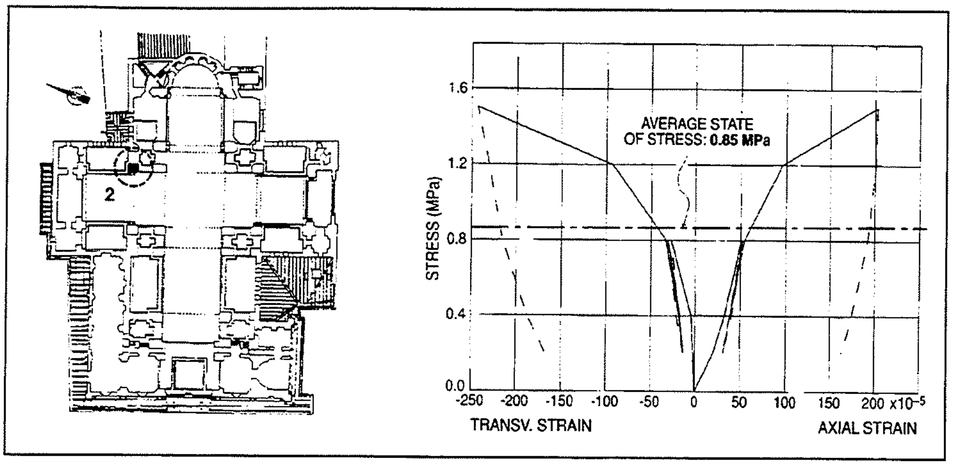


Fig. 6 - Stress-strain diagrams obtained by flat-jack tests on the pillar n. 2 with the indication of the measured state of stress.

5. NUMERICAL MODELLING

A significant contribution to the knowledge of the static conditions of the Basilica is provided by the mathematical model which utilise all the data and information obtained through in-situ and laboratory investigations and from the monitoring system.
The mechanical parameters of the masonry for the mathematical model have been obtained by flat-jacks deformability tests.
The validation of the model was carried out through the comparison between the calculated values of the state of stress and those measured in situ by flat-jacks tests.
Different loading conditions have been applied with the model (dead load, thermal effect, differential settlements of the foundation structures) and the deformaion behaviour of the structure is analyzed with great attention in order to obtain a better understanding and a more meaningful interpretation of the data provided by the monitoring system.
Due to the high degree of complexity of the structure the whole building is considered as the sum of suitable substructures.
Several analyses on simplified models have been performed in order to identify the most significant substructures.

It seemed advisable to divide the structure into 9 substructures in order to separately analyze the pillars, the lateral walls and the domes.
The boundary conditions of each single substructure correctly reproduce the stiffness of the adjacent substructures.
The complexity of this model is clearly shown by the very high number of degrees odf freedom (about 250000).
Fig. 7 shows a general view of the finite element model of the Basilica and the soil foundation.

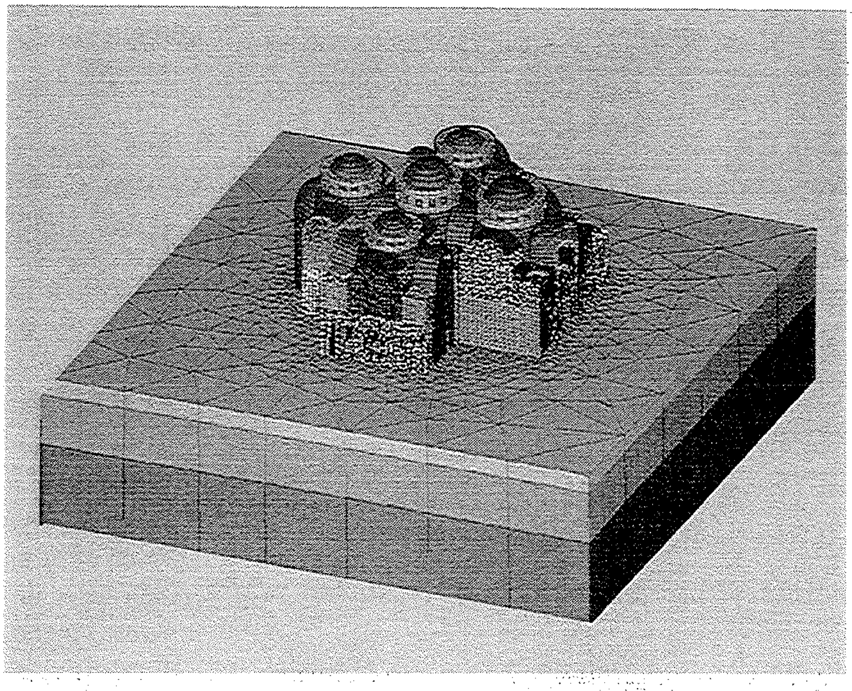


Fig. 7 - Finite element model of the Basilica and the soil foundation.

6. MONITORING SYSTEM

In order to obtain a continuous control of the static behaviour of the Basilica, in 1991 a structural monitoring system was installed by ISMES. The principal features which are monitored are as follows:

- opening of the main cracks in the pillars (8 extensometers) Fig. 8a.
- relative horizontal movements of the pillars (11 long base extensometers) Fig. 8b.
- tilting of the vertical structure (4 inclinometers)
- internal and external temperature (5 temperature sensors)

The purpose of each instrument of a structural monitoring system is to represent the evolution of a physical phenomenon (opening of cracks, relative movement of the pillars, evolution of temperature, ...) by regular recordings in time of physical quantities directly related to the phenomenon.

The characteristics of the trasducers used in the instruments installed in St. Mark's Basilica are showed in the following table:

	Long base extensometer	*Extensometer*	*Inclinometers*	*Temperature sensors*
MEASURING RANGE	*25 mm*	*12.5 mm*	*± 14.5 mm*	*± 100°C*
ACCURACY	*± 0.3% m.r.* (*± 0.075 mm*)	*± 0.3% m.r.* (*± 0.038 mm*)	*± 0.02% m.r.* (*± 0.0029°*)	*± 0.15% m.r.* (*± 0.049°C*)

All the instruments are connected to an automatic data acquisition and recording unit which systematically collects and stores the data every 2 hours and that can quickly indicate possible anomalies in the structural behaviour. In the beginning of 1995 the monitoring system was completed by adding geotechnical instrumentation including:

- 3 long base settlements gauges for detecting the evaluation of the vertical settlements of the soil foundation;
- 3 piezometers for estimating water-table variations;

Fig. 9 shows the general lay-out of the instruments installed in St. Mark's Basilica.

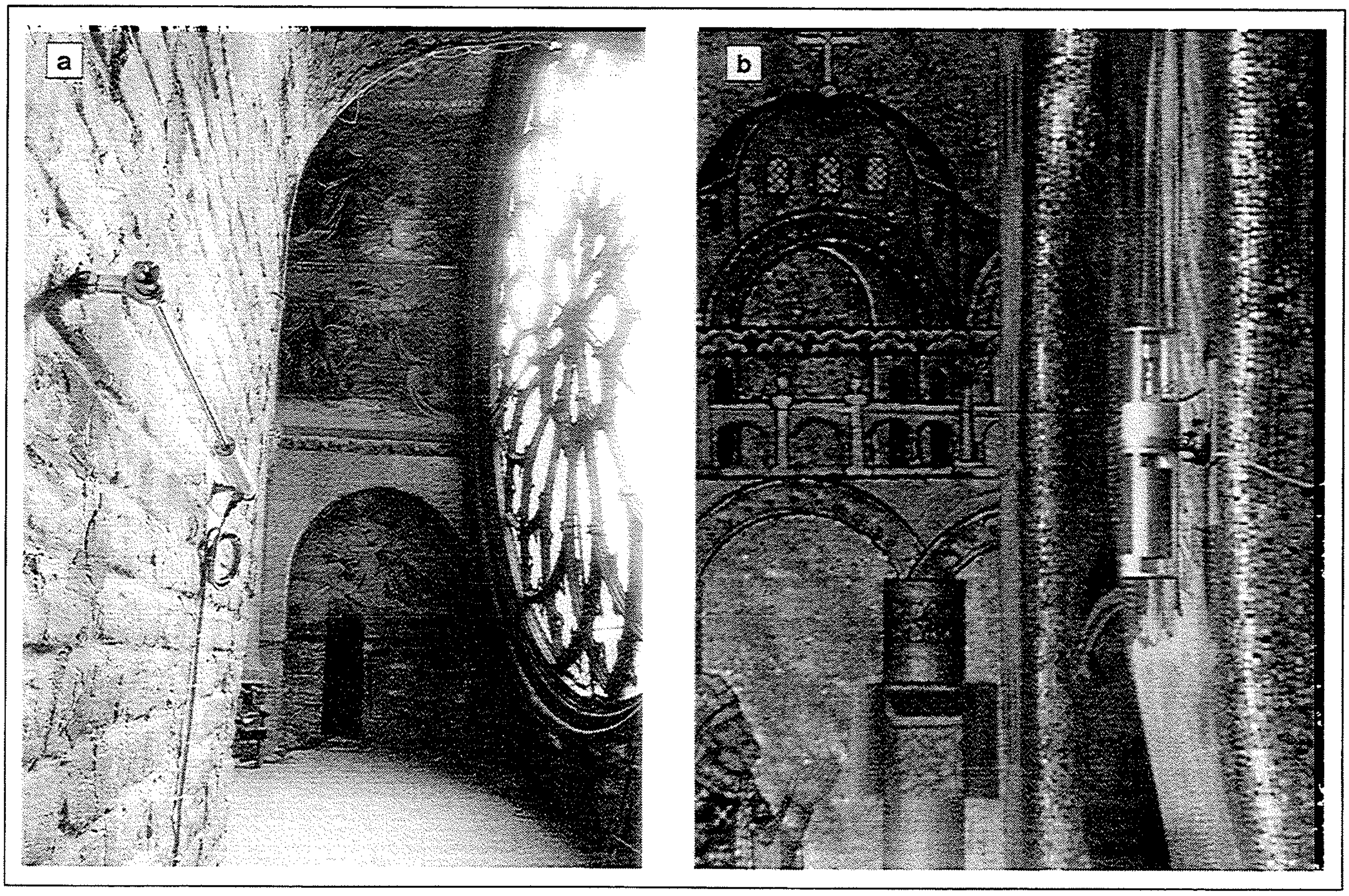


Fig. 8 - a) Extensometer installed on a vertical crack b) Long-base extensometer for measuring the relative displacement between two pillars.

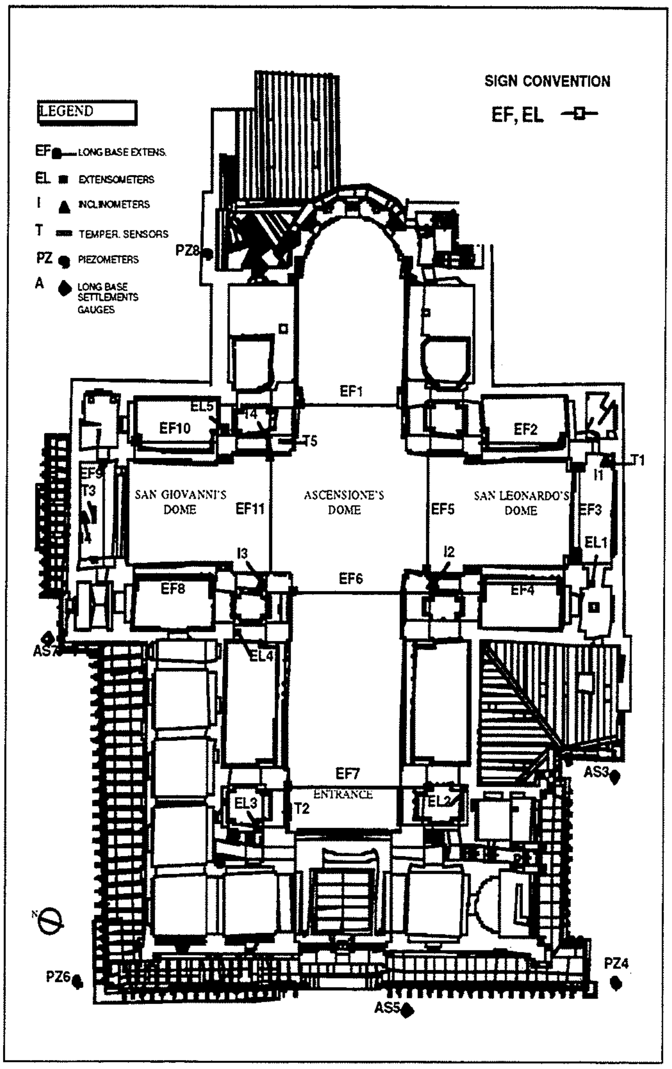


Fig. 9 - General lay-out of the structural monitoring system's instruments.

6.1 METHODOLOGICAL APPROACH TO ANALYZE STATIC MONITORING SYSTEMS DATA

The methodological approach for the analysis of the structural monitoring system data presented in this paper is 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 instrumens.

Direct analysis of the time-history diagrams of each instrument (i.e. Fig. 10 shows the diagrams of the temperature variations measured by a temperature sensors and the relative horizontal movements between two pillars measured by a long base extensometer) 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. This direct analysis is also important for planning numerical elaborations.

The mathematical techniques that are employed in the analysis of the time series provided by the monitoring systems are as follows:

- Analysis of correlations between the quantities measured by the various instrumens
- Signal analysis
  - Evaluation of signal's harmonic component;
  - Evaluation of the signal trend

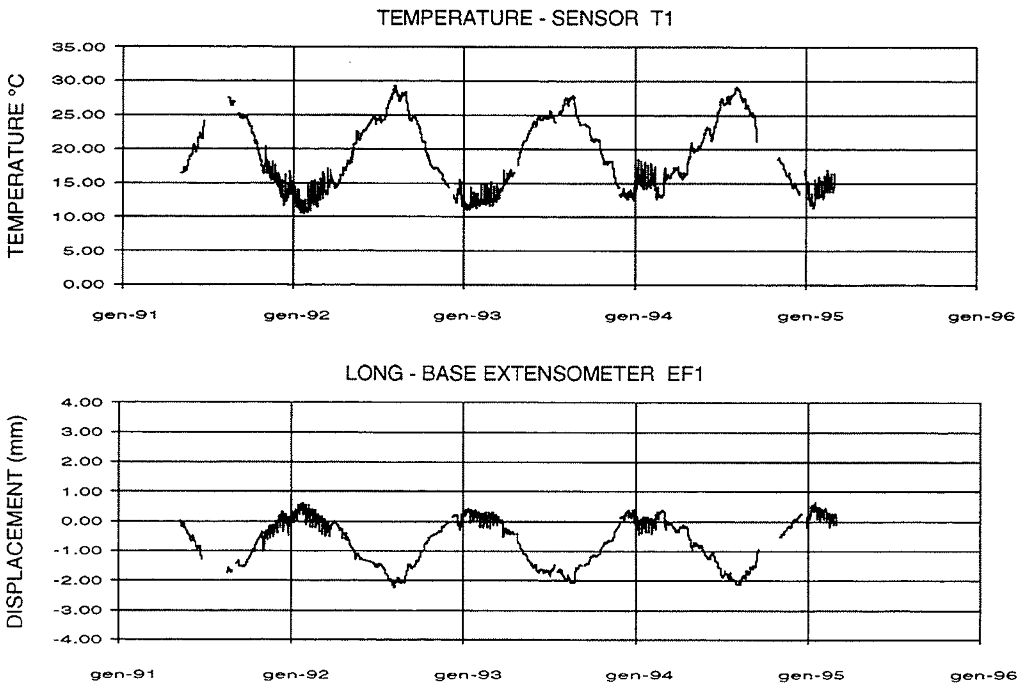


Fig. 10 - Time-histories of the recorded data of the temperature sensor (T1) and the long base extensometer (EF1).

6.1.1 Correlations analysis

The evaluation of correlations between the quantities measured by the various instruments is carried out by autocorrelation and crosscorrelation analysis with the following functions, respectively:

$$R_{xx}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} X(t)X(t+\tau)dt$$

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} X(t)Y(t+\tau)dt$$

where T is the time-interval in which the signal is sampled, $X(t)$ and $Y(t)$ are the value of the quantity recorded by two different instruments, τ represents the time delay between $X(t)$ and $Y(t)$. These correlation functions are an extension of the classical concepts of correlation between two sets of paired measurements x_i, $i = 1, 2, 3, ..., N$ and y_i, $i = 1, 2, 3, ..., N$ when an additional variable is introduced, namely a time delay between $X(t)$ and $Y(t)$.

The crosscorrelation function $R_{xy}(\tau)$ expresses the dependence of the value of signal $Y(t)$ at time $t+\tau$ on the value of the signal $X(t)$ at time t.

The existence of a time delay variable (τ) permits the use of correlation concept for the situation $X(t)=Y(t)$. In this case, the autocorrelation function $R_{xx}(\tau)$ expresses the dependence of the value of signal $X(t)$ at time $t+\tau$ on the value of the same signal at time t.

6.1.2 Signal analysis

The methodological approach proposed for signal analysis of the static monitoring system data is illustrated in the scheme shown in Fig. 11. Data processing can be described according to the following steps:

- *Signal irregularities and interruption removal.*
  The elimination of signal interruptions is an indispensable operation for any kind of data processing for frequency domain analysis. These algorithms in fact require signals sampled in regular time intervals without any discontinuities. The irregularities are removed by cleaning the signal of anomalies due to accidental impacts against the instruments or to malfunctioning sensors. These anomalies can cause an interpretation that does not correspond to the real phenomenon.

- *Treatment of signal for non stationarity.*
  The signal analysis proposed is based on the assumption of stationarity of the stochastic process that represent the phenomenon. Thus, the signal must be made stationary.

- *Signal frequency analysis*
  This operation, consisting in the identification of the main periodicities of the phenomenon, is carried out by examining the autocorrelation function, which contains the main seasonal behaviour of the signal, or directly analyzing the frequency characteristics of the signal by a trasformation from time domain to that of frequency.

- *Main periodicities removal*
  This step involves filtering the signal in the frequency domain. This operation is analogous to treating the signal in the time-domain by subtracting a sinusoid, containing the main period of the signal after having treated it for non stationarity.

- *Estimation of the signal probability density distribution*
  After signal filtering, it is possible to obtain the signal histogram. If all major signal periodicity has been removed, the signal residual must be characterized by a Gauss-like probability distribution. The filtered signal can be considered as composed of a purely random component which can be defined as “white noise”.

- *Deformation trend estimation from filtered signal*
  The signal characteristics described in the preceding point ("white noise") permit the use of a "least squares" linear regression to evaluate the annual deformation trend of each signal. This trend is pertinent to the stationary process: the real trend can be obtained by considering the method used to render the signal stationary.

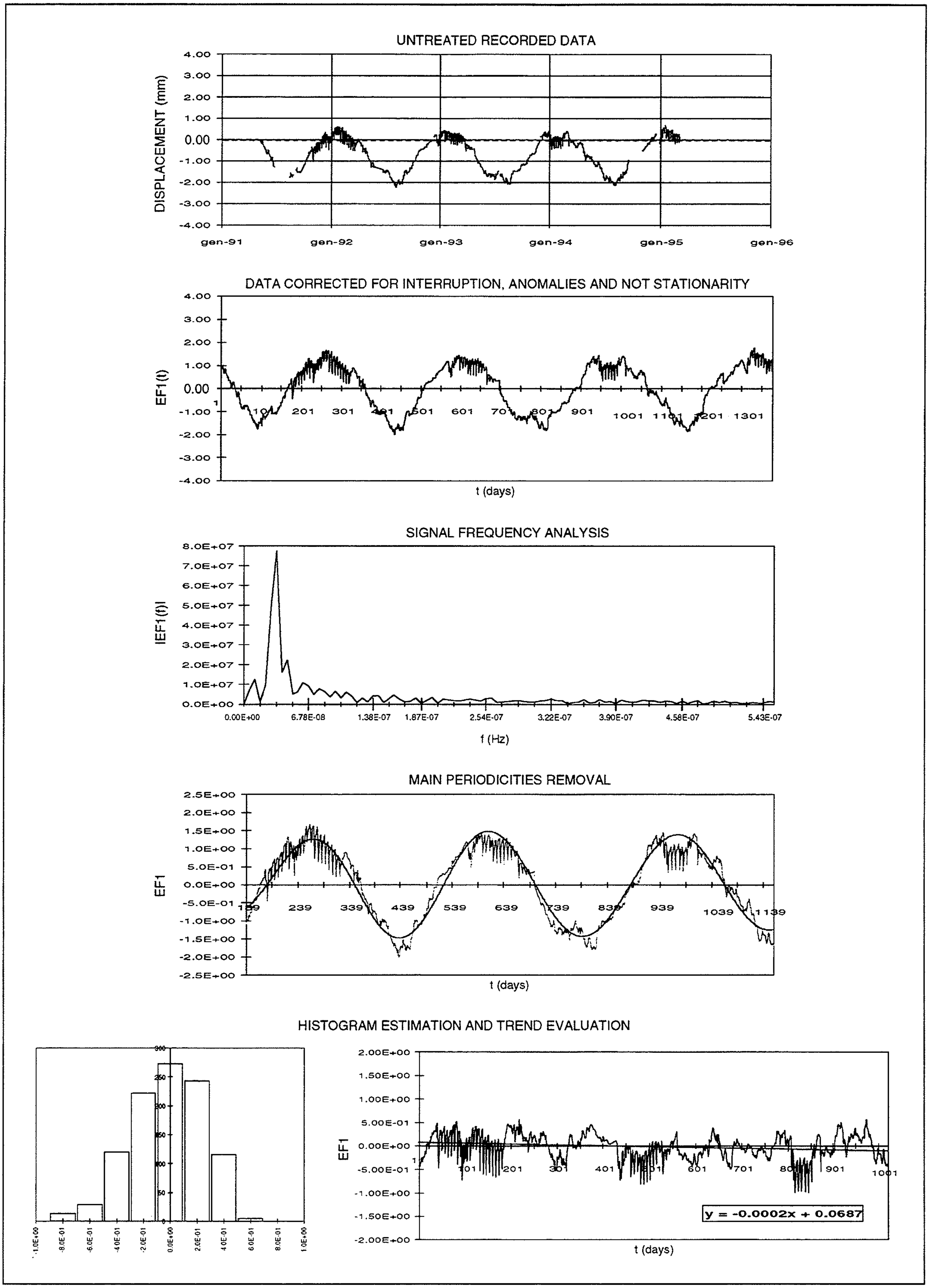


Fig. 11 - Methodological approach for signal analysis.

6.2 *INTERPRETATION OF CORRELATION FUNCTION*

Correlation functions analysis was carried out by first correlating the signals coming from instruments measuring the same quantities, and then analyzing the correlation between measurements of different quantities.

A large part of movements concerning the supporting structures of the Basilica is connected with the daily and seasonal temperature variations, so primarily a correlation analysis between temperature measurements coming from temperature sensors installed in different places in the Basilica is needed. Fig. 12 shows the diagram of autocorrelation function of temperature sensor T4 and the crosscorrelation functions between T4 and the other temperature sensors.

All the correlation functions are characterized by a periodicity of about 342 days. The signals coming from instruments T1, T2, T3 and T4 are well correlated, that means that the temperature variations are similar in all the temperature sensors installed at the level of "matronei". Thus, the phenomenon concerning temperature variations can be described using just one of the sensors. Sensor T5, installed inside the masonry, presents a 6 days delay in comparison to the other, because of the presence of the thermal inertia of the walls of the Basilica.

Correlation analysis between long base extensometers is carried out considering groups of instruments referred to the same structures of the Basilica. Good correlation between the extensometers of each group would permit the analysis of correlation between instruments of different groups using just a few instruments chosen as representative of the different parts of the structure (Fig. 13).

Fig. 13 shows a good correlation between instruments EF1, EF2 and EF9, while EF7 is less well correlated.

Extensometer EF7 presents a greater deformation trend than the other instruments. Besides, this extensometer is installed on the pillars near the entrance, a stiffer structure because of the presence of the perimetral walls and the nartece.

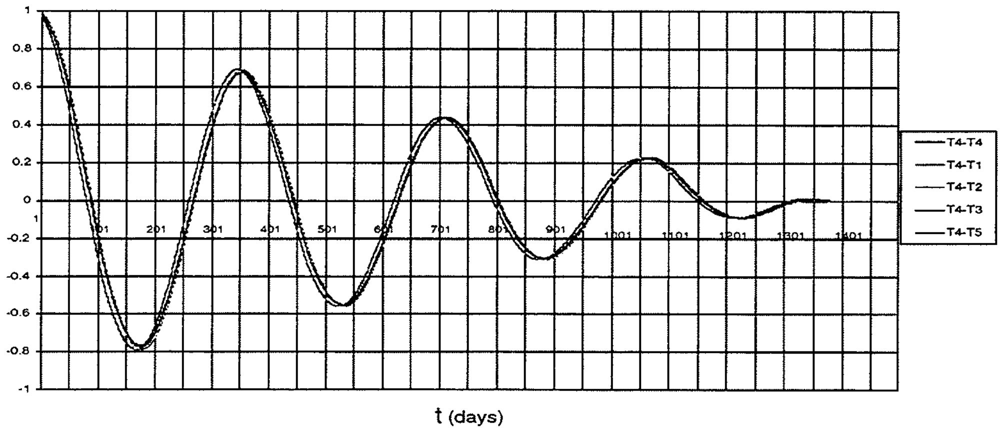


Fig. 12 - Correlation between the signals coming from five temperature sensors.

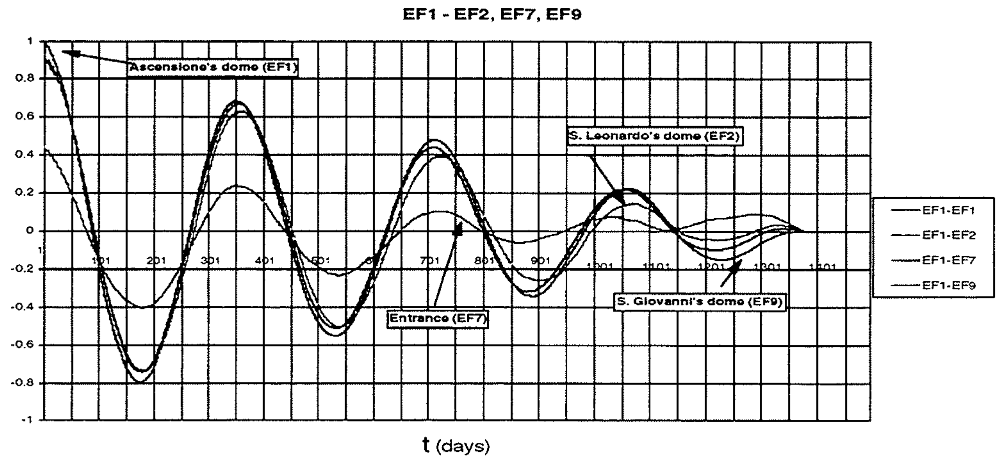


Fig. 13 - Correlation between four long base extensometer.

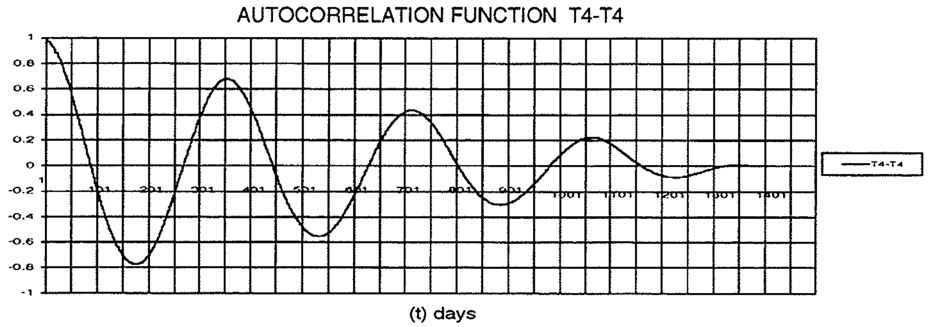
After correlating the results from instruments measuring similar quantities, it is useful to identify the degree of correlation between temperature variations and both relative movements and tilt variation of the structures (measured by extensometers and inclinometers) and between relative movement and tilt variations.

Fig. 14 shows an example of correlation between signals coming from temperature sensors (T4 was chosen as representive for all the sensors) and from long base extensometers representive of each groups of instruments previously described.

the temperature trend.

The temperature sensors indicate annual trend of 0.54 °C/year on the average probably due to temperature oscillation characterized by a period greater than the sample window.

According to the manifest influence of the temperature variations on the strain behaviour of the supporting structures of the Basilica (as resulted from the correlation analysis), it is assumed that part of the trend of the long base extensometer and the inclinometers is due to the temperature sensors trend.



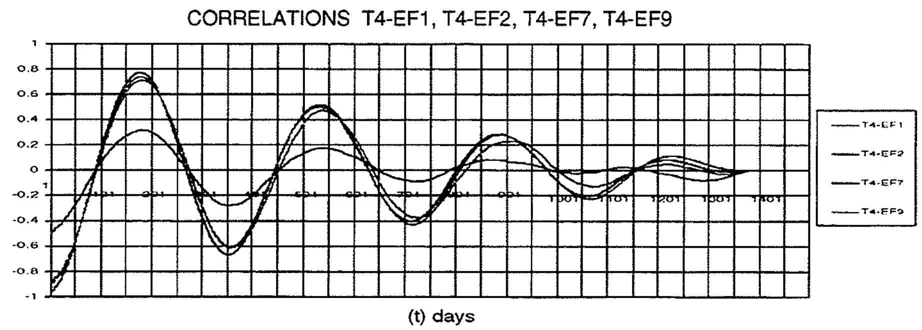


Fig. 14 - Correlation between temperature variations and relative movements.

Fig. 14 shows that temperature sensors and extensometer signal are in opposire phase and well correlated except in the case of extensometer EF7, because of its deformation trend and position on structures whose movements are less dependent on temperature variations

This analysis of correlation functions is the preliminary base for the evaluation of the deformation trend of the structure and possible anomalies in the structural behaviour.

6.3 TREND EVALUATION

Table 1 contains the values of the annual trend estimated for the static monitoring system signals. These values have been calculated according to the metodological approach for the interpretation of the signals illustrated in Fig. 11 prior to correcting for

In order to evaluate the influence of the temperature trend the ratios $\Delta L/\Delta T$ and $\Delta I/\Delta T$ between the average amplitudes of the annual oscillations of signals coming from long base extensometers and inclinometers and of those one coming form temperature sensors were calculated.

These ratios have been multiplied by the temperature trend obtaining an estimation of the values ΔL_{CORR} and ΔI_{CORR} corresponding to the part of annual movements trend due to the temperature variation.

Table 2 shows the final annual trends resulting for the long base extensometers and the inclinometers, correcte for temperature trend.

The long-base extensometers EF3, EF4, EF5, EF7, EF9 and the inclinometers I2, I4 demonstrate deformation trends that are significant when considering the accuracy of the trasducers. The maximum trend value is observed on EF7 which is located near the entrance of the Basilica.

LONG BASE EXTENSOMETER			INCLINOMETERS		
EF1	-0.046	(mm/year)	I1	0.0002	DEG/year
EF2	-0.008	(mm/year)	I2	0.0036	DEG/year
EF2	-0.156	(mm/year)	I3	-0.0029	DEG/year
EF4	-0.179	(mm/year)	I4	-0.0058	DEG/year
EF5	-0.120	(mm/year)	TEMPERATURE SENSORS		
EF6	-0.149	(mm/year)			
EF7	-0.464	(mm/year)	T1	0.497	°C/year
EF8	-0.008	(mm/year)	T2	0.548	°C/year
EF9	-0.135	(mm/year)	T3	0.528	°C/year
EF11	-0.084	(mm/year)	T4	0.604	°C/year
SIGN CONVENTION LONG-BASE EXTENSOMETERS decrease in distance (–) increase in distance (+)			INCLINOMETERS Tilt towards the outside of the Basilica (–) Tilt towards the inside of the Basilica (+)		

Table 1 - Annual deformation trends prior to correcting for the temperature trend.

	TREND EF mm/year	ΔLCORR mm/year	EF-ΔLCORR mm/year
EF1	-0.046	-0.097	0.051
EF2	-0.008	-0.038	0.030
EF2	-0.156	-0.006	**-0.150**
EF4	-0.179	-0.040	**-0.139**
EF5	-0.120	-0.103	**0.223**
EF6	-0.149	-0.127	-0.022
EF7	-0.464	-0.041	**-0.423**
EF8	-0.008	-0.009	0.017
EF9	-0.135	-0.046	**0.181**
EF11	-0.084	-0.106	0.023
	TREND I DEG/year	ΔICORR DEG/year	I-ΔICORR DEG/year
I1	0.0002	-0.0003	0.0005
I2	0.0036	-0.0004	**0.0040**
I3	-0.0029	-0.0011	-0.0018
I4	-0.0058	-0.011	**-0.0047**

Table 2 - Final annual deformation trends corrected for temperature trend. The trend which are meaningful, according to the accuracy of the trasducers, are in evidence.

7. CONCLUSIONS

The paper presents an example of the methodological approach which should be followed for the analysis of the static conditions of an existing masonry building characterized by great structural complexity. The diagnostic analysis was designed to obtain a deep knowledge of the mechanical characteristics of the main supporting structures of the Basilica by strictly integrating-destructive and slighly-destructive testing techniques. Particularly interesting were the results obtained by flat-jack tests which made it possible to evaluate the integrity of the supporting structures and, at the same time, to reach a reliable validation of the mathematical model.

The methodological approach presented for the interpretation of the monitoring system data is an important tool for the understanding the structural behaviour by separating the deformation related to thermal effect from that due to other phenomena.
The application of this methodology to St. Mark's Basilica gave interesting results regarding the behaviour of the structure in the annual and in long-term periods. In the annual period, the analysis of the harmonic components of the signals showed a great homogeneity in the behaviour of the different parts of the Basilica. In the long-term periods the extensometers and inclinometers show non negligible trends which are not related to thermal effect.
It's not possible at the moment to reach a definitive conclusion concerning these deformation trends because the observation period is not long enough for understanding the behaviour of such a complex structure. It is our opinion that it will be necessary to repeat this analysis after longer periods of observation so as to verify these trends are confirmed or not.

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