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Monitoring of the Brunelleschi Dome

Surveillance de la coupole de Brunelleschi

Überwachung des Brunelleschi-Doms

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SUMMARY

Owing to cracks instruments have been placed for centuries on the dome of the Santa Maria del Fiore Cathedral in Florence. Recently, a digitally-controlled monitoring system has been installed to observe and control the evolution of cracks. The first four years of acquired data allow both an understanding of the mechanical and structural properties of the behaviour of the dome and a suggestion for some considerations about the use of monitoring systems in the field of the structural preservation of ancient monuments.

RÉSUMÉ

Suite à la présence de graves fissures dans la coupole, plusieurs méthodes de contrôle ont été utilisées pendant des siècles à la Cathédrale Santa Maria del Fiore, Florence. Un système de contrôle digital a été installé récemment, afin d'observer et contrôler l'évolution des fissures. Les mesures faites en quatre ans permettent de comprendre quelques-unes des propriétés mécaniques structurales du comportement de la coupole et de faire des réflexions sur l'emploi de systèmes de surveillance dans le domaine de conservation de monuments anciens.

ZUSAMMENFASSUNG

Aufgrund der Rissbildung an der Domkuppel von St. Maria del Fiore in Florenz, wurden während Jahrhunderten Kontrolleinrichtungen installiert. Jüngst wurde ein digitalgesteuertes Kontrollsystem aufgebaut, um die Rissentwicklung kontinuierlich zu überwachen. Zwei Aspekte ergeben sich aus den Daten der ersten vier Jahre: Erstens klare Hinweise auf das effektive mechanische und statische Tragverhalten der Kuppel; zweitens wichtige Informationen und Erfahrungen über den Einsatz von Kontrollsystemen im Rahmen der Tragwerkserhaltung bei alten Baudenkmälern.

1. THE CRACKS SYSTEM OF THE BRUNELLESCHI'S DOME

Brunelleschi's Dome is affected by a number of cracks that, appeared as soon as the monument was completed, have been evolving during time. Numbering the eight webs of the Dome starting from the one corresponding to the nave of the Cathedral and moving counter-clockwise, the main cracks (passing through both the two masonry domes constituting the monument) are located on even webs; they started from the skylight as far as the tambour. Moreover, other cracks, even though smaller, can be observed in the odd webs and in the corners between the webs.
These cracks have always been matter of apprehension during the years, so that from the beginning of this century, many control systems have been placed. At the present time, two of them are still working: the one installed by the Opera del Duomo (O.D.) in 1955 and the one placed by the Soprintendenza ai Beni Ambientali e Architettonici (S.B.A.A.) in 1987. These systems have revealed able to point out the long-term structural behaviour of the Dome, but not to reliably describe the short-term one and the link between environmental loads and the variations in width of the cracks.

2. DIGITAL MONITORING SYSTEM AND RECORDED SIGNALS

In order to better understand the behaviour of the monument, a new monitoring system have been installed in 1987 [1]. This system allows the recording of 165 different signals (by mean of instruments placed on the Dome) four times a day. The instruments are deformeters (placed across the main cracks), thermometers (measuring both the air and the masonry temperature), levelling instruments (placed at the tambour level), telecoordinometers (to control the verticality of the pillars) and a piezometer.
All the instruments are controlled by remote units connected to a central control unit, linked via modem to the Engineering Faculty of the University of Florence. This peculiarity allow to make a real-time control, in such a way to point out every possible ill-functioning of some components. The recorded data, after a preliminary control, are stored on magnetic supports, converted into mechanical units and checked, in order to perform successive analyses.
The system has been working since January 1988, and so as many as four years of recorded data are now available.

3. ANALYSIS OF THE EXPERIMENTAL DATA

The aims of the installed monitoring system are mainly three:
- the investigation of the structural behaviour of the monument, with a particular regard to the correlation between environmental actions and structural response;
- the study of long-term behaviour by mean of the trend analysis, based on the mean-rate estimation of the cracks amplitude variations;
- the assessment of a control procedure capable to give information about non-standard values.

The numerical analyses have then been carried out in order to give responses to the previous questions.
After a preliminary investigation about the recorded time-histories of all the different instruments, two types of correlation functions have been studied: correlation between signals recorded by instruments of the same kind (i.e. temperatures Vs temperatures, displacements Vs displacements) and between different ones (displacements Vs temperatures).
Figure 1 reports, as an example, some of the obtained functions referred to the web no. 4.
The following observation can be achieved:
- the cross-correlation curves between temperatures [Figure 1b] recorded by the internal instruments with respect to the external ones, show a time-shift compared to the auto-correlation function: this is related to the thermal diffusion between different layers of the dome and to the thermal inertia of the masonry. Nevertheless the curves look very similar, this implying that, in

view of a structural description, only one of the time-histories can be utilised as a first approximation;

- along the main cracks, the cracks themselves shows a different behaviour in the lower part with respect to the higher one; as a matter of fact, while the inferior part is opening, the superior is closing, and vice versa. This can be seen from the correlation graph [Figure 1a], which shows a phase delay of about 90° between curve no. 1 (auto-correlation of the instrument placed in the higher part of the Dome) and no. 4 (cross-correlation between the previous and the one placed in the lower part);
- in the radial direction, every crack shows a behaviour similar to that previously described, that is, its opening and closing are not in phase between the internal part of the Dome and the external one;
- the correlations between temperature values and cracks amplitude variations [Figure 1c] confirm what was previously asserted: for example, an increase in temperature (warm months) induces a closure of the cracks near the tambour (curves no. 1 and 2) and a growth in the upper part of the Dome (curves no. 4 and 5).

With regard to the trend analysis, this has been carried out mainly in order to understand the long-term behaviour of the cracks layout. A particular procedure has been set up, based on the following steps (see Figure 2):

- a first trend removal is performed, evaluating the best fit, in a least squares sense, of the experimental data through a linear plus harmonic function, the period of the latter being of one year; this was chosen because of the particular shape of the autocorrelation function, clearly showing this periodicity (Figure 2b);
- the autocorrelation of the residuals obtained in this way shows another strong periodicity of about six months (Figure 2e), so that a new fit with an harmonic function having the same period is performed;
- the new autocorrelation function of the residuals (Figure 2h) does no longer show any particular periodicity, and so the residuals can be considered as being delta-correlated (white noise) with a distribution very similar to a Gaussian one (Figure 2i); the obtained approximation seems to be sufficiently reliable, and the derivative of the linear component gives a trend estimation.

In order to evaluate the correlation between the obtained trends and the behaviour of the temperature data, the same analysis has been performed with regard to the data recorded by the thermometers.

The above described analysis will be utilised in order to define a control procedure that will be built in this way:

- by means of the previously recorded data, some approximation functions can be achieved, for the deformeter signals as well as for the thermometer signals. These functions can be utilised to set up a forecasting procedure; the comparison between the forecast values and the acquired one allow us to single out non-standard behaviour, that could depend either on an ill-functioning of the system or on a variation in the structural behaviour.
- moreover, it is necessary to set up a control procedure based on the correlations between different instruments, in order to single out if the recorded non standard value of mechanical quantities is due to particular thermal conditions or to different structural response of the monument.

4. COMPARISON WITH HISTORICAL DATA AND OTHER SYSTEMS DATA

The surveys carried out on the bases of 22 deformeters installed (on the main cracks at various heights) by O.D., provided a total of some 2,400 measurements manually taken four times a year since 1956. These data are particularly significant in that they cover a long period of time (more than 30 years) which includes such noteworthy events as the great flood of 1966, little earthquakes and some variations in climate. On these data, some analyses have been performed in order to evaluate the trend of the cracks mean width variation: a linear regression has been utilised (see Figure 3), thus

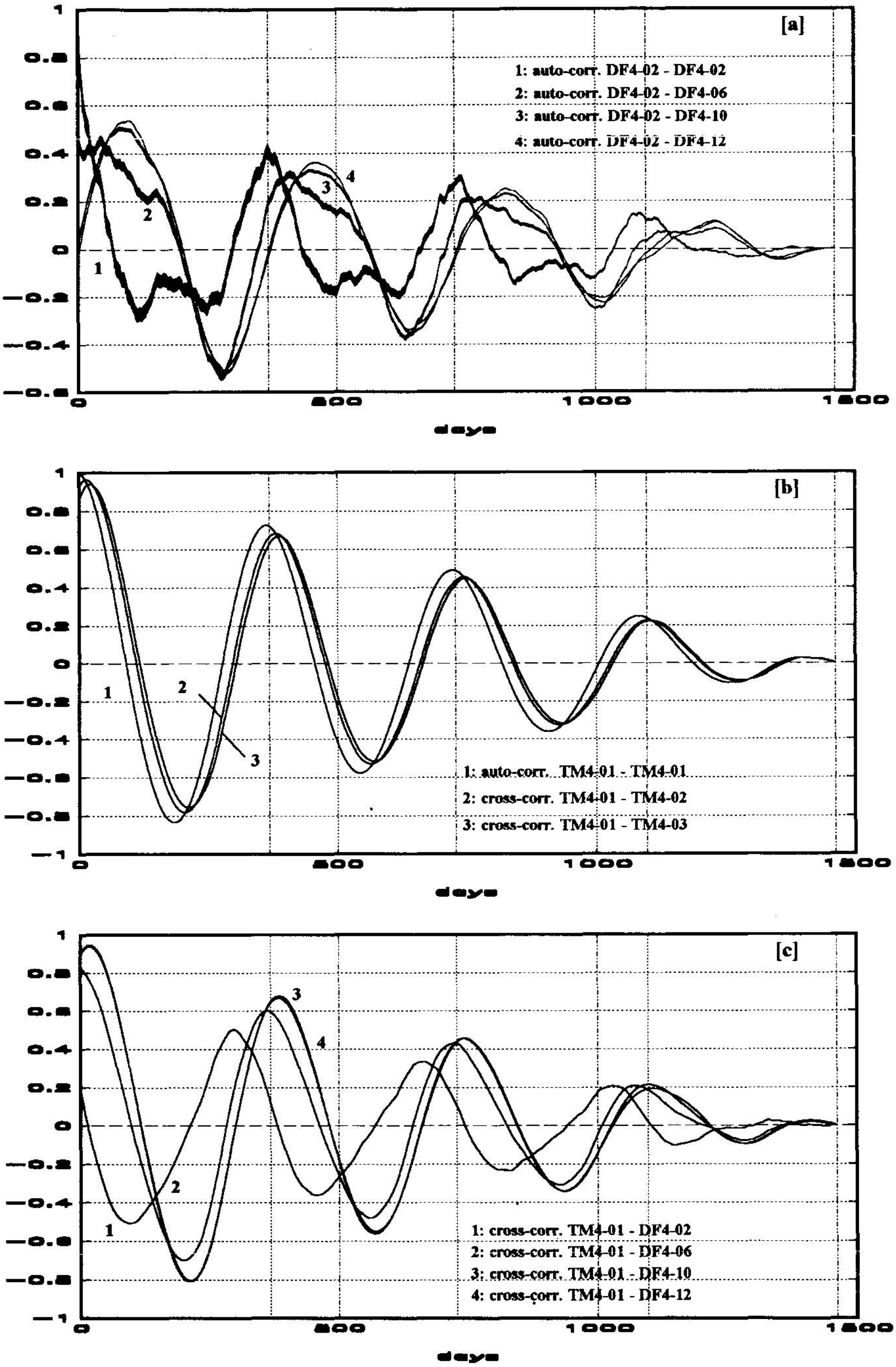
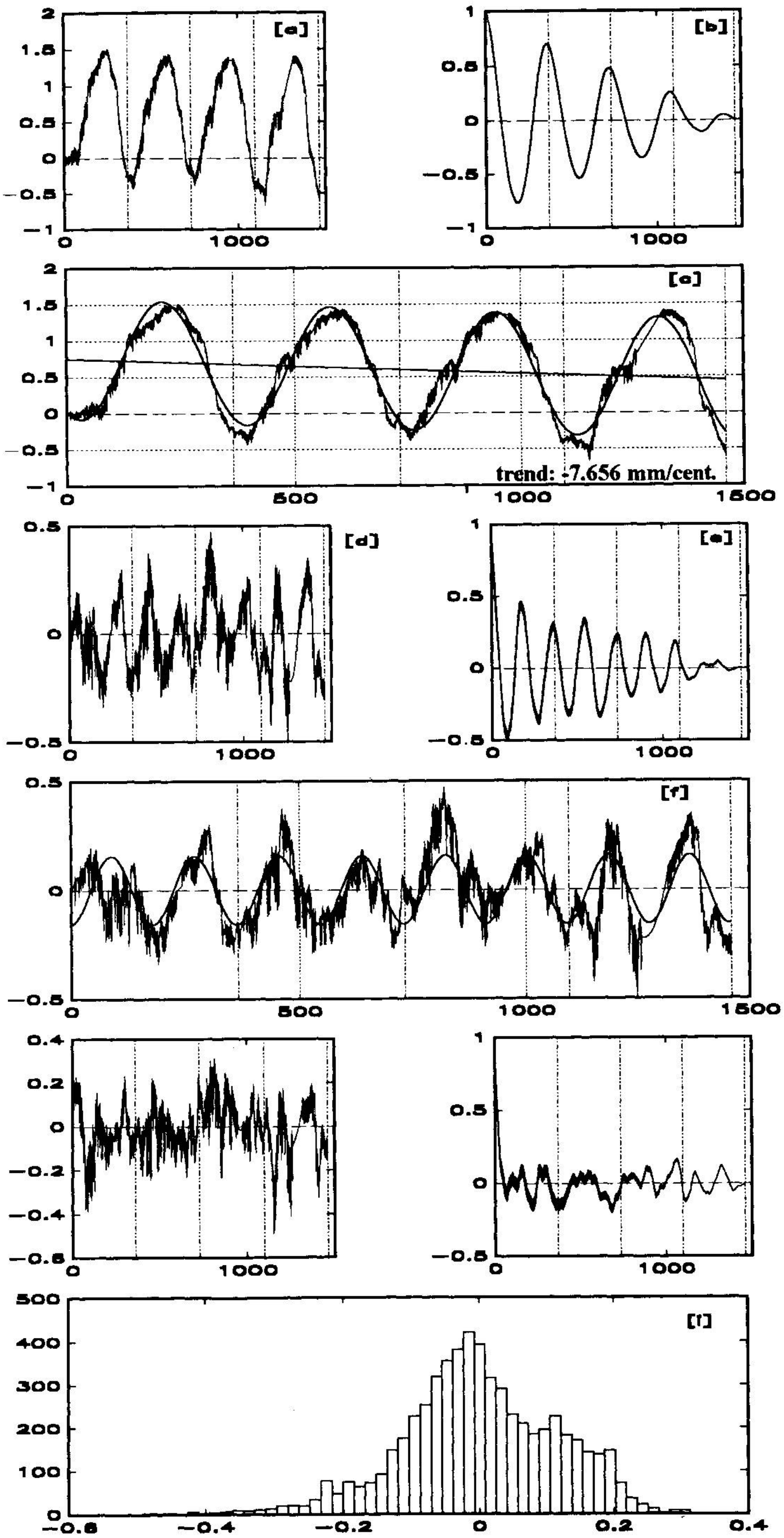


Figure 1: Correlation analyses on data recorded in web no. 4:
[a]: correlation between data recorded by deformeters
[b]: correlation between data recorded by termometers
[c]: correlation between data recorded by termometers and deformeters



[a]: recorded data (deformeter DF4-10)

[b]: autocorrelation function

[c]: approximation, step one: linear plus harmonic trend removal

[d]: first step residuals (recorded data minus linear plus harmonic approx.)

[e]: first step residuals: autocorrelation function

[f]: approximation, step two: linear plus harmonic trend removal on step one residuals

[g]: second step residuals (recorded data minus double linear plus harmonic approx.)

[h]: second step residuals: autocorrelation function

[i]: second step residuals: distribution histogram

Figure 2: Trend removal procedure; application on data recorded by deformeter no. DF4-10 (web no. 4, internal dome, lower part [negative values=cracks opening])

obtaining a trend value less than 6 mm per century (for the main cracks). A cubic regression has been performed too (Figure 4), so to single out the non-stationarity of the increases during the years; this is an important aspect that has to be considered when analyses utilising shorter period of time are taken into account.
The recorded data acquired from the 48 deformeter bases installed by the S.B.A.A. have been analysed too. These data are very interesting because they give information about the cracks near to the Dome scaffolding holes which have been utilised for the restoration of the frescoes. The data have been recorded twice a month since October 1987. An analysis similar to the one performed on the data recorded by the digital monitoring system has been carried out, thus estimating the increasing trend in the develop of the cracks: an example is shown in Figure 5.
Further analyses are ongoing in order to assess a comparison procedure between the data recorded from different monitoring systems (historical and digital).

5. SOME CONSIDERATIONS ABOUT THE STRUCTURAL BEHAVIOUR

The recorded data and the performed analyses allow to make some considerations about the overall structural behaviour of the Dome.
The variations in width of the cracks is mainly due to temperature effects, as regards both of the annual and the daily variations. As it can be seen, the signals recorded by the deformeters show daily variations as well as the external recorded air temperature does. On the contrary, the temperature values recorded inside the monument, both about in air and in the masonry, show a progressive smoothing moving from outside to inside. The recorded data analysis confirms results already known [2]: the external (thinner) dome plays the role of a thermal shield with respect to the internal (thicker) one, but the structural links between them allow the two domes to exhibit the same dependence upon thermal effects.
Nevertheless, as it was mentioned before, the cracks amplitudes seem to show some evolution in time, pointed out by the presence of a trend. This tendency is generally toward an increase in the cracks mean width, and so a particular attention must be devoted to the control of this phenomenon, even if the comparison with historical data shows that the behaviour is not different to the one recorded during last decades.
On the whole, the temperature seems to be the main cause of the movements of the edges of the cracks; last researches [3] showed (by numerical modelling and considering the historical evolution) that the main cracks have been caused by the self-weight of the monument and its distribution between the pillars and the arches sustaining it, and this fact can be considered as the main reason of the progressive increasing in time of the cracks width.
The overall structural behaviour is very difficult to understand and it is not possible to be summarised by simplified models. As an example, the main vertical cracks in the even webs, were thought to be thermal joints capable to permit the expansion of the webs in warm months. The analysis of experimental data have shown that its behaviour is not constant both along the height and along the radial direction and so the previous simplified hypothesis must be removed.
The differences between the behaviour along the height can be explained considering that actually the Dome is not behaving like a dome, that is with a radial symmetry, but as four almost independent sub-structures, separated in correspondence of the main cracks. As a consequence of this, flexural deformation can arise in the meridian direction, and then the behaviour along this direction is not constant.
Further researches and modelling are necessary in order to better understand the structural behaviour and to design possible intervention to preserve the monument.

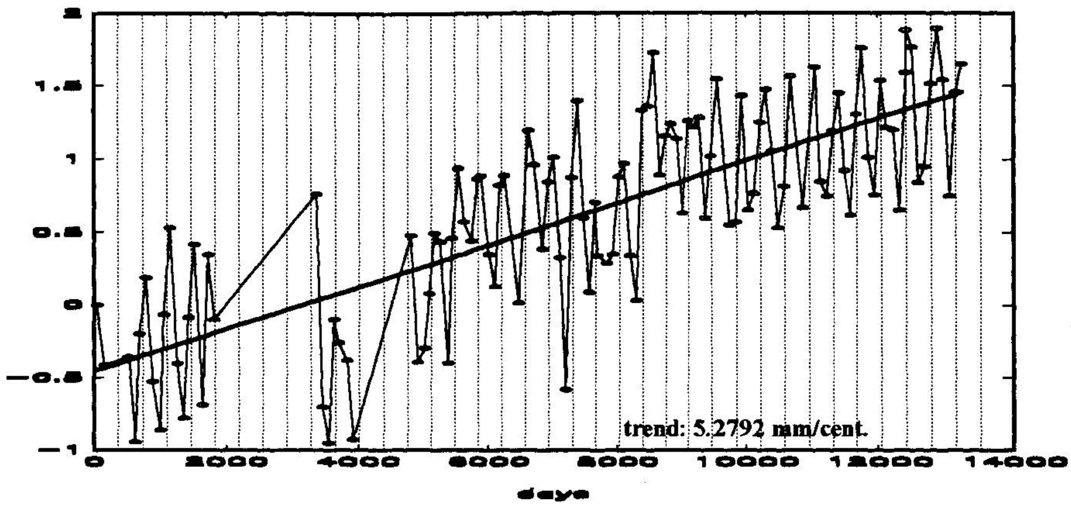


Figure 3: O.D. data (years 1956-1992), base no. 5: linear regression (values in mm [positive values=cracks opening])

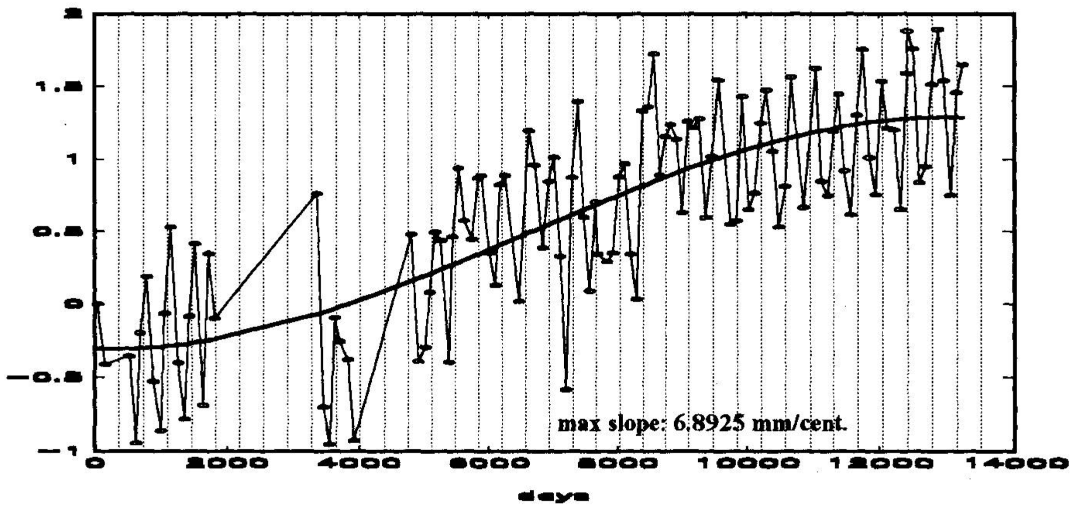


Figure 4: O.D. data (years 1956-1992), base no. 5: cubic regression (values in mm [positive values=cracks opening])

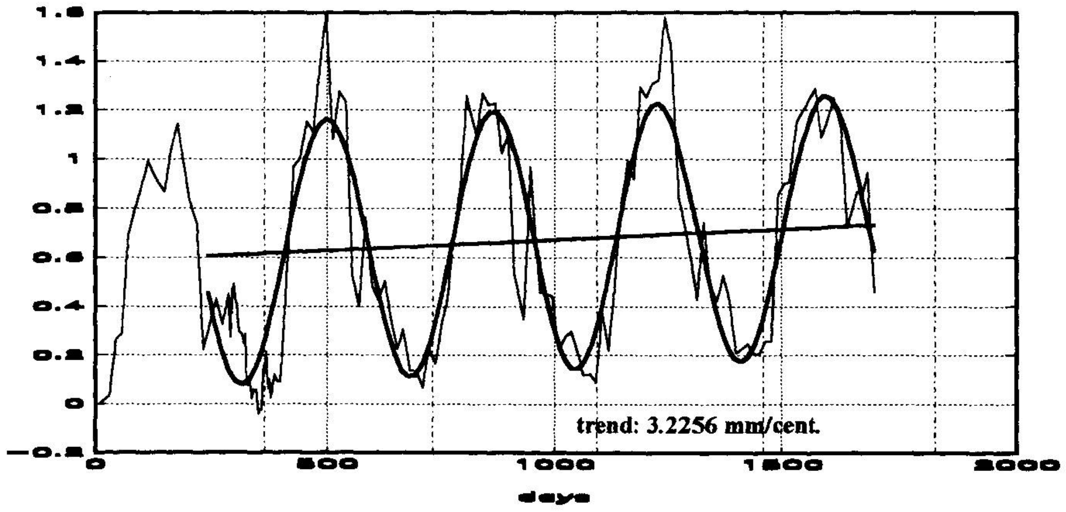


Figure 5: trend analysis of S.B.A.A. data (years 1956-1992), deformeter no. 6, web no. 4: linear plus harmonic approximation (values in mm [positive values=cracks opening])

6. CONCLUDING REMARKS

The digital monitoring system has been a fundamental tool in order to achieve a better knowledge of the Brunelleschi's Dome; correlation between environmental actions and periodical movements of the cracks as well as the presence and the values of the trends have been singled out.
Moreover, the recorded data and their analyses will allow to set up numerical models capable to forecast the structural behaviour under non standard events (such as strong earthquakes) and to evaluate the effects of some preservation designs.
Nevertheless, the results obtained from mechanical instruments as well as from the monitoring system at present installed, don't seem to give rise to any worrying about the evolution of the cracks layout.
Some considerations about the experience done can be carried out:

- the data acquired from the monitoring systems are not enough to make a reliable estimate of the trends of the increment of the cracks width. This can be seen from the fact that temperature data show some trends too and so the evaluated tendencies could be due to those recorded by the thermometers. In other words, a more correct assessment of the expected values could be done only when no trends (or a very small one) will be obtained from thermometers data; maybe other 1 or 2 years of records, could enable the procedure to give appreciable results. Nevertheless, the obtained values are in accordance with those estimated by the values recorded from mechanical instruments.
- as the historical data show, the increment in the cracks width hasn't been evolving in the same way during the years, but it showed a "stairs" course. In fact, there have been some periods in which the cracks did not show any variation while, in others, some increments occurred. The period investigated by the present monitoring system could, however, be too small to decide which of the previously described classes the present time-interval belongs.
- the data recorded by monitoring systems "poorer" than the one at the present time installed have shown their great utility in long-term evaluation of the phenomena. As a matter of fact, simple monitoring system can give appreciably results mainly for three reasons. The first one is that simpler systems are easier to be used, so that even a not skilled staff can utilise them, and this one is the circumstance related to the monitoring of historical monuments. The second reason is due to the fact that uncomplicated systems require less control with respect to most sophisticated ones. The latter, directly related to the first two, is the possibility of using them for long periods and so to acquire a considerably large amounts of data.

Large (and most expensive) systems can so be used for a limited period of time, in order to clearly understand the physical phenomena and so to properly design systems simpler but capable to give information about the quantities that have been revealed as the most interesting ones. The use of less expensive systems allow them to be used in as many situations as possible and so to control a great part of the historical monumental heritage that actually gives apprehension.

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