SUMMARY

The Dome of Santa Maria del Fiore Cathedral in Florence is affected by a system of cracks which appeared as soon as the monument was completed; the crack pattern have been expanding during time, so that many instruments have been placed during the centuries to control it. In 1987 a large digitally controlled monitoring system has been installed to observe and control the propagation of cracks. Acquired data allow both an understanding of some of the mechanical and structural properties of the behavior 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.

In the paper, the main characteristics of the system are reported as well as some of the main results obtained from the data analysis. A final paragraph reports the studies concerning the mechanical identification by means of numerical F.E. models.

1. THE BRUNELLESCHI DOME AND THE CRACKS LAYOUT

Construction of the S. Maria del Fiore Cathedral began in 1295 and lasted for all of the next century. The Dome was designed by Filippo Brunelleschi and was finished in 1434, while the clerestory was set in 1472. The octagonal structure includes an internal thick dome and an external thin one. These two domes are structurally linked by joining elements, which are constituted by masonry walls.

The first historical information about structural damage was reported in early seventeenth century, but they were mentioned even before. One of the most complete description went back to 1757 when a complete survey of the cracks was done and 13 different crack sets were described. Two main cracks were noticed, located in web no. 4 and no. 6\(^1\). They started from the tambour and continued as far as the higher part of the Dome, passing through both the two structural internal and external domes.

\(^1\) The eight webs of the dome will be numbered from one to eight, 1 being the web facing the nave and following the counter-clockwise direction. From a geographical point of view, web no. 7 is the northern one, while no. 3 is the southern one. Even webs are located over the pillars, while the uneven numbered webs are located over the arches.
Nevertheless, other two main cracks which are nowadays present in web no. 2 and no. 8 were not mentioned. These cracks formed after 1757, and are of the same type of those in webs no. 4 and no. 6 (indicated as Type A cracks). Overall, the main crack pattern in the dome is, at this present time, quite symmetric about its center. Other than the cracks already mentioned there are three additional types of cracks which are present on the dome (see Figure 1). These include:
- several vertical cracks near the circular windows (eyes), just above the keystones of the arches, in the uneven webs (type B);
- some minor vertical cracks, even if with less amplitude with respect to type A, and not passing through the width of the two domes, around the eight internal edges of the dome (type C);
- four cracks in the upper internal part of the uneven webs which do not pass through the dome (type D).

![Figure 1 - Plan view of the main cracks on the Brunelleschi Dome](image)

The presence of this complex crack pattern has modified the structural behavior of the Dome. Instead of a circular shell, the Dome now behaves like four drifting half-arches, linked just below the upper clerestory which backs are constituted by the pillars, the chapels and the nave of the church. The crack pattern has evolved through the centuries, and cracking can be ascribed to the dome's geometry and the combined effect of its self-weight and insufficient resistance of the tambour [1]. Differences in cracking between even and uneven webs, is due to the variation of the structure below the dome. Four heavy pillars support the tambour in correspondence of the even webs, while the uneven webs are located over four arches. It can be argued that the tensile stresses in the parallel direction, at tambour level and due to the shell structural behavior, are partially balanced by the compressive stresses due to the presence of the arches in the uneven webs, so limiting the cracks amplitude (see Figure 2). The presence of the arches themselves is also responsible for the increment of the tensile stresses (and consequently of the cracks amplitude) just above the pillars.
The cracks have always been of a concern, so several control devices have been installed in order to measure their evolution. At the beginning of this century, some mechanical control systems were installed. At the present time, two of these 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 helped to illustrate the long-term evolution of the cracks, but not to describe reliably the structural behavior and the link between environmental loads and the variations in width of the cracks.

Figure 2 - Static sketch of the Brunelleschi Dome

In order to better understand the structural behavior and to describe the link between environmental loads and the variations in width of the cracks, a large digital monitoring system was installed in 1987. This system included 166 instruments, and it has been working since 1988.

2. MONITORING SYSTEM DESCRIPTION

The goals of the monitoring system were mainly three: (a) to provide descriptions of the dome movements and the time variations of the width of the cracks; (b) the study of the correlation between temperatures and the time evolution of the cracks; (c) to provide early warning of potential structural problems, through the designation of threshold values of certain parameters being measured.

The monitoring system needed to allow the gauging of time variation of the crack widths as well as the movements of the structure. These two quantities were believed to be the most important in the description of the present condition of the Dome. Moreover, due to former studies, the monitoring system needed to allow for the logging of temperature values. These were thought to be the main cause of the crack width variations. In order to address this problem, both air and masonry temperatures needed to be measured.
Displacement transducers have been placed mainly across the full depth cracks and near the wedges of the dome, at five different heights. In addition other instruments have been positioned near the lower edge of the circular openings, in order to evaluate possible relative sinking between the Dome basement and the superstructure. All the instruments are marked with the initials DFn-mm, where DF indicates the instrument type, n is the number of the web in which the instrument is located and mm indicates the position. The 72 installed displacement transducers are inductive types. They are precise to about ±0.02 mm. The logged data was recorded relatively to the day in which the instruments were placed, so that the data are able to represent only variations of the cracks width. Because of the position of the devices, they show only cracks' width variation in the "tangential" Dome direction (i.e. in the plane tangent to the Dome surface).

Relative horizontal displacements between the pillars and the tambour of the Dome are measured by means of eight plumb-lines placed near to the wedge of the dome whose in-plane position is recorded at three different heights by photoelectric cells (in the sequel indicated as telecoordinometers). This system allows the evaluation of horizontal displacements. The data recorded by the different instruments are indicated by the initials TLn-mm, where TL indicates the instrument type, n the web in which they are placed, mm the height at which the data refer to and d the direction of the datum (i.e. X or Y with respect to a given reference co-ordinate system).

Vertical displacements of the horizontal plane just below the edges of the circular openings are measured by means of a system of eight level instruments (marked with LIV00m, m being the number of the instrument) linked by a hydraulic oil circuit. The acquired data permit the evaluation of both rigid movements of the whole dome (i.e. rotations of the plane) as well as relative movement among different parts of the tambour. The installed instruments allow measurement of displacements up to 0.8 mm.

Thermometers were installed on each web at the second corridor level, in such a way so as to measure the internal dome temperature in three different points and the external dome one in two. Webs 2 (facing north) and 7 (southwest facing) have been provided with additional thermometers, since these structures are under maximum and minimum solar exposure. The 60 installed thermometers provide data for evaluation of temperature gradients. The instruments (marked as TMn-mm (or TAn-mm)), indicating thermometer in the masonry (TM) or in air (TA) in web number n and position mm) are resistive ones, allowing a precision of about ±0.05 °C.

To evaluate variation in the level of underground water, a piezometer has been placed externally of the monument, in the vicinity of web no. 4.

Four devices linked to a central control unit compose the acquisition system. The devices are placed peripherally with respect to the central unit, and provide for data logging, analogic-to-digital conversion, and the temporary storage of data. The central control unit consists of a personal computer which functions to manage and control the acquisition system, as well as the permanent data storage.

Data can be logged either at certain pre-fixed times or over uniformly distributed intervals during the day. The operator also has the option of collecting additional data points. The system checking is performed automatically by the computer, indicating every malfunctions (i.e. temporary off-line of the instruments or out-scale measurements). Recorded data are then converted into physical units and controlled.

A peripheral control device has been installed at the Engineering Faculty of the University of Firenze. This enables remote control and monitoring of the whole system. The system is programmed to automatically log data every six hours for all instruments, starting at 6:00 a.m.
3. ANALYSIS OF THE EXPERIMENTAL DATA

The acquired data has been analyzed in order to:
- investigate the structural behavior of the monument, with a particular regard to the correlation between environmental actions and structural response;
- study the long-term behavior by means of trend analyses, based on the mean-rate estimation of crack amplitude variations;
- assess a control procedure capable to signal unusual readings.

3.1 Structural behavior understanding

The recorded data is first corrected for data errors. These errors can be caused by electrical problems, bad protection against lightning, and other causes. Missing data is replaced by a linear interpolation between the last available "good" data points.

Next, the recorded time-histories of all the different instruments are evaluated for correlation. Two 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 types (i.e. displacements vs. temperatures).

Based on this evaluation, the following observations are made.

3.2 Seasonal behavior

From visualization of the time-histories of displacement and temperature data (see Figure 3 as an example), two periodic phenomena are observed. The first (and main) phenomenon involves long-term variation of the data, showing a periodic annual behavior (Fig. 3a). The second one is for between day and night (Fig. 3b).

![Figure 3 - Time-history of recorded data by one displacement transducer in web no. 4: a) long-period evolution; b) short period evolution.](image-url)
3.3 Temperature distribution

Cross-correlation curves between temperatures measured by different instruments placed in the same web show a time-shift compared to the auto-correlation function (Figure 4a). This is related to the thermal diffusion between different layers of the dome and to the thermal inertia of the masonry. Because of the fact that the curves look very similar, temperatures on different layers can be modeled by the same harmonic function. In this way, the small time-shift is neglected while the functions simply possess different amplitude due to diffusion phenomenon.

Cross-correlation curves between data recorded at the same level in different webs show good agreement (see Fig. 4b). This fact implies that the temperature distribution can be assumed as constant along the parallel direction of the structure.

Similarly, correlation curves between instruments placed at different levels in the same web and at the same distance from the center of the dome exhibit very small variation (see Figure 4c). The temperature can then be thought as uniform along the meridian direction too.

On the whole, because of the previous consideration, the temperature distribution can be assumed constant along both meridian and parallel direction, leaving only a gradient along the radial direction, in view of a simulation of the structural response by finite element techniques.

Figure 4 - Correlation functions between data acquired from thermometers in several webs: a) radial direction; b) parallel direction; c) meridian direction.
3.4 Cracks behavior

Along the main cracks, a different behavior is seen in the lower part with respect to the higher part of the crack. While the inferior part is opening, the superior one is closing, and vice versa. This can be seen from the correlation graph (Figure 5a) which shows a phase of delay of slightly more than 90° among curve no. 1 (auto-correlation of the instrument placed in the higher part of the internal dome in web no. 4) and nos. 4 and 5 (cross-correlation between the previous and those placed in the lower part). It is to be noted that greater opening of the cracks in those areas of the Dome that are freer to expand follows increases in temperature. The opposite behavior is found in those areas where effective restraints are present (especially due to nave and chapels), and so thermal dilatation can only take place by a diminution of cracks. The phenomenon of variations in crack width therefore cannot be explained simply by considering the crack as a “thermal joint” (i.e. uniform behavior along its extension) as was previously thought [2]. Instead, the behavior is characterized by a considerable complexity that is related to the inherent complexity of the structure (interaction between the dome and other structural elements, such as the nave, the chapels and so on).

In the radial direction, every crack shows a behavior similar to the previously described one. Crack opening and closing are not in phase between the internal part of the Dome and the external one (see Figure 5b).

3.5 Correlation between temperature and cracks displacements

The correlation between temperature values and crack amplitude variations (Figure 6) confirms what was previously believed. For example, an increase in temperature (warm months) induces a different behavior in the cracks near the tambour (curves no. 3 and 4) and in those situated in the upper part of the Dome (curve no. 2). This fact implies a very strong correlation between thermal input and cracks movements, as long as it is concerned with the seasonal behavior of the structure.

3.6 Estimation of the trend

With a better understanding of the seasonal behavior of the dome, the second part of the analysis focused on the study of cracking trends, the understanding of the long-term behavior of the crack layout.

Long-term cracking can be better understood by considering the drifting behavior of the four half-arches nowadays constituting the dome. It is important to determine if cracking is increasing with time. This can be evaluated by removing seasonal effects from the recorded data and analyzing the residuals.

A procedure has been established (as described in [3]), based on a recursive approximation of the recorded signal. A first trend removal is performed, by fitting the experimental data by a linear plus harmonic function with a time-period of one year. The period of one year was chosen because of the particular shape of the auto-correlation function, clearly showing this periodicity. Due to the fact that the auto-correlation of the residuals obtained in this way shows another strong periodicity of about six months, a new fit with a harmonic function having the same period is performed. The resulting auto-correlation function of the residuals does not show any particular periodicity. So, the residuals can be considered as almost being delta-correlated (white noise) with a distribution very similar to a Gaussian one. The obtained approximation seems to be sufficiently reliable, and the derivative of the linear component gives trend estimation.
Figure 5 - Correlation functions between data acquired from displacement transducers in web no. 4: a) meridian direction; b) radial direction.

Figure 7 reports the original signal and the superimposition of both recorded data and the approximating function. Table 1 shows some results obtained by this analysis on data coming from displacement transducers placed in web no. 4. Parameters reported in Table 1 refer to the following expression:

\[ \bar{x}(t) = A + B \cdot t + A_1 \cdot \sin \left( \frac{2 \cdot \pi}{365.25} t + \phi_1 \right) + A_2 \cdot \sin \left( \frac{4 \cdot \pi}{365.25} t + \phi_2 \right) \]

where \( \bar{x}(t) \) represents the least squares approximation of a generic recorded time-history \( x(t) \).

This procedure allows for the estimation of trend values. The reliability of obtained values is confirmed by the fact that thermometers show, over the same time-period, negligible trends. A stability analysis of the trend estimation with respect to the acquisition period (that is, the influence of the available data on the evaluated quantities) has been performed. This analysis has been done on temperature data, looking for the sample length that gives a stable estimation of the trend. It is
reasonable to think that temperature data must not show any linear trend over a long enough period of time. When temperature data no longer show this trend, we have assumed that, over the same period of time, the trend obtained from the analysis of displacement transducer data was reliable.

Figure 6 - Correlation functions between data acquired from thermometers and displacement transducers in web no. 4.

Figure 7 - Trend removal analysis (referred to data recorded by DF406, a displacement transducer in web no. 4): a) recorded signal; b) recorded signal and linear plus double harmonic approximation
The obtained results show that, over time-periods longer than 5 years, the temperature data seem to be stable. Temperature data show trend values not greater than 0.1220 °C per year, which is negligible. Table 2 shows, for the some displacement transducers reported in Table 1, the trend estimation performed over different periods of time. As it can be seen, the results seem to stabilize using a period of 5-6 years for almost all the instruments. Nevertheless, since the monitoring system is still acquiring data, further analyses will be performed over longer periods of time, increasing the reliability of the results.
4. ANALYSIS BY FINITE ELEMENT MODELS

The behavior of the Dome under the effect of thermal loads has been investigated by using finite element models, comparing the deformations obtained by numerical analysis with the measured ones. Due to the complexity of the problems it could be difficult to start the study with a complete model and in a first time partial and simplified models has been prepared to analyze specific aspects. Finite element analysis has been performed using three kinds of models described below, starting from the simplest plane models, then axial symmetric models and concluding with the most complete tridimensional model.

The analysis of the daily thermal variations effects have been carried out by means of plane models. This can be done considering a strip of Dome along the parallel direction, placed at a general level and having a unit thickness. These models are necessary in order to understand the crack variation amplitude in the horizontal plane.

Concerning over the opening and the closing of the main cracks which is not in phase between the lower part and the higher one (yearly thermal variations), it has seemed basic to make reference, as a first approach, to simplified axial symmetric models, using in this part of study the general theory for shells forming surface of revolution. With these simple models it has been possible to understand the general characteristics of the physical phenomenon, in order to correctly reproduce the experimental measurements.

After these two steps a final tridimensional model, which reproduces, as close as possible, the Dome geometry and the part below it (tambour, pillars, chapels), has been elaborated, in order to understand the constraint effect due to the chapels.

In all these models the masonry has the mechanical properties of a linear, elastic, homogeneous, isotropic solid (Young modulus $E=500000$ N/cm², Poisson ratio $\nu=0.1$; thermal dilatation coefficient $\alpha_t=0.8\times10^{-5} \, ^\circ C^{-1}$), ([1], [4]). The used structural analysis code was FEMAS90, made at Institut für Statik und Dynamik, Ruhr Universität - Bochum, Germany.

4.1 Analysis by plane models

The recorded data clearly shows that the internal dome is isothermal with respect to the daily temperature variations but a daily variation in width of the main cracks in both the domes takes place. Comparing temperatures and cracks width (Figures 8 and 9) it can be observed that an increase of temperature in the external dome in warm hours produces the opening of the cracks along the whole thickness of the Dome and vice versa.

These observation allow to affirm that the cracks movements are not due to the dilation of the internal dome, which is isothermal all through the day, but to that of the external one. This means that the dilation of the external parts is able to induce a coercive flexural effect on the parallel strips, whose result is the relative rotation between the faces of the main cracks. The external dome produces a "drag effect" on the internal one because of the connection between the two shells (realized by corner ribs and by two equally spaced ribs for every panels), thus proving that, by means of the adopted building technology, a perfect monolithic connection of the two domes has been realized.

Curves in Fig. 8 and 9 have been obtained by averaging the approximating functions of the recorded signals (in a least squares sense), concerning the instruments having the same position in the thickness of the Dome. These data have been logged in two specific days, when measurements were carried out every 1.5 hours [5].
Figure 8 - Average of the daily temperature in the thickness of the Dome (1: intrados internal shell; 2: extrados internal shell; 3: middle external shell; values in °C).

Figure 9 - Average of the daily cracks amplitude variations (second internal gallery level): (1: intrados internal shell; 2: extrados internal shell; 3: intrados external shell; values in mm [positive variations = cracks closing]).

The behavior of a strip of Dome in the parallel direction, lying at the second internal gallery level can be considered. Because of the symmetry of the structure and the thermal loads, it is enough to consider a quarter of strip cut by two vertical planes containing the Dome axis and orthogonal to the panels not crossed by the main cracks (Figures 10 and 11). It has been assumed that the strip can get deformed only in its plane, and in the two sections previously described symmetry boundary conditions for the uncracked structure were considered: these points must move only in the radial direction and their displacement has to be established in advance, otherwise the formulated static problem is indeterminate.

A uniform increase of temperature in the external dome produces the deformed shape shown in Figure 10 (in this phase the radial movement of the symmetry sections is not allowed). It is possible to observe the closing of the crack along all the thickness of the Dome, not in accordance with the experimental data recorded by the deformeters. In fact, curves in Figures 8 and 9 show that an increase of temperature in the external shell produces the opening of the main cracks. Figure 11 reports the deformed shape obtained setting the radial rigid body movement of the two symmetry sections in such a way as to have the opening of the cracks along all the thickness; in this way a cracks amplitude variations at the Dome intrados greater than the one at the extrados can be observed, in accordance with the recorded data (Figure 9).
As a matter of fact, daily cracks amplitude variations in the horizontal plane can be explained by the superposition of two effects: a) the relative rotation between the two faces of the crack, due to the temperature gradient; b) the radial displacement of the symmetry sections generated by the interaction between "parallel strips" and "meridian strips".

In order to better understand the previously described phenomenon the temperature distribution shown in Figure 8 can be assumed as thermal loads for the model. Obtained results are shown in Figure 12. If the model were able to exactly reproduce the deforming behavior of the strip, we should have obtained, in every instant, that the difference between obtained displacements and experimental one, should have been constant, representing the described radial rigid body movement. This difference has been evaluated using data reported in Figure 12; the graph showing the radial displacement of the symmetry sections in the plane model is represented in Figure 13.

Concerning the comparison between experimental values of the main crack amplitude variations, and the theoretic one, some differences are necessarily present because the plane model disregards the flexural rigidity of the "meridian strips". This implies that the relative theoretic rotation between the two faces of the cracks is always greater than the experimental one. This proves that, even if the Dome is actually divided in four "segment" connected in the higher part (because of the main cracks), there is all the same a certain tridimensional behavior; this effect, typical for the shell forming surface of revolution, shows that meridian strips still give an "elastic" constrain to the deformation of the parallel strips in their plane.
Figure 12 - Analysis with the plane model: cracks variation amplitude under the thermal variations of Figure 8 (1, 2, 3 see Figure 9).

Figure 13 - Radial displacement ($u_R(t)$) of the symmetry sections in the plane model (strip at the second internal gallery level; [positive values induce cracks opening]).

4.2 Analysis by axial-symmetric models

In order to better understand the physical phenomenon of the phase differences in the crack amplitude variations (yearly movements), some simplified models have been elaborated. The structure composed by the "Dome plus tambour" was considered (Figure 14). This one has been modeled by means of shells forming surface of revolution. Under an uniform increase of temperature ($\Delta T>0$) two extreme cases for boundary conditions in the lower edge have been examined: a) without any restraints for the radial displacements; b) radial displacements completely fixed.

In the first case, there is no variation in crack width, and the deformed shape would have been the same even if the cracks in the model were removed. The radial displacement for each point on the middle surface of the shell is proportional to the parallel radius $R$ at that level ($\Delta u_R = \alpha R \Delta T$), moreover any tensile stresses is present [6]. On the contrary in the second case, the radial restraints produce a deformed shape of the meridian strips typical for prismatic bars supported by a continuous elastic foundation; this is due to the induced forces on the lower edge of the shell. This can explain how (because of the flexural deformation in the meridian direction) an increase of temperature produces the closing of the main cracks near the tambour and their opening in the higher part of the Dome (Figure 14).
Moreover, on the Dome a temperature gradient in the normal direction can be also observed, producing a relative rotation between the faces of the main cracks. The further temperature distribution to be added to the previous one is then a non uniform one, causing the opening of the main cracks at the intrados and their closing at the extrados. This effect has to be superposed with that previously described, due to a uniform increase of temperature. The final results of this superposition is: at the intrados, a smaller closing of the cracks in the tambour and a greater opening in the Dome; at the extrados, the opposite behavior according to the recorded data (Figure 15). The five different curves in Figure 15 are referred to the levels where deformers are placed along the four main cracks (1: extrados of the pillars; 2: lower part of the circular windows; 3, 4, 5 respectively the first, the second and the third internal gallery level of the Dome).

4.3 Analysis by a tridimensional model

A finite element model of a Brunelleschi-type dome, according to an overall shape reproducing the monument one, was defined introducing some necessary simplifications and regularization. In spite of the introduced simplifications, the model made possible to understand the global interaction between the "Dome plus tambour" structure and the chapels. As described before, the real boundary conditions assumed at the basis edge of the tambour are fundamental, in order to reproduce the main cracks movements. The geometry of an ideal octagonal, regular, double shell, symmetric dome, with circular vertical profiles at the corners, was considered. The two shells are connected by corner ribs and by two equally spaced ribs for every panel.
The F. E. mesh was built up for a quarter of Dome (including the pillars and the chapels), cut by two orthogonal vertical symmetry planes (Figure 16). The mesh takes in 2248 isoparametric plane elements (with 3 or 4 nodes) and 1722 nodes, for a total of 8538 degrees of freedom.

Figure 15 - Average of the best fit for signals recorded by deformeters placed on the main cracks on intrados internal dome; (values in mm [positive = cracks closing])

Figure 16 - Tridimensional model: deformation under thermal loads. Maximum yearly variations of the mean temperature in the external dome
The main crack position was defined by schematizing the actual cracking pattern, following two vertical planes symmetrically intersecting four out of the eight dome panels (those at ±45° from the church main axes). This structure was completely constrained at the nodes of the lower surface, whilst on the side vertical planes obvious symmetry conditions were applied for the uncracked structure. In the following, the main results obtained by analyzing the structure under yearly periodic temperature variations are shown.

The stochastic analysis of the recorded data allows defining the time-dependent temperature in the thickness of the structure (Figure 17), as well as the time-dependent crack amplitude variations (Figure 15).

This model correctly reproduces the deformative behavior of the main cracks. The maximum yearly variations of the mean temperature in the external dome were considered as thermal loads (Figure 17). The deformed configuration due to this temperature distribution is shown in Figure 16. Figure 18 reports the comparison between the experimental crack amplitude variations and those obtained by means of the model: a curvilinear coordinate along the meridian line corresponding to the main crack is reported as abscissa in the graph. A fairly good agreement between experimental and obtained results is evident.

Figure 17 - Average of the yearly temperature in 1988-1992 (values in °C [1: intrados int. dome; 2: extrados int. dome; 3: middle ext. dome]).

Figure 18 - Cracks variations amplitude: comparison between experimental results (Figure 15) and those obtained by means of the F.E. model (Figure 16) (values in mm [positive variations = cracks closing]).
5. CONCLUDING REMARKS

The digital monitoring system has been a fundamental tool to achieve a better knowledge of the structural behavior of Brunelleschi Dome. Following aspects have been pointed out:
- temperature distribution is quite constant along both the meridian and the parallel direction, only exhibiting a gradient in the radial direction, despite the orientation with respect to the sun; yearly and daily width variations are very well correlated to temperature data;
- the external dome behaves as a "thermal shield" for the internal one, while the two domes act like a unit from a static point of view because of the presence of the structural linking between them;
- meridian line cracking does not behave as a thermal joint, since there are some out-of-phase differences between data recorded in the upper and the lower part of the dome;

Trend analyses have been performed on data recorded from the monitoring system showing an average annual increase of width cracks of about 0.06 mm.

The structural analyses under thermal loads carried out using finite elements models of the Brunelleschi Dome have made possible to correctly reproduce the behavior of the monument under these loads.

REFERENCES