MONITORING OF THE MAIN SPIRE OF THE DUOMO DI MILANO

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ABSTRACT:

The incoming restoration work of Duomo di Milano cathedral main spire requires a structural health monitoring. A weight of 90 t due to scaffoldings was applied to the dome and a complex monitoring system was designed in order to measure the deformation of the church and its spire. The paper gives a presentation of the different methods used to investigate the different structural components including: optical leveling, robotic total stations, accelerometers, strain gauges, optical plumbs, clinometre, and extensometre. In particular for the analysis of structural elements at higher risk of collapse, fiber optic sensors were selected, based on FBG (Fiber Bragg Grating) technology. Strain of the lower part of the vaulting-rigs inside the octagonal doom is the measurement of interest. As the expected signals are very small and the thermal disturbances very significant, a thermal characterization of two types of commercial strain gauges was carried out in laboratory with a thermal chamber. A block of the same marble used for the cathedral was tested. This allowed to find a relationship to be used later to compensate for any thermal effects. Finally, some sensors are placed at critical points to record real time deformation measurements. A central control unit will host an alarm system and GUI to show all results.

1. INTROUDUCION

Duomo di Milano (Figure) is the well-known gothic cathedral of Milan, Italy. This building took five centuries to be completed and is one of the biggest churches all over the world. The monumental structure is very complex: in the past - and still now - it underwent many restoration work owing to a lot of reasons. For example, the strong changes of the water table level during the latest 50 years resulted in the differential movement of the bearing pillar foundations. The harsh environmental conditions (weather cycles and air pollution) strongly affects the 'Candoglia' marble, that is the main material used to build up the monument. This process results in the alteration of chemical, physical and mechanical properties, with the consequent detachment of some parts. A continuous restoration work to reinforce and replace the damaged parts is necessary. This activity has been involving many workers who execute repair operations along a continuously updated schedule of interventions.

The restoration of the main spire of the cathedral is now the main planned priority (Figure 2). Related works started in summer 2010. The spire hosts a popular statue designated as 'Madonnina', which is assumed as the symbol of the city. Recent checks found a main degradation of the decorative marble surfaces, with the chance that some parts could fall down. Urban pollution has been undoubtedly an important cause of degradation here, but also the thermal stresses has had a relevant impact. Indeed, the structure is 108 m tall and has been fully exposed to sun, rain and pollution for centuries.

This intervention is scheduling a complete geometric survey of the spire, as described in Fassi et al. (2011). Planned activities encompass mapping marble degradation, surface cleaning, consolidation, fastening and stuccoing of the healthy parts, and removal and substitution of the unrecoverable parts. A particular scaffold is being positioned around the main spire, with a mass of about 90 t, resting on the top of the underneath dome. The additional load that the cupola will have to support, due also to the building yard and the increased wind load, suggested to start to monitor the deformations of the spire. Being this an ancient building, and being the geometries, construction procedures, materials and past restorations not completely known, the structural behaviour of this structure was considered highly critical and almost unpredictable. Then a new monitoring system has been designed in order to achieved as much information as possible to forecast any possible collapse. The existing monitoring system has been improved and enlarged by incorporating newest measurement and data management techniques. The main objective of this new system is, among others, the continuous measurement of the strain of the dome in order to assess the effects of the restoration work on the main structure supporting both spire and scaffolding. The need of measuring mechanical strains as low as 20 µm/m and the harsh environment (also for the risk to be struck by lightning), fiber Bragg grating (FBG) sensors were selected (Kreuzer, 2006; Rao, 1997). Inclinometers and accelerometers were also mounted in order to check continuously the inclination and vibration of the spire.

Figure 1. Historical image of Duomo di Milano

Figure 2. The main spire of Duomo di Milano cathedral with the ‘Madonnina’ statue at the top.

2. PERIODICAL MONITORING

The restoration work of the main spire is supported by multi-temporal measurements to check the stability of the structure. A series of measurement campaigns was carried out one year before the installation of the big scaffolding in order to determine the solely effect of thermal variations. This allowed the analysis of displacements due to the new load, with the separation of the thermal component.
To accomplish this task different kind of controls were carried out:

- analysis of vertical movements;
- analysis of horizontal movements;
- analysis of slope variations;
- convergence analysis between the pillars;
- dome cladding displacements with strain gauges;
- crack measurement.

2.1 Analysis of vertical movements

The vertical displacement of the dome can be measured with a leveling network. A series of stable benchmarks was mounted on the structure. The overall layout comprehends 27 points as shown in Figure 3: 7 are located inside the structure on special shelves (Fig. 4) that allow the stable connection of rods (with the possibility of setting up the optical level as well); 16 points on the external wall; 2 points on small spires; one permanent rod connected to the top of the spire with a metal wire.

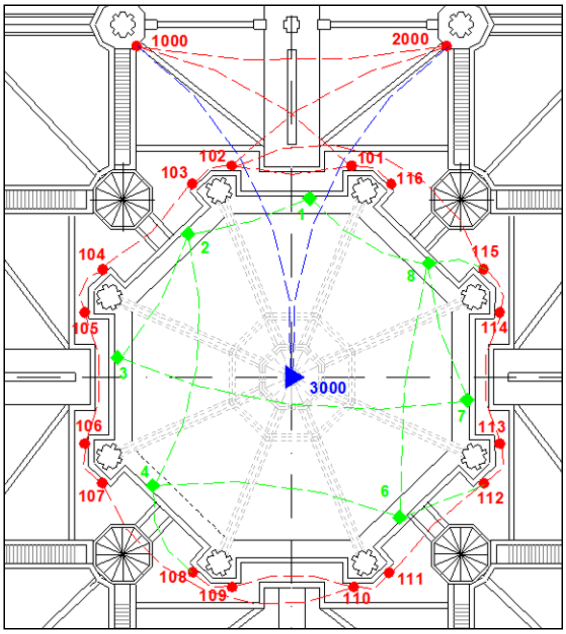

Figure 3. Layout of the geometric levelling network at the base of the dome. Green and red lines represent the internal and external networks, respectively. The blue point (3000) is hung on a cable that is connected to the top of the spire.

Figure 4. Plate for small leveling rod, optical level or total station.

A second leveling network was installed on top of the dome, where the spire is based. As can be seen in Figure 5, this network is made up of 12 points that are connected to the lower part of the spire with some extensometers. This allows a direct link between the levelling networks and gives the possibility to adjust the dataset together.
Measurement have been done with a Zeiss Ni1 optical level obtaining a precision of about ±0.1 mm.

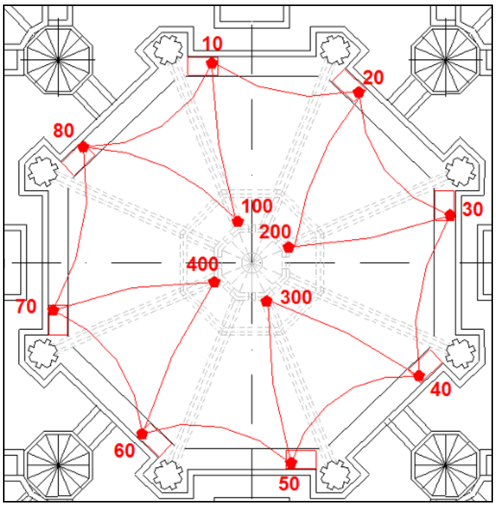

Figure 5. Geometric leveling at the base of the spire

2.2 Analysis of horizontal movements

In correspondence of the leveling network (green lines in figure 3) a planimetric network was planned in order to measure the convergence of the ribs of the dome (see Fig. 6). Measurements are carried out by robotic total station TCA 2003 and the point position is measured with an average precision of ±0.4 mm. During this operation, the instrument has been placed on the same plates (Fig. 4) used as standpoints for optical leveling.

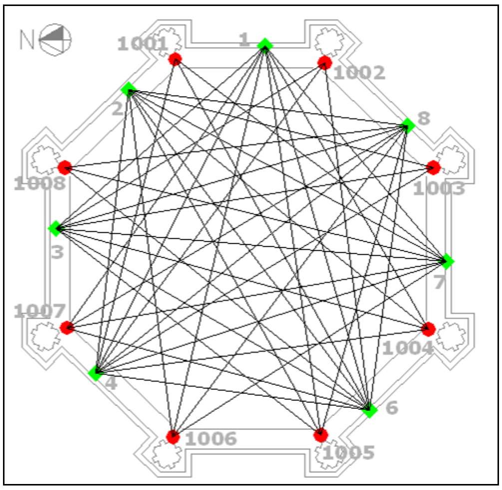

Figure 6. Planimetric network at the base of the dome

2.3 Detection of slope variations

The analysis of spire slope variations is carried out with a metal wire connected to the top. A big mass hung at the bottom end tightens the wire, which gives the plumb line direction. The relative change of inclination of the spire can be measured using a sequence of reference points on the structure. Here the reading devices are installed to obtain measurements at different heights.

The system is made up of automatic sensors that provide a continuous series of data, and manual measurements carried out in different seasons.

Close to the bottom part of the wire a *coordinatometer* (see Giussani et al, 1989) is used to measure the displacement of the wire along two orthogonal directions. This device has two movable telescopes (used to collimate the wire) and a graduated scale where the displacement can be manually read or, in the case of automatic measurements, is automatically estimated with the sensor VK4000VS (see SISGEO, 2011).

The precision is sub-millimetric (usually σ = ±0.1mm) and the system is very robust with respect to external error sources.

2.4 Convergence analysis between the pillars of the dome cladding

The goal of this measurement is the detection of horizontal deformations between two stable points.

The distance variations of the big pillars of the dome cladding are measured with 8 extensometer tapes (34 m above ground). This system is not new, as the same solution was adopted in 1984 for the restoration work of the pillars. However, the system was re-established and automated in 2008. The position of the sensor is illustrated in Figure 7.

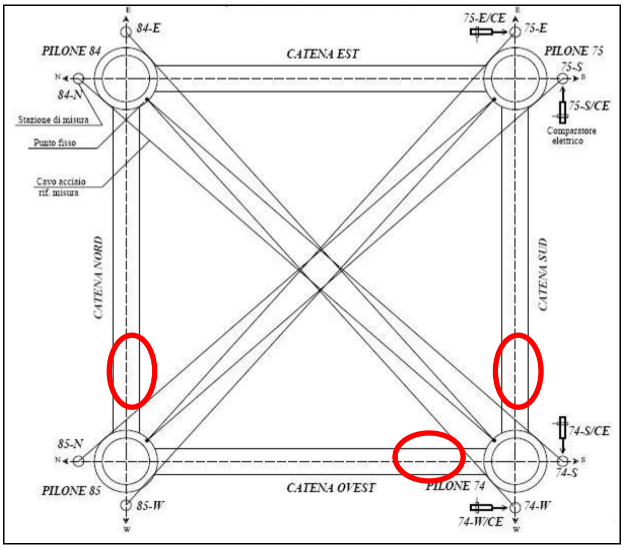

Figure 7. Extensimeter cables and the position of the vibrating wires strain gauges (in red).

2.5 Monitoring the tie-beam of the dome cladding with vibrating wire strain gauges

During October 2008 a new monitoring system was installed to check the stability of the iron chains between the pillars of the dome cladding.

The system is based on the *vibrating wire* strain gauges VK4100 produced by SISGEO, which were connected to the northern, western and south sides of the structure. The location of all sensors is shown in Figure 7.

For each chain, a couple of sensors was installed with a small relative distance (Fig. 8). In addition, a thermometer was applied to the western chain to measure air temperature.

2.6 Crack aperture variation

The instruments usually used for crack aperture estimation during a measurement campaign are based on a simple mechanical principle. The most cheaper devices, with a cost of a few dollars, are made of plastic materials and are composed by two mobile plates. On the upper plate there is a reticule, while on the lower plate is reported a calibrated scale in millimeters. The reading of the displacement between both sides of the crack is carried out manually, by evaluating the relative position of the reticulum compared to the position of the fixed reference. The accuracy achievable is about ±0.5÷1 mm.

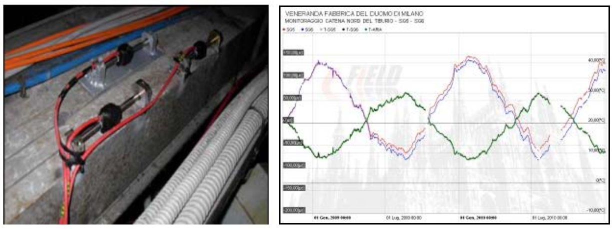

Figure 8. On the left, an image of the vibrating wire strain gauges installed. On the right, the variation of a couple of sensors (blue and red lines) and the corresponding temperature (green line).

If a higher accuracy is needed, instruments like *deformometers* coupled by a *comparator* can reach an accuracy of ±0.01÷0.001 mm. These instruments can measure the distance between two metal plates fixed to the structure. The displacement between the conic head of the deformometer positioned into the incisions of the marks coincides with the displacement of the plates and it is measured by the comparator of the instrument. Although very precise, this kind of sensors presents some drawbacks for the analysis of the main pillars of the major spire. Here, several cracks are evident and a monitoring campaign would require many manual measurements to understand the behavior of each pillar. For this reason a photogrammetric solution was chosen.
A series of coded target (Fig. 9) was applied to the pillar and was imaged with a Nikon D700 (roughly 70 images). 3D target coordinates were estimated with a bundle adjustment, where a calibrated bar was employed to remove the scale ambiguity. The final results is a list of distances between all target combinations.
To check the accuracy several block of images were acquired and processed independently. The time between different epochs was quite limited, therefore without an expected target movement. The statistics showed a discrepancy of about ±0.02 mm (the object is 40 cm wide) for points lying on the same side.

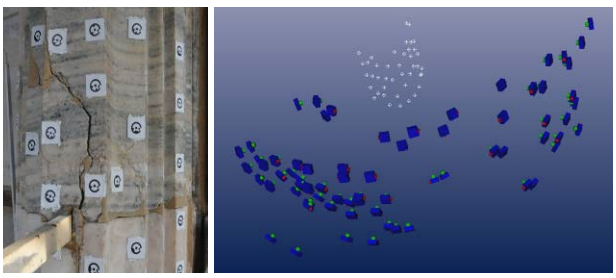

Figure 9. Cracks are investigated using a photogrammetric block and a series of coded targets.

3. CONTINUOUS MONITORING

In addition to the automatic sensors previously described (pendulums and strain gauge), other automated systems were installed to obtain continuous readings. These include:

- fiber optic sensors;
- accelerometers and inclinometers;
- LVDTs;
- cable extensometers.

3.1 Fiber optic sensors

On the market a wide selection of sensors is available. A strain gauge can be easily produced with a *Fibre Bragg Grating* (FBG) inscribed in an optical fiber. The adopted solution was to use devices as a reliable sensor designed for harsh environments. The requirements for the measurement sensors are: best available strain sensitivity, 100 mm long baseline, wavelength range 1510-1590 nm, double sided connectors, low thermal sensitivity. This last requirement is quite difficult to obtain with FBG sensors, being their thermal sensitivity a well known problem. Some 'self-compensated' sensors are available on the market, but their compensation is not specifically designed for the chosen marble. Therefore it was preferred to carry out a specific thermal calibration, as explained below.
After a first phase of tests directly carried out on the interested structure, FBG sensors were selected for the monitoring system. For each rib a strain sensor FS 6200 (see FIBERSENSING, 2011) fixed with bolted forks coupled to a temperature sensor was installed. All sensors are connected in series and a single optical fiber 40 m long was laid out to a cabinet containing the FBG interrogation unit (a MicronOptics sm130-700).
A well known fact is that FBG sensors are sensitive both to strain and temperature (Othonos, 1997). In this work the separation of the two contributions is fundamental as the quantity to be measured is the strain due to load effects. Consequently, any thermal effect must be cleared out. Three main contributions can be found in the measured strain signal, (ε_{mis}):

- mechanical strain due to the load in the marble (ε_1);
- mechanical strain due to the thermal expansion of marble (ε_2);
- apparent strain due to the temperature sensitivity of the fiber (ε_3).

The load effect can be easily computed as $\varepsilon_1=\varepsilon_{mis}-(\varepsilon_2+\varepsilon_3)$. The contributions within brackets must be evaluated and subtracted from the overall measurements. This can be done by a direct measurement or a posteriori sensor calibration: the first solution was found to be inapplicable, being nearly impossible to provide a completely unloaded part in the nearside of the selected measurement region. Conversely the selected solution was the calibration of sensors and their compensation by a numerical model which depends upon the temperature.
To obtain the relationship between the temperature T and the thermal strains $\varepsilon_T=(\varepsilon_2+\varepsilon_3)$, a calibration setup was prepared in Politecnico di Milano laboratory (Fig. 10a). A sample block of 'Candoglia' marble was put inside a thermal chamber (Fig. 10b) which is able to maintain a stabilized temperature. The same sensors that were placed later on the Duomo ribs were used for this calibration, except for the type "A" that must be glued and so it cannot be re used. The dimensions of the marble block were 350x300x250 mm^3, nearly the maximum values that can be placed inside the chamber. The sensor direction was selected to match the one of the vaulting-ribs. The tested temperatures were selected in the range from 5 C to +40 C, at about 5 C steps, to cover all the possible values inside the cupola during a year. Many of the tested temperatures were tested twice or three

times to check repeatability. Due to the dimensions of the block, a minimum testing time of 12 h (usually 24 h) was adopted before reading the output values: all the transient phase was acquired so that a steady state condition was verified.
The analysis of the temperature tests are summarized in Figure 11, where the raw data points are interpolated with a 3rd degree polynomial. At the bottom of the figure, the residuals are shown, i.e. the differences between the measured data and the interpolation. To understand which sensor should provide the best signals, an uncertainty analysis of the thermal calibration was carried out (Cigada et al., 2011).
This work demonstrated that an a-posteriori thermal compensation is a feasible solution for the monitoring of Duomo di Milano, and, more in general, for any structure showing big thermal inertia. The first results from one of the installed sensors show nearly zero mechanical loads, as expected and also desired. The first step of this work allowed to estimate the minimum measurable strains, that are in the order of 20 µm/m.

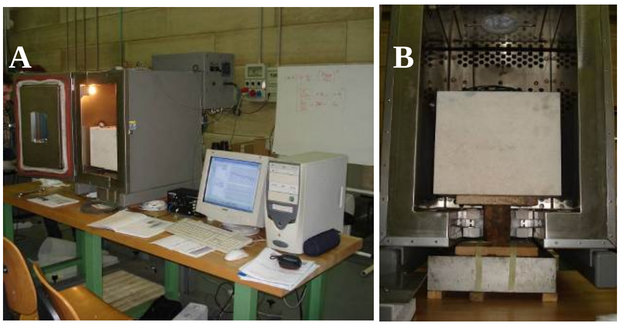

Figure 10. (a) The thermal chamber with the setup for the calibration of FBG. (b) Detail of the inner thermal chamber with the block of marble inside.

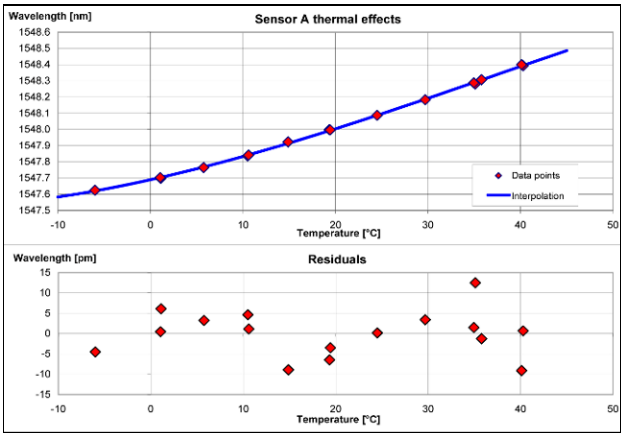

Figure 11. Thermal calibration results of the two strain sensors used in the preliminary phase.

3.2 Accelerometer and inclinometer sensors

The inclinometer sensors were used to measure the inclination of the different part of the main spire. The instruments chosen for this purpose are Precision Biaxial Tiltmeter (model 98046-01 'Tuff Tilt 420' - Codevintec, 2011). In total 5 inclinometers were installed (see Fig. 12):

- 3 around the base of the main spire on the spurs, with a distribution of 120°;
- 1 in correspondence of the first terrace;
- 1 above the 'Madonnina' on the last terrace.

The vibration of the main spire is measured by 6 accelerometers (model 393B12 of PBC - PCB, 2011). A couple of sensors, installed at the same levels of the inclinometers, were disposed in orthogonal position with the sensible axis on the horizontal plane.
All the accelerometer and inclinometer data are acquired and controlled remotely by the same interrogation unit utilised for the optical fiber read out.

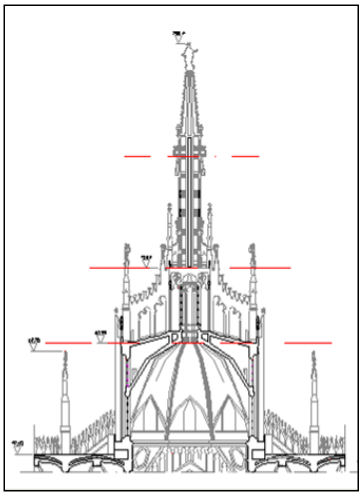

Figure 12. Position of the inclinometer sensors

3.3 Control of the distance between the main spire and scaffolding

The control is carried out on the highest terrace of the spire in three symmetrical positions around its edge. The scaffold, similar to a hollow cylinder, is an independent structure from the first terrace. The aim is to control the relative displacement between spire and scaffold in order to prevent any contact.
The relative movements are measured by Cable-extension position transducer PT8110 (see CELESTO, 2011). These features the following properties: range 0-60 in, accuracy ±0.25-0.10% full stroke, repeatability ±0.02% full stroke). The measurement range of sensors was chosen to work inside the scaffold displacements calculated during the plan.

3.4 Cable extensometers

The basement of the dome is a very important structural element because it transmits the roof and scaffold weight to four pillars. For this reasons, in addition to the total station measurements described at paragraph 2.2, a new automatic control system was planned. Four cable extensimeter was installed as reported in Figure 13. Each extensimeter (Fig. 13 left) consists of an INVAR cable that is tensioned by a weigth, and two sensors. The first is used for automatic reading and the second (manual) for backup. The automatic sensors are LVDT Inelta IEDT50 (stroke ±25mm, linearity tolerance <0.75% F.S. - INELTA, 2011).

4. SYSTEM FOR DATA ACQUISITON AND ALERTING

To complete the measurement chain, after the sensors and the network, a strategical role in a monitoring systems is represented by data acquisition (see Cigada et al., 2011).

All automatic sensors sends data to a unique collection center (Fig. 14). An *interrogation unit* (IU) is installed on PC in a protected position. Under normal operating conditions, its main task is to collect and analyze the data stored in the peripheral nodes, thus becoming the final destination of all data. During set-up phases, it constitutes the user-interface for node configuration and sensor calibration. The IU also serves as the gateway for remote access to the system through the Internet.

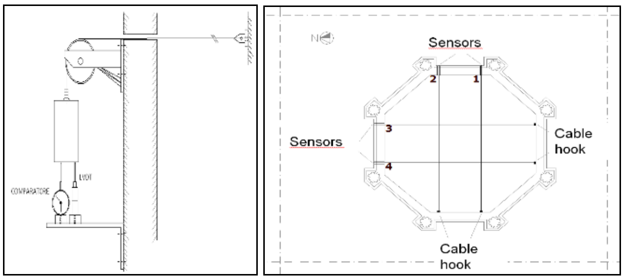

Figure 13. Position of extensometer sensors (right) and scheme of sensors (left).

The system was completed with an UPS device able to assure a continuous power supply for many hours and moreover able to work as an overload relay for any lighting that can damage the electrical parts (power supply is the only electrical connection to the outside world, and so prone to the lightning danger).
At the moment a management software is being implemented, whose actual functions are:

- remote control of sensors;
- acquisition data and backup;
- real-time processing, time averaging, statistic parameters computation, and graphical visualization.

The second part of SW implementation is focused on the automatic alerting system. The main goal is to compare the real-time data with different thresholds in order to activate various alarm levels. For the well-functioning of warning system is very important the correct definition of the alarm thresholds. These will be chosen by structural engineers on the basis of previously acquired control measurements (manual and automatic) and on numerical simulations. If a threshold is overcome, a set of predefined alarms will be activated (e-mail, SMS, acoustic and visual messages).

5. CONCLUSIONS

A complex monitoring system has been setup to assess the safety of the main spire of Duomo di Milano cathedral during ongoing restoration works. The paper gives a presentation of the different instruments and methods used to control the different structural components.
Manual and automatic systems have been used in order to give a real-time alerting system without losing the reliability of traditional techniques for structural health monitoring.
The automatic sensors were installed in strategic positions of the structure. The data acquisition system has been implemented to integrate different kinds of sensors and without any limitations in their number.
Today the data acquired did not show any critical situation, but they reported important information about the thermic cycle of the structure. This information will be used to better understand the real deformations and refining the alarm threshold to complete the automatic safety system.

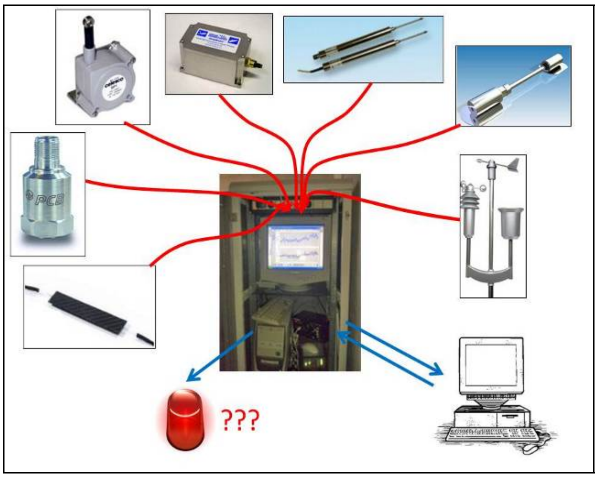

Figure 14. Scheme of system of data acquisition, remote control and alarm.

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