Structural Health Monitoring of an Historical Building: The Main Spire of the Duomo Di Milano

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ABSTRACT

Health assessment of historical buildings by means of monitoring systems is for sure a funda-mental step to preserve architectural heritage, especially for countries as Italy, rich in ancient monuments. Events such as earthquakes or severe weather phenomena constitute a major risk for these buildings because of their age and the related weakness to sustain exceptional excitations. The availability of a continuous, real-time, and automatic structural health monitoring system is considered a useful tool for early detection of a potentially dangerous situation for the structure and its occupants. The choice of the best measurement strategy provided by the monitoring system is crucial: a compromise must be found between the need of information, complexity of the measuring system and the related costs.

Due to the difficulty in modelling most historical structures, it is a hard task to fix proper and safe limits relying on model-generated predictions only. The availability of long-term records of the structural response can help get this goal, not just relying on models, but also detecting changes in some parameters obtained from time records.

This article presents a challenging example: the structural health monitoring of the Duomo di Milano main spire during and after restoration.

KEYWORDS

Automatic monitoring system;
continuous monitoring;
dynamic measurements;
experimental techniques;
restoration;
static measurements;
structural health monitoring

1. Research aims

The aim of this article is to describe the design and the development of an automatic system for the structural health monitoring of an historical building: the Duomo di Milano, specifically its main spire.

The motivation comes from the need to have a deep restoration of this marble structure (the first after more than 200 years), which in turn meant building a heavy scaffolding on top of the dome. During restoration operations large damaged blocks of marble were removed and substituted by new ones; these activities are far from any common practice and continuously affected the response of the structure.

Any interference between the spire and the scaffolding caused by the wind or any other environmental condition had to be avoided: that is why any possible check to avoid potentially dangerous situations had to be set. A real-time monitoring was designed and realized, to early detect any possible damage and to send alerts about any odd situation for the structure and its occupants. The system can also perform a self-internal check to generate alarms in the case of any monitoring system bad functioning.

Although the main aim of the monitoring system was to detect the effects of the wind action, it was extremely useful also to measure the effects of a strong earthquake, occurred during the restoration activities.

A description of the monitoring system design as well as of the choices related to the proper instrumentation is provided: this relies on previous works in which numerical models of the spire, the dome and the scaffolding have been developed to fix the framework into which the system has been developed. This article also describes the strategies for the data acquisition, management, elaboration, and storage, in order to provide an effective and prompt feedback about the spire health: in this scenario the choices to filter out false positives and false negatives, as well as the chosen limits to generate alarms has been a crucial point for the project success.

2. Introduction

Civil structures having social, cultural and architectural relevance often require a systematic and accurate

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monitoring system, to check their health. This may become a necessary requirement when the structure is occupied by a high number of people or when the building, as such, is characterized by a bold shape (Accornero 2014, Cantieni 2014, Caprioli 2009, Caprioli 2007, Cigada 2010, Lombillo 2016, Lorenzoni 2016).

Many natural events could affect a structure health, such as earthquakes (Carpinteri, Lacidogna, and Niccolini 2007) or severe weather phenomena, and can produce effects that are to a large extent unknown in advance. The intensity of these phenomena as well as the moment when they will occur are not predictable. Restoration or reinforcement works are additional situations in which the static and dynamic conditions of a structure could be impaired. In an urban environment, vibrations due to human activity (e.g., traffic) might damage a structure as well. Under all these conditions, the availability of a continuous and real time structural health monitoring system (SHM, Sanchez 2015, Anzani et al. 2010) is, without any doubt, a useful tool in the detection of a potentially dangerous situation for the structure and its occupants. The state of the art in measurements and data acquisition systems allows us to provide efficient continuous monitoring facilities, also being cost effective, with high reliability. Progress in this field is running very fast, with an interesting evolution, making structural monitoring more and more attractive. Italy is rich in historical buildings and unfortunately, it is also a seismic area: that's why a big experience has been developed on monitoring and preserving architectural heritage, in a balance between the structural safety needs and the respect for their architectural and cultural value. Among the many contributions on this topic we remember the recent article from (De Stefano, Matta, and Clemente 2016), which can be considered a milestone. In the case of historical buildings, the utility of having a health monitoring system is even more evident, because of the greater fragility of most among these structures. All these motivations brought the need to design a monitoring system for the main spire of the Duomo di Milano.

The Duomo is generally described as a Gothic cathedral, since its construction began in 1386, but it continued for several centuries, ending up in the second half of the19th century, so its design incorporates different architectural styles. It is the fourth largest cathedral in Europe in terms of surface area and it is characterized by 135 spires that crown the roof. The highest, on top of the *tiburio*, is 109 m high and it was finished in 1769. Five years later, the golden "Madonnina" statue was placed on top of the spire, becoming the best-known symbol of Milan. The *Veneranda Fabbrica del Duomo di Milano* is the company founded in 1387, entrusted with the cathedral construction. Now the *Fabbrica* is responsible for taking care of maintenance and restoration of the building.

In 2010, a large-scale restoration project of the Duomo Main Spire was started, in order to renew the ornaments of this building portion, which had been severely degraded by harsh weather and pollution. However, as for most Gothic Cathedrals, quite often its decorative elements also perform a structural role and therefore ornament degradation might lead to structural safety problems. For example, the marble blocks at the grafts of the tie-rods are particularly damaged by the mechanical effect of the differential thermal expansion of the employed materials (i.e., marble and iron), or by the corrosion of the metallic parts. These parts, which actually have a structural task, must be removed and replaced by new blocks. So, the *Veneranda Fabbrica* entrusted the Department of Mechanical Engineering, *Politecnico di Milano* with the design and set up of an automatic monitoring system, capable to detect the onset of any possible damage and anomalous conditions on the spire and the *Tiburio* upper part. The restoration of the Main Spire was nearly over by the end of 2014. The monitoring system has worked continuously since the spring of 2011, with some updates or changes in its layout.

This article presents the adopted choices to ensure an effective continuous monitoring, first of all by describing which kind of measurements have been deemed appropriate. Second, a description will be provided about how data are acquired, managed, elaborated, and stored by showing some example of analysis. Third, we show how the acquired information are provided to the end user giving a synthetic description of the static and dynamic conditions of the spire and the scaffolding at any moment, even to not expert people. The project aims at producing early warning when one of the measurements exceeds a specified threshold. The identification of a suitable limit set for any static and dynamic parameter is not an easy task for an historical building such as the Duomo, due to a series of reasons. There is no historical trend in the data before the monitoring was started and in addition there is some difficulty in modelling such complex structures (these are made up of unconventional construction materials). A long-term analysis of the monitoring data can provide evidence about which are to be considered the acceptable ranges for the parameters to be taken into account. In the end, as one of the main requirements of a monitoring system is flexibility, some updates of the system configuration during the different restoration phases will be discussed, up to the planned final solution, when restoration works will be completely over.

3. The restoration of the main spire

The Duomo Main Spire is a very slender structure, a 30-m high marble vertical tower, having an octagonal cross-section. It consists of a central column surrounded by eight thinner columns. The spiral staircase leading to the structure top also plays a structural role, connecting the vertical elements. The structure is reinforced by iron elements. They form a weft of longitudinal and transversal bars, which connect the structural and decorative marble parts. This gives the structure the ability to absorb tensile stresses. The spire rests on top of the *tiburio*, above the cupola. The spire is supported by eight flying buttresses which contribute to balance the stresses resulting from the lateral loads acting on the spire itself. The whole structure weighs about 60 tons (Nascimbene 2012).

Less than a century after the construction end, the spire was already showing clear signs of material deterioration. Several restoration works have tried to redress this situation. However, the corrosion of iron elements was compromising the overall structural capacity and incessantly yielded damages to the marble parts. Moreover, the chronic differential thermal expansion between marble and iron has caused fractures on the marble blocks. Corrosion has made this problem even worse. The last important restoration of the main spire, in 1968, introduced steel elements whose main function partially replaced that of the old iron parts. However, this operation has not blocked the continuous degradation of the marble parts at the grafts of the iron tie-rods. In a similar way, the ornaments have been severely degraded by weathering and pollution through the centuries (Corradi Dell'Acqua 2009).

For these reasons the *Veneranda Fabbrica* decided to start a systematic replacement of all the most severely degraded marble elements, both structural and ornamental, and to recover the elements damaged to a lesser extent. This plan has involved designing a scaffolding surrounding the spire, along the whole height. Figure 1 shows the scaffolding before it was fully raised. Its design had to ensure an available area to safely work at each level of the spire and to move the marble elements to be replaced: in some cases the size of those marble blocks was considerable. Since it was feared that the scaffolding full extension could offer a significant area exposed to the wind, the scaffolding layout has been designed to offer the minimum resistance to the wind action and to minimize the interaction with the spire.

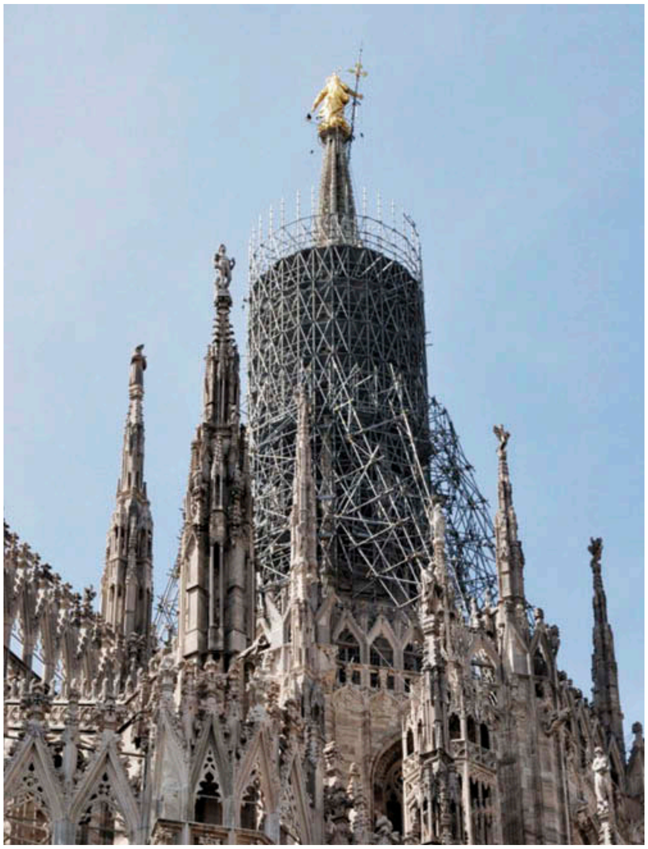

Figure 1. Duomo main spire and the partially built scaffolding.

As for the scaffolding design, the *Veneranda Fabbrica* paid major attention to a couple of issues: the overall weight of the additional structure supported by the *tiburio* and the effects of the wind loads to which the scaffolding could be subject. The latter is a relevant question in relation to the inability of a marble structure, such as the spire, to bear lateral stresses which any contact between the two structures might involve, so it is important that the two structures do not touch each other, for any reason. In order to prevent any contact between them, the scaffolding was designed to self-balance the lateral load given by the wind, by adding eight braces, despite the related weight increase. The whole added load, that had to be supported by the top of the *tiburio*, was about 100 tons (Nascimbene 2012).

As the project was considered complex and to some extent hazardous, a preliminary modeling was an unavoidable step to define the main design parameters of the scaffolding and of the monitoring system. Although the focus of the present article is on the experimental part, a very short summary of this preliminary modeling stage is given here. A model of the dome (Calvi et al. 2012; Corradi Dell'Acqua and Calvi 2009) served to define the allowable loads, therefore providing proper information for the scaffolding design. The main difficulties were related to the use of marble as the construction material for the dome, exhibiting nonlinarites, a not homogeneous

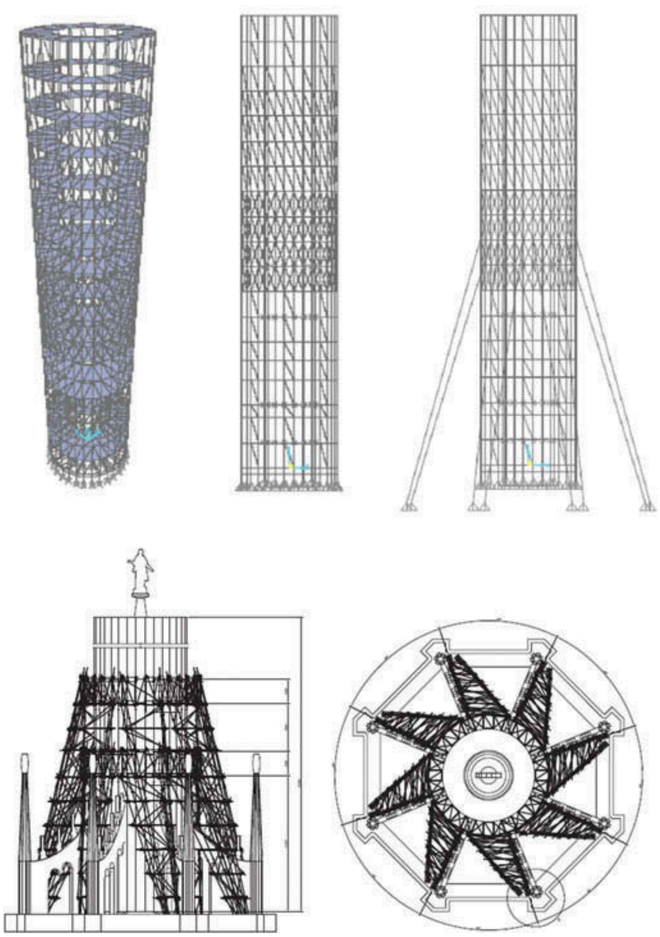

Figure 2. Some solutions for the scaffolding design: (a) from Corradi 2009; (b) from Nascimbene 2012.

nor isotropic behavior and a special sensitivity to external parameters, like temperature. From this first model, a forecast on the maximum allowable loads came out, as well as some possible solutions for the scaffolding shape (see Figure 2). In order to obtain experimental data contributing to the validation of the numerical models, a set of fiber optic fiber strain gauges was installed along the eight dome ribs. Each fiber optic strain gauge was equipped with full temperature compensation, obtained by means of an additional fiber optic sensor. The design, implementation, and testing of the optical fiber strain gauges for the model validation and the completion of the monitoring system here described is in (Cigada et al. 2011).

The first models have then been refined: those of the scaffolding (Rugarli 2011) have been useful to fix all the necessary design details, providing the needed structural stiffness, although preserving the design masses, with the aim to prevent any contact with the spire (Figure 3).

Parallel to the scaffolding design, a number of models have been created to give a forecast of the spire motion due to all the possible external loads, mainly the wind and earthquake. These models have been both static and dynamic (Postoli and Giorgetti 2012), and have been supported by a specific experimental modal analysis (Nascimbene et al. 2012) which has then been repeated every year, to validate the numerical model outputs and their sensitivity to the structural changes occurred during restoration. These calculations have also served to confirm the preliminary choices for the sensor positions and number (see Figure 4).

The monitoring system that was developed by the Department of Mechanical Engineering of Politecnico di Milano, is described in the next sections: it takes into account two main aspects. The first is of course the monitoring during the restoration works. This means checking both the spire static attitude, eventually modified by the additional scaffolding loads or by the replacement of the marble blocks, and the relative displacement between the scaffolding and the spire at different heights, especially where the distance between them is expected to be the lowest, (meaning higher risk). The second goal was to design a monitoring system for reliable and continuous measurements also

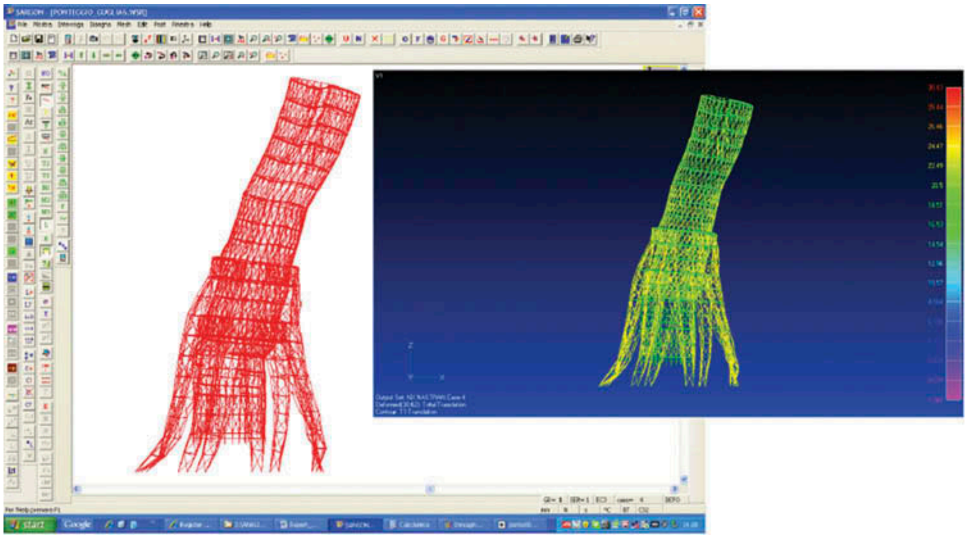

Figure 3. FEM models of the scaffolding (© Rugarli, 2011. Reproduced by permission of Rugarli. Permission to reuse must be obtained from the rightsholder.).

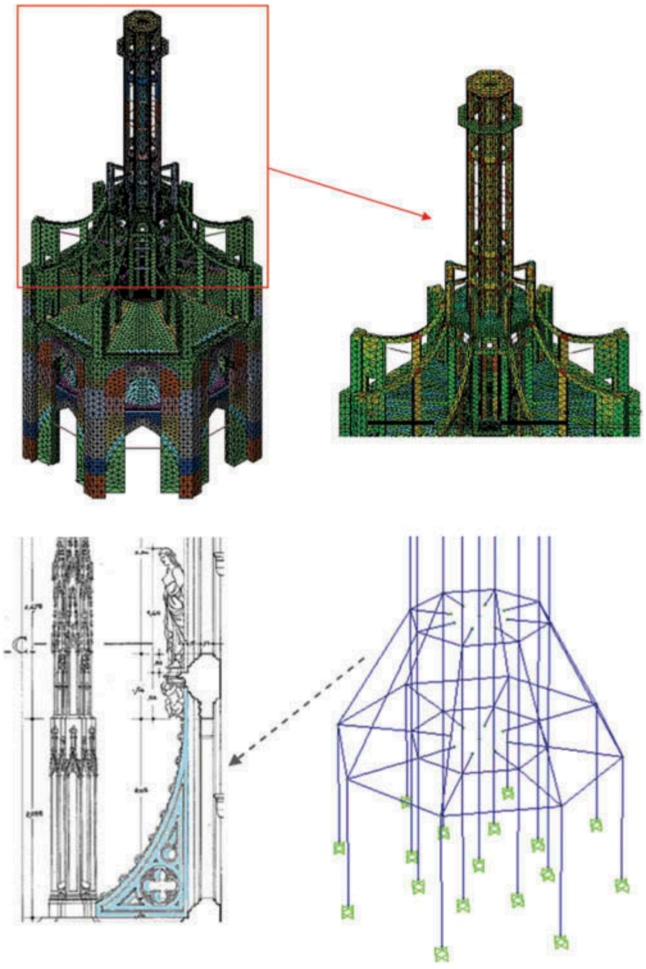

Figure 4. FEM models of the dome and the spire (adapted from Calvi et al. 2012 Postoli et al. 2012).

after the end of the restoration works. Moreover, the measurements had to describe both the dynamic and static effects which any events could cause on the spire or on the scaffolding. The monitoring had to be continuous, 24 hours a day, 7 days a week. In the next section, we will introduce the instrumentation choices, the chosen positions to fix the sensors, the measurement data management.

4. Instrumentation and measurements

During the restoration work, the need to have a system which could help identifying the static and the dynamic behavior of the spire and the scaffolding has led to a mix of different sensors:

- 6 high sensitivity accelerometers;
- 4 biaxial tilt-meters, placed at several heights along the spire;
- 3 wire potentiometers to measure the relative displacement between the scaffolding and the spire;
- 1 weather station;

The sensor choice took into account previous experiences in structural health monitoring, gained by the same research group in similar applications (Cigada 2010). Furthermore, an experimental modal analysis test was carried out (Busca 2011), to define the first eigenfrequencies of the spire with the corresponding vibration mode shapes. This test was scheduled prior to the restoration works start, to fix an initial dynamic picture of the structure, without the mutual effects between the scaffolding and the spire. The obtained results have been useful to support the interpretation and the analysis of the dynamic measurements,

Table 1. Technical specifications of the instruments used.

Devices	Full scale	Bandwidth	Sensitivity	
Accelerometers: Piezo PCB 393B12	0,5 g	0.1 Hz—500 Hz	10 V/g	**Noise** 3.1 (μm/s^2)/√Hz
Displecement transducer: Celesco PT8101	500 mm	/	1.86 mV/V/mm	**Accuracy** 0.15 % of F.S.
Biaxial tilt-meter: Applied Geomechanics Tuff Tilt 420, Hight-gain	± 0,5 °	0 Hz—3 Hz	0.0625°/mA	**Resolution** 0.0001°

performed during the monitoring phase, in which a reduced number of sensors could be used. This helped identifying the most suitable bandwidth to monitor the spire dynamic behavior too. Table 1 shows the specifications for the chosen devices.

The sensors' positions on the spire and the scaffolding are shown in Figure 5. Despite many works in literature deal with the use of wireless sensor networks for monitoring of historic buildings (i.e., Zonta 2010), the specific case concerning the Duomo main spire could not rely on standard or literature approaches. In fact, the dense metallic mesh of the scaffolding made it an effective Faraday cage, able to shield most of the radio waves transmitted from and to the spire. Due to this reason and to the absolute need of reliability, as the system had to provide real time alarms, it was chosen to work with wired connections, able to ensure a robust and synchronized connection between the sensors and the data acquisition unit. Moreover, the wire connection allowed to provide the needed power supply to the sensors. With wired connections, especially along long distances, proper insulation must be provided: the sensors have been insulated from the structure with thick polycarbonate blocks and the connecting cables had a separate sheath each, grounded to the earth network in a single point: this has protected

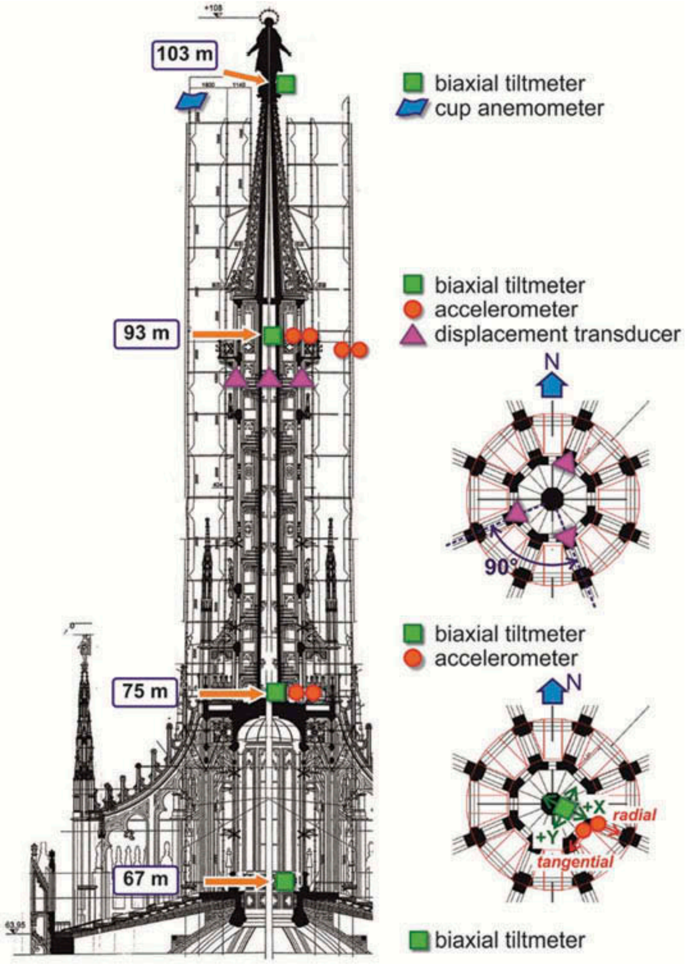

Figure 5. Sensor positions on the spire and scaffolding.

the system against ball lighting, also maintaining a good signal/noise ratio. With respect to other applications, peak voltage discharge devices have not been necessary.

4.1. Acceleration measurements

The measurements carried out by means of the piezo-accelerometers selected for this application allowed to identify the dynamic response to different excitation kinds, related to the spire as well as to the scaffolding. Their bandwidth proved to be suitable to identify the dynamic response of both structures, getting their first vibrations modes. As shown in Figure 5, a couple of accelerometers have been placed on the scaffolding (Figure 6) and two couples on the spire (all of them measuring in the horizontal plane): one at the lower balcony level and the other at the upper balcony level. Each couple of accelerometers has been laid down in order to measure along the radial and the tangential directions (with respect to the structure main axis). The dynamics in the horizontal directions is the most relevant, considering the first vibration modes of these thin tall structures, which are roughly modelled as cantilevers (Busca 2011).

The good signal to noise ratio of the adopted transducers guarantees the identification of the dynamic response generated by even a moderate forcing action, such as that produced by wind or traffic. The power spectral densities of the accelerometer signals, shown in Figure 7, identify the spire and the scaffolding response to an environmental forcing, that are the micro actions coming from the wind, traffic, people working on the spire, assuming the excitation input is a wide band noise. This identification, simply made available even after a few hours of data acquisition, produces data comparable to those obtained by means of specific experimental modal analysis, performed with more sensors, to get a complete and deeper spire screening at least once every year (Busca 2011, Ceravolo 2016, Nascimbene 2012). Any change in the dynamic behavior of the spire or the scaffolding could be evaluated by observing a change in natural frequencies, mode shapes and damping ratios. Different approaches are shown in literature for SHM: by means of oprational modal analysis, applied to civil structures (Cigada 2008) as well as to historical buildings (Ramos 2010, Gentile 2014). Although these techniques have been periodically employed on the Duomo's main spire, in order to assess its dynamic behavior, it is thought that a thorough understanding of the spire behavior needs a proper sensor fusion, merging dynamic information with those obtained from other kinds of sensors. Into details this means joining the dynamic parameters identification with static instrumentation information, like those provided by clinometers or crack opening sensors, whose outputs have to be analyzed over very long periods: long-term continuous monitoring of slow varying data opens new possibilities related to long-term evaluations, less present in literature (Cattaneo 2013; Cigada et al. 2010).

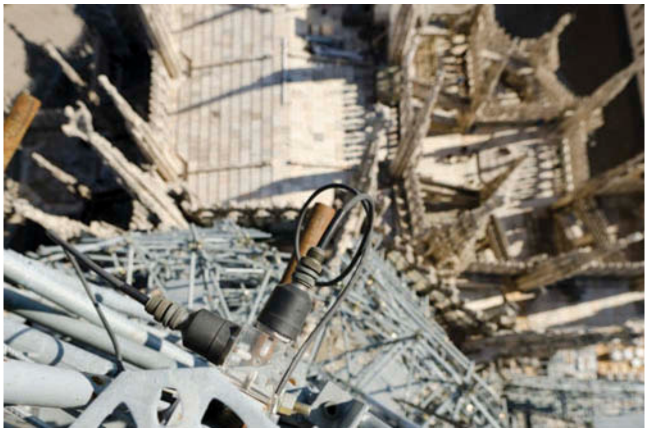

Figure 6. The couple of accelerometers on the scaffolding.

In the present case, the systematic restoration activities in many cases consisted in removing and replacing structural elements. Moreover, the frequent changes in the scaffolding layout continuously modified the boundary conditions. Due to the mentioned reasons, it was not possible to monitor the health of the structure relying on the dynamic properties only. In fact, any change in the dynamic behavior of the structure might be due to either the onset of a structural damage or to the above-mentioned restoration activities, but it is not always possible to detect which is the real case. This induced to focus also on static measurements, in order to complete the general information about the structure health, as better described in Section 3.3. Anyway, dynamic measurements are still considered an essential step to investigate the dynamic behavior of historical buildings (Clemente 2010).

The installation of the scaffolding was carried out at different stages, before reaching the final maximum height; it was also necessary to stop its construction a few times in order to run new numerical models, to better predict the scaffolding response to the wind and validate the calculation outputs. Sometimes these numerical analyses highlighted the need to add new elements to the scaffolding, to stiffening purposes. Through these steps, a lot of attention has been paid to the evaluation of the relative displacement between scaffolding and spire (as described in Section 3.2), the measurement directly accounting for the risk of contact between the two structures. This goal is best achieved

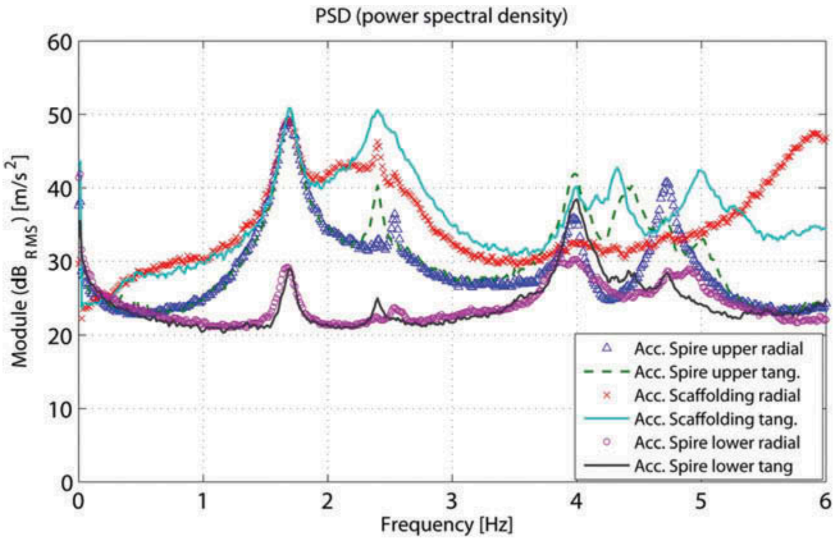

Figure 7. Example of power spectral density for the accelerometer signals (reference acc 1*10^{-6} m/s^2).

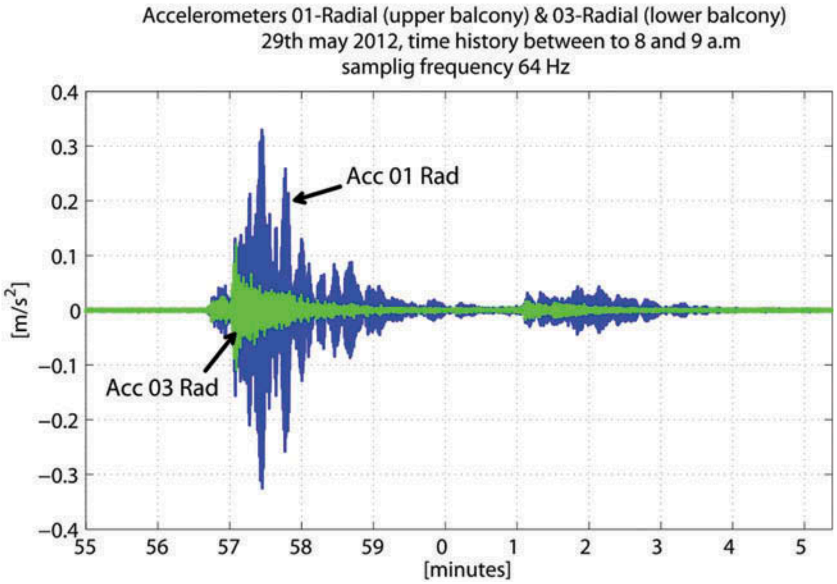

Figure 8. Time history of the spire's radial accelerations at two different level during an earthquake, May 29, 2012 from 8:55 to 9:05 am.

by considering the slower dynamic behavior of the structures; to this purpose the quasi-static measurements provided by the relative displacement transducers (Section 3.2) as well as by a series of tilt-meters (Section 3.3) has been considered the best solution.

As people work on the scaffolding during the day, some events recorded during these hours have led the acceleration signals to saturation, due to bumps induced by the workers in the vicinity of the sensors. All the same these events are easily identified and discarded through a cross check with the other signals (especially the wind speed, a value of major interest for our evaluations). The trade-off among the different needs led to a choice for accelerometers with the maximum allowed sensitivity, to get even the lowest level ambient vibrations, therefore deleting those records where saturation occurs.

Although the system was not specifically designed for seismic purposes, the instrumentation selected for the dynamic measurements provided some important information concerning the spire and scaffolding responses during a series of significant earthquakes occurred in Emilia in spring 2012, which produced meaningful shakes also in Milan. An example of these events is given in Figure 8 concerning the spire radial acceleration at two different levels. Since the monitoring system allows to measure the vibration on the top of the spire due to earthquakes, it was decided to fix an additional three axis accelerometer measurement point at the cathedral foundations, approximately below the main spire. In this way, it will be possible, in case of future shakes, to measure the transfer function between the ground vibration and the corresponding one on top of the spire. An additional vertical measurement point has been put at the spire base to allow a sort of transfer function of the cathedral behavior in case of new earthquakes. Accelerometer measurements at the basement are useful also to monitor the vibration intensity due to the subway trains passing close to the cathedral foundations.

The analysis of the peak acceleration values as well as the root mean square (RMS) values measured during extreme events (related to earthquakes or wind) can be useful to fix the alarm thresholds on the main parameters under investigation. Regardless, the occurrence of events, such as an earthquake, has further highlighted the importance to have also a static monitoring, as described in Section 3.3.

4.2. *Relative displacement measurements*

The importance of monitoring the relative displacement arises from the need to evaluate the possibility of any contact between the scaffolding and the upper part of the main spire. The risk resulting from this eventual case was already pointed out in Section 2. Concerning that risk, the scaffolding designers have placed greater emphasis on the uncertainties related to the effects of the wind load, due to several points. First, the lack of long term statistics about the wind speed and direction in the boundary layer overlying the urban area of Milan. Second, the extreme effort required for an accurate modelling of such a structure made by many elements connected by complex constraints. To end up, the lack of accurate knowledge of the actual dynamic and static behavior of the main spire, particularly in terms of its response to factors such as the wind load. All these elements made it necessary to have experimental data achieved before the scaffolding was entirely built, in order to tune the scaffolding numerical model through an iterative model updating approach. Measurements highlighted what supposed, i.e., the relative displacement between the spire and the scaffolding was mainly affected by the wind load (in addition to temperature). So, in order to properly evaluate the gap change between the structures, the 3-s average displacement has been considered as the best choice to correlate the dynamic behavior of the scaffolding with the wind gust effects, as shown in Figure 9. The relative displacement measurements where performed where the worst wind condition in terms of clearance between the spire and the scaffolding occurred, i.e., at the level of the higher balcony, where the maximum allowed gap was equal to 10 cm in every direction

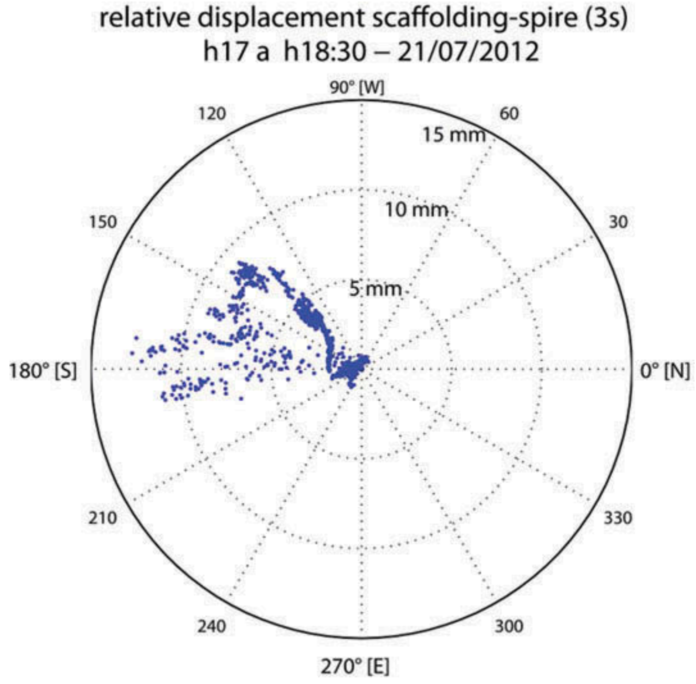

Figure 9. Relative displacement, evaluated from the position at the beginning of time history (at time 0 the spire position is 0□0°), July 21, 2012 from 5:00pm to 6:30 pm.

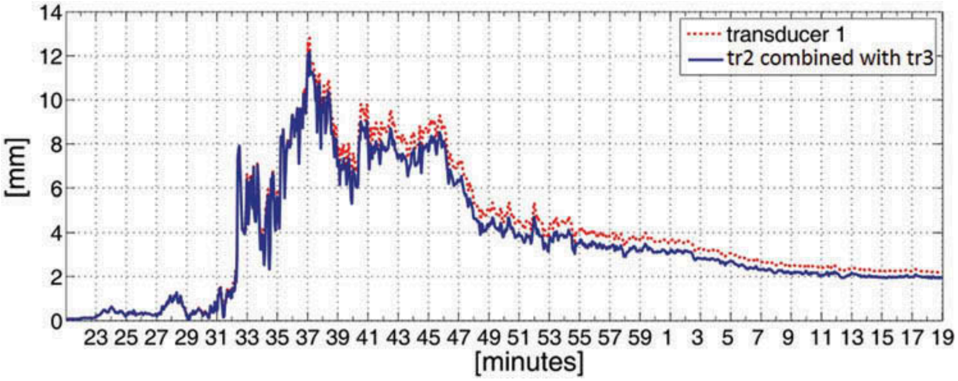

Figure 10. Compatibility between combined displacement 2–3 and the measurements provided by transducer 1.

In order to get this measurement with some redundancy, to grant a high reliability level (this was initially considered the most critical measurement), three displacement transducers have been used. The measurements are provided along three different horizontal directions (Figure 5), thus the relative displacement can be completely evaluated in terms of amplitude and direction, by a vector composition from measurements provided by any couple of sensors, keeping the third as a backup, as shown in Figure 10. The third sensor also offers the possibility to check the output of the other two, improving uncertainty issues, or, in case one of the other two fails, it allows continuity of such a critical measurement. Working on the same data of Figure 9, a metrological compatibility check for the measurements provided by the displacement transducers is shown in Figure 10. The displacement calculated by means of the vector sum of transducers 2 and 3 was projected on the working direction of transducer 1 (in this case changes in the relative angles of the potentiometer wires due to the motion of the target have been neglected). The comparison shows a good match, except for a bias which appears after the highest displacement peaks. Taking into account the high wind speed of that case (shown in Figure 15-bottom), the bias in displacement may be due to a scaffolding settlement, to friction, which might slightly modify the relative position of the two structures. Anyway, according to the transducer accuracy (Table 1), equal to 0.75 mm, the measurement can still be considered acceptable.

To perform this evaluation an initial relative position must be fixed, because the sun exposition and the temperature responses continuously change the attitude of both the scaffolding and the spire (there is not a "rest" position, to be considered a zero). Normally, the position taken as a reference is that acquired just before the wind speed rises. Thus, the dependence of the average displacements upon the incoming wind can be detected, as shown in Figure 11. A good matching

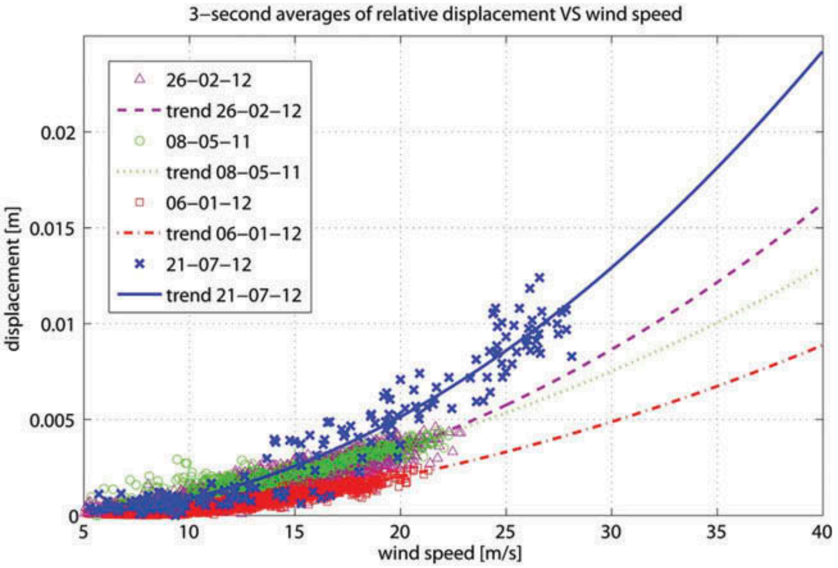

Figure 11. Relative displacement scaffolding-spire vs. wind speed, comparison of different events.

between the experimental data and the second-order polynomial curve fitting (characteristic of drag effects due to wind-structure interaction) allowed to extrapolate the relative displacement trend also for wind speeds higher than those really measured. In reality, due to the high scaffolding transparency, the wind effects are exerted on both the spire and the scaffolding, making the problem of separating the contributions a complex one, but, apart from the real distribution of loads, the main interest remains in the relative position between the two, which is directly measured.

The events of Figure 11 were recorded with different scaffolding configurations, in terms of both height and stiffness. This change in configuration leads to the differences among the plot trends. Although some dispersion is observed in the estimated maximum displacement, the limit of 10 cm is much higher than the expected values derived from the experimental results. The data measured on July 21, 2012 refer to the maximum recorded wind speed, and they show the behavior of the scaffolding at full height, reaching the statue on top of the spire. Previous events occurred when the scaffolding was only partially built, with lower displacements for the same wind speed (even if the direction is not the same).

To get weather data, a station was placed on the top of the spire, allowing to get simultaneous data acquisition of the wind speed and direction, in addition to other atmospheric parameters like temperature. These data travel through a wireless connection directly to the data acquisition system, lacking of a perfect synchronization with the other sensors. Due to this reason, another cup anemometer was placed on top of the scaffolding: its analog output was synchronously acquired with the SHM measurements, allowing for the proper correlate static and dynamic measurements with the wind intensity.

The device was placed in such a way not to be sheltered by the main winds blowing over the city of Milan, until the scaffolding height has allowed it. When the scaffolding started being dismounted, only the cup anemometer integrated in the weather station and placed on the halberd of the Madonnina statue offered a reference for the wind speed measurement in terms of average value and maximum gust value, which are sent to the computer for data elaboration every 10 min.

One of the main problems with monitoring systems is always fixing thresholds to produce alarms. In the present case, however, a criterion to define these thresholds has been easily defined. Some trigger limits have been fixed when half the design speed is reached, as well as when a relative displacement equal to 50% the maximum allowed is trespassed. A third kind of alarm was generated every time any of the acquired data exceeded the maximum value stored in the data base for that channel. That's why a historical evaluation of the past records has been considered an essential part of this job, also useful to reassure about the chosen safety bounds and the adopted stiffening solutions, before reaching the maximum scaffolding extension.

An additional alarm had to be fixed to recognize any malfunction of each single sensor and eventually switch to the backup one, in the case of wire potentiometers; this check has been easily performed by controlling the trend of each sensor on a daily basis and in comparison to the other sensors. Anomalous peaks as well as too steady outputs have been considered situations worth sending an alarm.

4.3. Tilt measurements

Dynamic measurements are recognized as a common solution for structural health monitoring (Ramos 2010). However, there is a very low-frequency dynamics, which consists in a sequence of static or quasi static measurements, offering a variety of indicators, often easier to understand, even if the time base necessary to localize damage is quite long, in the order of many months or even years. Tilt measurements proved to be an effective solution to monitor these low-frequency changes.

The two-axis tilt-meters chosen for this application have been tested for a long time in other important monitoring applications, such as the "Meazza" Stadium in Milan (Cigada 2010). They have proven to exhibit a very low sensitivity to any temperature change. In any case, these sensors are equipped with an internal temperature sensor, providing data for compensation of thermal effects. Moreover, they show very high sensitivity to tilt, optimal resolution and suitable bandwidth. Therefore, it is possible at the same time to measure very slow and small tilts, made free from any temperature effect, and the chosen clinometers also offer the chance to have limited dynamics, from 0–3 Hz, in case of faster events (wind gusts or earthquakes). The adopted devices measure tilt values along two normal directions around axes in the horizontal plane, though knowing that it is generally impossible to provide a neutral condition of the structural attitude. In fact, the change in the boundary thermal condition (i.e., temperature and solar radiation) also changes the attitude of such a thin and tall structure as the Duomo main spire. Thus, the reference position for tilt measurements is assumed to be that at the time of tilt-meter installation. Figure 12 shows the tilt-meter placed at the top of the spire, just below the statue on top.

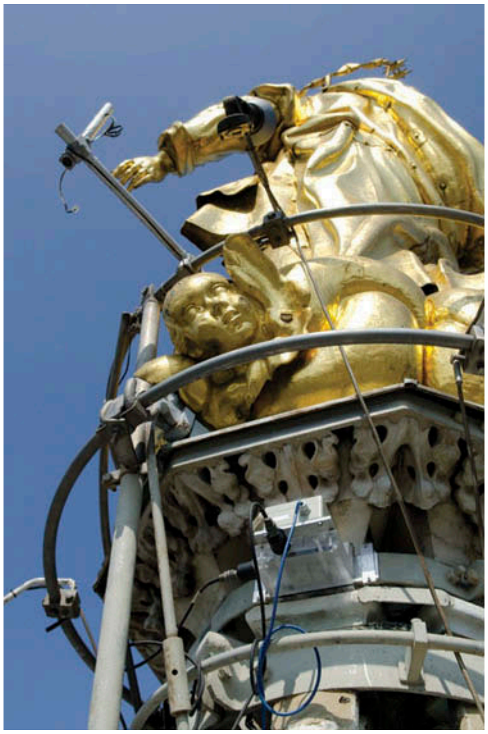

Figure 12. Tilt-meter placed at the base of the Holy Virgin statue named “Madonnina”, at the spire top. The couple of accelerometers visible in the picture were used for a periodic experimental modal analysis test.

As an example, Figure 13 shows the trend of the relative tilts measured by the clinometer at the height of 75 m; time 0 is the start activation day. Data are provided here in terms of 10-min average value. In the figure, a strong correlation is visible between the temperature data and the tilt of the spire along the X direction (which is approximately aligned with the East-West direction, as shown in Figure 5).

4.4. Assessment of tilt thresholds

Some additional remarks can be drawn from Figure 13. The effectiveness of a tilt measurement to help identifying a damage onset is related to the capability to show a change in the structure attitude which differs from the normal variation due to environmental effects. The complexity of the spire makes the identification of a maximum acceptable tilt amplitude a daunting task for civil engineers, because of the difficulty in modeling such a marble structure. A long-term continuous monitoring has allowed to observe a “normal” range of change in attitude, correlated with standard environmental conditions. Long-term measurements can provide an interval of tilt values which can reasonably be assumed as acceptable for the structure.

As Figure 13 shows, the long-term tilt value records are closely related to the daily mean temperatures: they have a daily trend and a yearly trend of different amplitudes, each typical of a specific measurement point. The four-year long time record highlights the structure stability during the restoration period, showing a small drift of around 1/100 deg., almost entirely covered in the first year of monitoring. As the global observation period includes both the scaffolding mounting and dismounting, it can be drawn that the added structure did not significantly affect the spire attitude.

Since the tilt of the top of the spire can be considered as the sum of the behavior at the lower levels, Figure 14 gives a glimpse of the data recorded on top, together with those recorded at 75 m and the contemporary temperature data. A sharp difference is noted between tilts at the two levels, these being strongly dependent upon temperature.

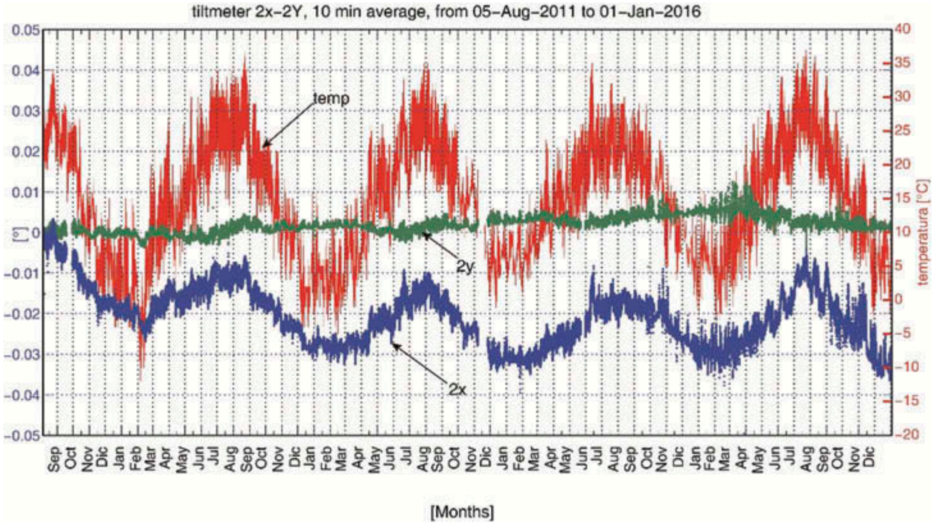

Figure 13. Tilt values time history, at the lower balcony of the Spire (75 m): red is temperature, blue is rotation around the X axis, green is rotation aroung Y axis: X and Y are normal in the horizontal plane.

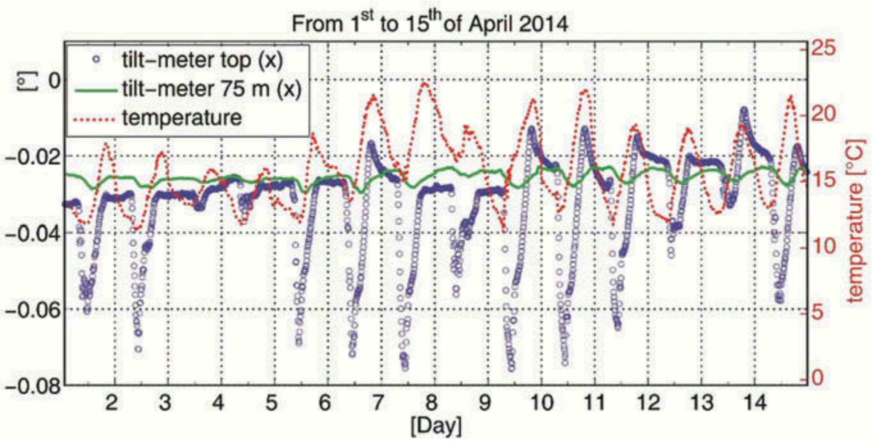

Figure 14. Daily tilt trend measured in x-direction (E-W) at the very top of the spire and at the lower balcony level (75 m), compared with temperature trend acquired on the top.

Any structural changes, like the substitution of parts of the main spire and the different erection stages of the scaffolding, could have played a role in modifying the observed normal trend of the spire attitude, being this superimposed to the "regular" one. That is why these measurements have never been stopped during the restoration work and specific attention has been devoted to these measurements. This long-term monitoring of quasi static parameters has been considered an effective monitoring of the spire structural health, so that it has been decided to protract it beyond the end of the restoration works.

As the mean temperature affects the attitude of the structure, the day/night temperature change superimposes a daily trend to the seasonal trend. The higher is the level where the measurement are given, the higher is also the daily change in the spire attitude.

A short-term analysis is shown in Figure 14; the daily attitude changes, packed up in Figure 13 due to scaling reasons, are now clearly seen. It is observed how daily changes can be a meaningful percentage part of the seasonal trend. This time-record was collected after the scaffolding disassembly: therefore, the absence of any shadowing effect on the spire points out the influence of the solar radiation on the structural attitude.

Figure 14 also shows that in some days the negative peak in the tilting measurements is lacking or it is strongly reduced, although temperature follows its usual day/night changes. The analysis of the acquire data allowed to confirm that the main negative peak (e.g., the tilt movement from East to West direction) is due to the direct solar radiation in the morning. During clear sky days, at the top of the spire, the peak-to-peak amplitude of the tilting signal can reach 0.06°, therefore much higher than the yearly trend: this appears to be dependent upon radiation and not upon temperature.

Other environmental effects were taken into account to describe the spire static behavior. As discussed above, in Section 3.2, on July 21, 2012 a rather high wind speed was recorded. The contemporary measurement of the wind speed and of the tilts at different levels has allowed to try filtering the wind effects out of the global response influenced by temperature. Figure 15 shows the change in the tilting values at different levels; the chosen time window is narrow, to highlight the event, in which rather high wind speed (Figure 15b), has been recorded, reaching a peak value of 28 m/s.

On a rather hot summer day a storm caused a sudden wind, lowering temperature and causing the spire to displace from its initial position. Until the event start, only temperature and the solar radiation drove the spire motion. In the considered situation, the negative tilting peaks are mainly due to the wind action and partially to the loss of direct radiation, as the effects of temperature are usually slower. After the storm the wind calms down, the temperature starts raising again, though not reaching the same values as before the storm, so also the spire attitude moves back to a new balance, different from that before the event.

During this event, the gusts came from North, so it is a good approximation to consider just the the measurements along the Y-direction of each tilt-meter, which are almost aligned to the N-S direction. The response of the structure at the highest level is about 0.02°, also in the worst case, which takes into account also the offset due to temperature. It is reasonable to note that the peaks due to the wind action are comparable, in most cases lower, to those caused by thermal effects.

Anyway, sudden changes in the tilting signals, not directly related to the wind action nor to thermal

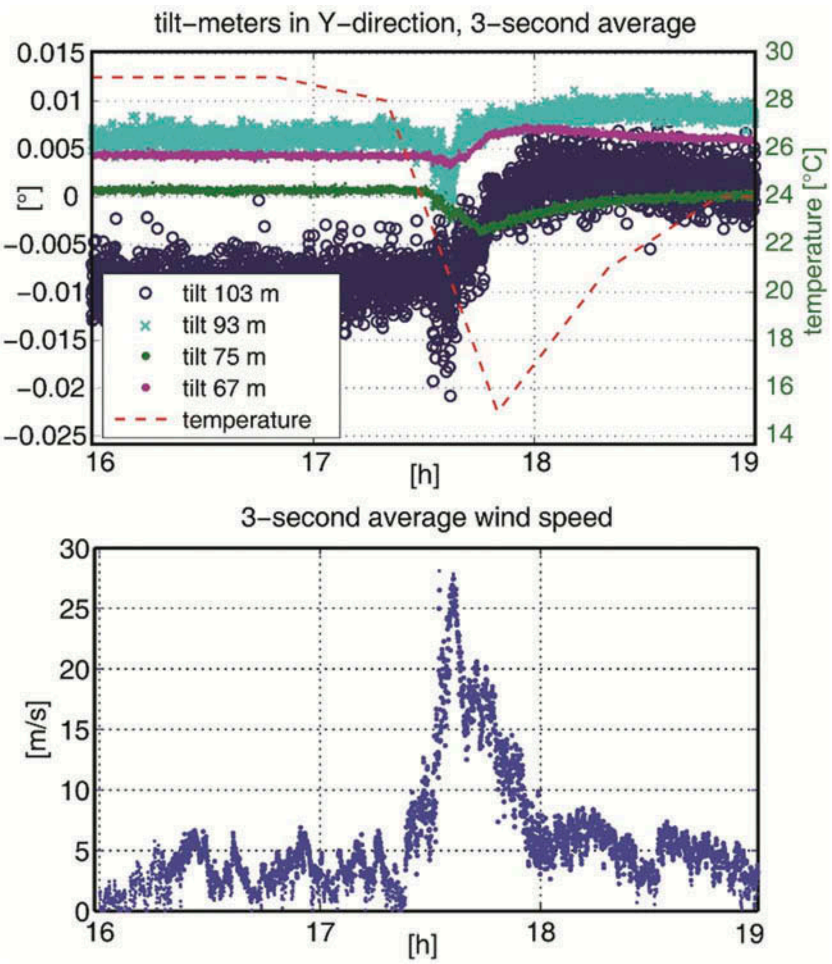

Figure 15. (a) 3-s average tilt measurements compared with (b) 3-s average wind speed and temperature.

effects, can be considered a possible damage onset, even if during restoration works the spire underwent meaningful structural changes (but again these were slower).

These remarks are rather important in case of earthquakes: a series of strong shakes stroke the Duomo di Milano, during the Emilia earthquakes, in spring 2012. In the case of this event the monitoring system was useful to analyse the response of the spire to vibration levels stronger than usual. Therefore, after the earthquake or during replacement of marble blocks on the spire, the monitoring system helped to understand if any damage was born or had increased. It is noted that in case of earthquake, the simultaneous presence of tilting and acceleration brought the high sensitivity output of some clinometers to reach their full-scale. However, the absence of bias in the mean tilt values after the shakes, gave a first check about the structure health, but the peak values could not be considered, as it was not possible to separate tilt from acceleration (typical of clinometers—those considered here have a bandwidth up to 3 Hz). This information represented an effective and fast way to determine if the structure was still safely accessible or not. This approach has demonstrated to be very sensitive and it has been considered an important completion of the dynamic measurements provided by the accelerometers.

Alternatively, a change in the spire's attitude could slowly appear as a drift in the recorded values not consistent with the normal trend. The additional weight of the scaffolding could have caused this latter condition, but it didn't.

5. Data acquisition and processing

In order to design a suitable data acquisition system, two main issues were taken into account: the environmental conditions and the needed flexibility to easily reconfigure the number and kind of acquired channels. These requirements led to choose a stand-alone system, consisting of an embedded real-time controller paired with an FPGA (field-programmable gate array) chassis. In the early development of the monitoring system the opportunity to easily reconfigure its layout has helped evaluating the best choices for the final solution. The system has no moving parts (i.e., it is fan-less and with solid state memory); this is a basic condition for a system working in a harsh environment, dusty and wet, like a construction or restoration site.

The system sampling frequency was set to 2048 Hz (the minimum allowed by the chosen Sigma-Delta converter, with an anti-aliasing filter. To save storage space, the acquired signals are low-pass filtered with a cutoff frequency of 16 Hz and then decimated to obtain a final sampling frequency of 64 Hz. The 16 Hz bandwidth includes the spire dynamic behavior related to the first mode shapes (experimentally evaluated in earlier test, Busca 2011), but it deletes the high frequency noise.

Data from each channel are stored in a new file every 10 min. A central control unit periodically pings the data acquisition system searching for new files. If present, they are downloaded and, once successfully copied, they are deleted from the data acquisition unit: this redundancy helps reducing the risks of data loss. The need of a user-friendly interface is mandatory, to face any emergency, and providing clear outputs also to not experienced users. A fit to the purpose software processes data and shows a set of parameters describing the static and dynamic conditions of both the spire and the scaffolding. Every time a new file is downloaded, this software shows the actual RMS from the accelerometers and the average values for the other data (i.e. relative displacements, wind speed and tilt values), considered static or quasi static. Then the evaluated RMS and the average values are compared with a set of predefined thresholds based on the past data recorded over a couple of years (and continuously updated). For each parameter, in case of threshold crossing, the system automatically activates an alert on the panel and warns a list of recipients by means of an e-mail or, optionally, a SMS. The software also sends email messages providing info on its correct working conditions (i.e. number of files and their size) and about the operating status of the monitoring system.

A screenshot of the control panel is shown in Figure 16, as an example. On the top part, the tab panel page is set to show the time histories of the tilt values, during the last seven days. This page allows for a quick overview of the whole system status. Another tab page shows the polar diagram of the relative displacements between the spire and the scaffolding, or again a third page gives an RMS chart of the acceleration values against the wind speed. In the lower part, the dials providing the instantaneous tilt values and the set of warning indicators are visible. Ease of use has been considered a fundamental pre-requisite, for the system acceptance by the workers.

The system can quickly provide some elements to evaluate the static condition of the structure after any relevant event. For example, during the year 2012 a series of significant seismic events occurred; a real-time evaluation of

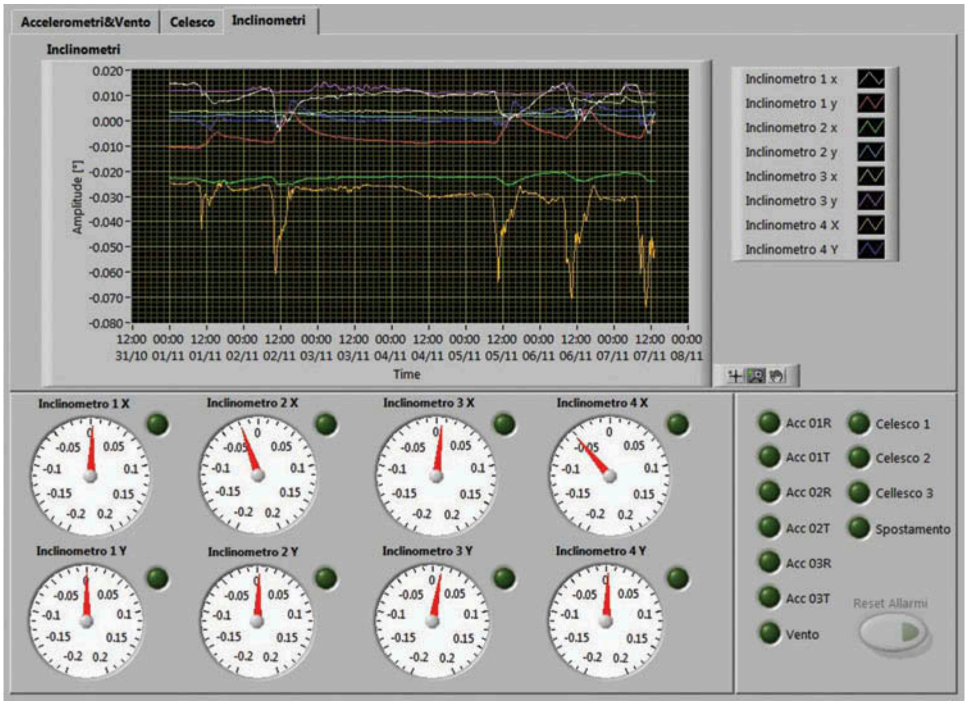

Figure 16. Screenshot of the processing software control panel.

the spire tilt values and the relative position between the spire and the scaffolding, before and after the transient response to the quake, allowed to exclude a permanent deflection of the main structures after the shakes, although an alarm was produced, as expected. The information shown in the control panel are useful to produce an early risk warning for the men working on the scaffolding around the spire. The continuous storage of the time series from the sensors also allows to perform a more detailed analysis of the dynamic and static effects of any significant event, or to look for any eventual correlation among them.

This way to elaborate and display the measurements may be completed by employing any algorithm able to ascertain the onset of a damage. As both the static and dynamic behavior of a civil structure are affected by environmental conditions, a data normalization should be performed on the measured data in order to effectively assess a damage detection (Ramos 2010, Gentile 2014). Sohn's work (Sohn 2007) deals with the effects of environmental and operational variability on SHM. It provides an overview of many approaches available in literature. Most of them focus on dynamic parameters. The environmental data usually taken into account are temperature, wind speed and humidity. As mentioned above, a slender structure such as the Duomo's main spire has a static behavior strongly affected by solar radiation, in addition to temperature. A paper from (Xu 2012) highlights that SHM needs a deep investigation about thermal effects induced by the ambient air temperature as well as the solar radiation. The latter is relevant to cause a non-uniform distribution of temperature, which affects the overall deflection and deformation of the structure. A network of temperature measurement points is required and a measurement of the solar radiation is needed as well, as temperature alone cannot be considered enough. As shown in the comments to Figure 14 the temperature distribution of the structural elements may be applied to the spire model to obtain its thermal response. This predicted response can be validated through the field monitoring data, in order to point out any behavior not correlated with thermal effects, which may be caused by damage.

The system has been working for nearly five years, with almost no stops, with the exception of some strong lighting, causing system stops, but not serious damage.

6. Configuration update

After more than four years of restorations, the work on the main spire is close to the end. The scaffolding surrounding the spire has almost been completely disassembled. At present, there is not yet any possibility of dangerous contact between the scaffolding and the top of the spire. The relative displacement transducers were removed. The present configuration of the monitoring system still includes the tiltmeters at four different levels, two accelerometers by the top balcony (93 m) and on other two by the lover balcony (75 m). It is scheduled to place three accelerometers at the spire base (i.e. the top of the dome), two of them with the same measurement directions as the other couples, but also adding a third accelerometer, measuring in the vertical direction, for a direct comparison with the three at the cathedral basement. This solution offers the chance to define a sort of "cathedral transfer function" from the ground to the top of the dome, in case of an earthquake.

7. Conclusions

This article focuses on the importance of a continuous health monitoring for historical monuments and describes the case history of a high value piece of cultural heritage, the Duomo di Milano. The four years' restoration activity, which has been considered hazardous for the structure age, for the particular construction material and its degradation, required the creation of a modern monitoring system, supporting any decision making and checking the structural integrity with a careful eye and a prompt reaction to any unconventional situation. Continuous measurements made the structure smart, capable of damage self-diagnosis, and helped to develop a clever maintenance plan. Specific care has been devoted to the workers' acceptance of the monitoring system, also taking care of user experience issues, to make it a tool used by everybody, as part of their individual protection equipment.

The system has helped in detecting the spire-scaffolding relative distance, avoiding any unwanted interference due to the wind or to seismic events, which could have meant a tragic collapse. Data have been collected for over than four years, offering a complete check-up of the structure. The choices for every detail and the adopted redundancies have allowed for a very high reliability and robustness.

An important effort has then been devoted to semi-automatic data management and to the generation of synthetic reports and alarms: luckily, when an alarm was switched on, it was to signal a sensor problem and not a real structural concern. The only exception was the earthquake, when the monitoring system offered a precious tool to assess the structure integrity.

Although the monitoring system has been designed and implemented for the restoration of the Duomo main spire, it is still working past the end of the works. The processing of a suitable set of parameters, extracted from the measured data, allows for the discerning of the onset of any damage conditions out of the normal dynamic behavior of the structure or from cyclic changes in the static attitude. This approach to structural health monitoring is less popular than the classic dynamic analysis based on spot data acquisition, nevertheless a continuous data acquisition offered the chance to record extreme events, like strong winds or earthquakes, providing a useful tool to assess damage risks. The system designed and developed for the Main Spire of the Duomo di Milano has been effective to provide the required targets, for over than four years. It still acquires 19 channels, creating a useful database to define the standard behavior of the structure. It has proven to be robust, as the real-time controller has always worked, (provided it had power), in very harsh environmental conditions, including dust, pollution, rain, snow, hail, earthquakes, and strong lightening.

The monitoring system for the Duomo di Milano can be considered a first milestone, possibly to be replicated for historical monuments and cultural heritage: the combination with other kinds of measurement, is at present under investigation: it can provide a much more effective tool to preserve the health conditions of an important monument such as the Duomo di Milano.

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