12th International Conference on Structural Analysis of Historical Constructions
SAHC 2020
P. Roca, L. Pelà and C. Molins (Eds.)

ONE YEAR STATIC MONITORING OF THE MILAN CATHEDRAL

ANTONELLA SAISI[1], ANTONELLO RUCCOLO[1] AND CARMELO GENTILE[1*]

[1]Department of Architecture, Built environment and Construction engineering (DABC)
Politecnico di Milano
P.za Leonardo da Vinci 32, 20133 Milan, Italy
e-mail: {antonella.saisi, antonello.ruccolo, carmelo.gentile}@polimi.it (*corresponding author)

Keywords: Historic Cathedral, Environmental Effects, Long-term Monitoring, Strain, Tilt

Abstract. *The paper focuses on the long-term monitoring of the Milan Cathedral. After a concise historic background on the monument and the description of the sensing devices installed in the church, selected results obtained during the first year of static monitoring are summarized as well as the lessons learned in view of the Structural Health Monitoring (SHM) of the Cathedral. In more details, the time evolution of different static features (i.e. strain of metallic tie-rods and tilt of columns) is presented, along with the correlation between those features and the environmental parameters and the possible minimization/removal of the environmental effects with SHM purposes.*

1 INTRODUCTION

The Milan Cathedral is the most iconic symbol of Milan and is world-wide known for being one of the largest Heritage monuments ever built. The construction of the cathedral took more than 4 centuries, from the apse erection in 1386 until the façade finalization in 1814 [1]; subsequently, architectural and maintenance works were carried out for a long period, so that the installation of the last iron gate in the façade (on January 6th, 1965) is usually indicated as the official building completion.

Since 1387 all operational aspects related to the construction, maintenance and restoration of the Milan Cathedral are managed by the historic Institution named *Veneranda Fabbrica del Duomo di Milano* [2] and denoted as *Fabbrica* in the following. After the completion of the church structures, the *Fabbrica* main mission moved to continuous inspection, maintenance and architectural restoration of the monument, with those activities being especially related to surfaces, decorations and statues in Candoglia marble. In the last decades, the traditional inspections have been often coupled with the installation of different sensing devices, aimed at monitoring local strengthening interventions (see e.g. [3]) or investigating the evolution of possible structural issues. Remarkable examples of sensing systems operating in the past includes: (a) the inverted pendulum installed in the main spire on late September 1904 to measure the horizontal displacements induced by strong winds [4]; (b) the traditional monitoring system, based on geometric levelling and established to measure the horizontal deflection of the piers in the late sixties. Although the latter system is not computer based, it has been active in measuring the piers deformation at pre-selected intervals (May and November) for more than 50 years and is still fully operating.

During the recent assessment of the state of preservation and the tensile force of the metallic tie-rods of the Cathedral [5], the idea of implementing a Structural Health Monitoring (SHM) strategy has been taking shape and a monitoring system was designed [6] and implemented with the two-fold objective of providing the information needed for the condition-based structural maintenance and the creation of a large archive of experimental data useful to improve the knowledge of the monument.

The long-term monitoring system [6], fully computer based and with efficient transmission of the collected data, includes static and dynamic measurements. The static monitoring system consists of: (a) bi-axial tilt-meters installed at the top of selected piers and at 3 levels of the main spire; (b) vibrating wire extensometers mounted on the iron tie-rods which are characterized by the higher tensile stress; (c) temperature and humidity sensors for the measurement of internal and external environmental parameters. The dynamic monitoring is performed through seismometers (electro-dynamic velocity sensors) installed at the top of 14 selected piers and at 3 levels of the main spire.

After a brief description of the Milan Cathedral, the paper is mainly aimed at describing the monitoring system installed in the church with emphasis on the static (i.e. tilt of columns and strain of metallic tie-rods) and environmental (temperature and humidity) measurements collected in the first year of continuous monitoring. Selected results are presented on the evolution in time of the environmental and static parameters and extensive comments are given on the removal/minimization of the environmental effects with SHM purposes.

2 THE MILAN CATHEDRAL

The Milan Cathedral (Figs. 1-2), spreading over an area of more than 10400 m^2 and with a volume of about 300000 m^3, is the second largest Gothic cathedral in the world by volume and area. Moreover, the church exhibits the second tallest main nave among Gothic cathedrals, with the height of the vault intrados of the main nave being at about 45 m from the ground (Fig. 3a).

A longitudinal section of the Cathedral is shown in Fig. 2, along with an essential chronology of the construction phases.

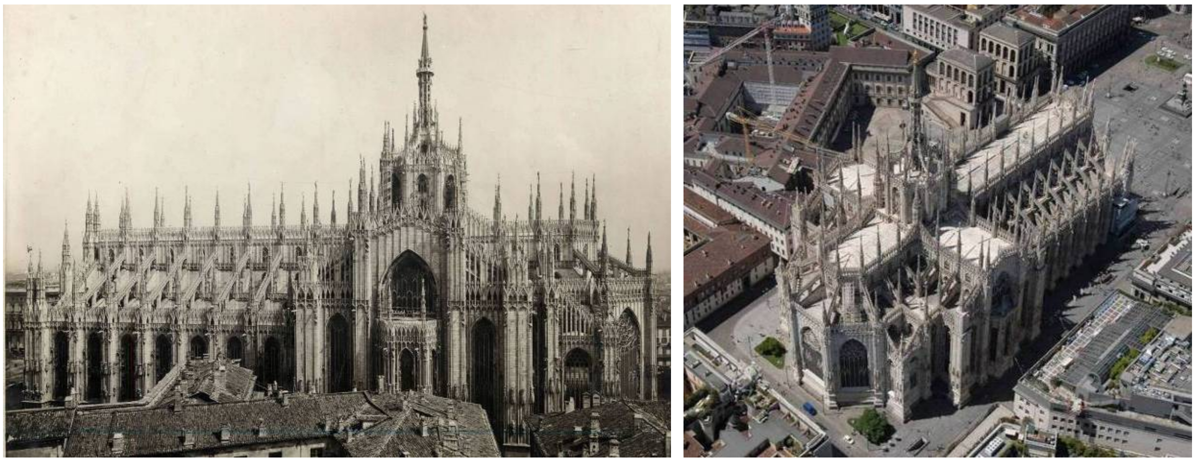


Figure 1: Views of the Milan Cathedral (courtesy of *Veneranda Fabbrica del Duomo di Milano*)

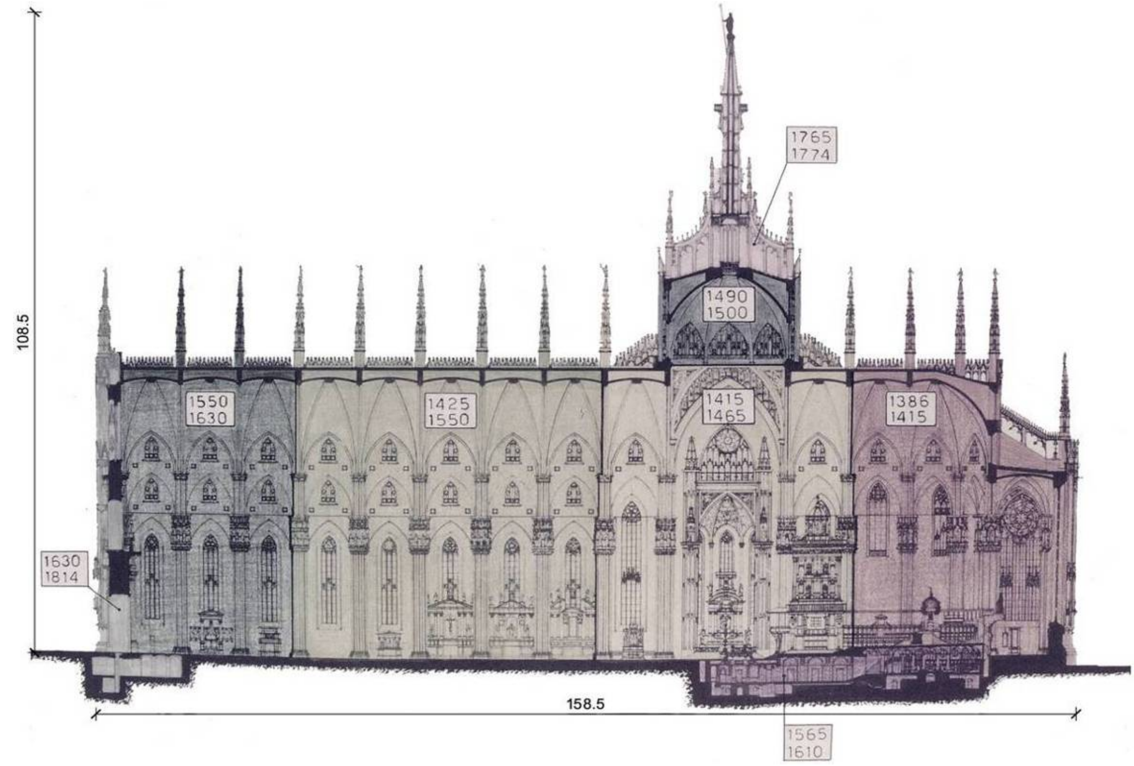
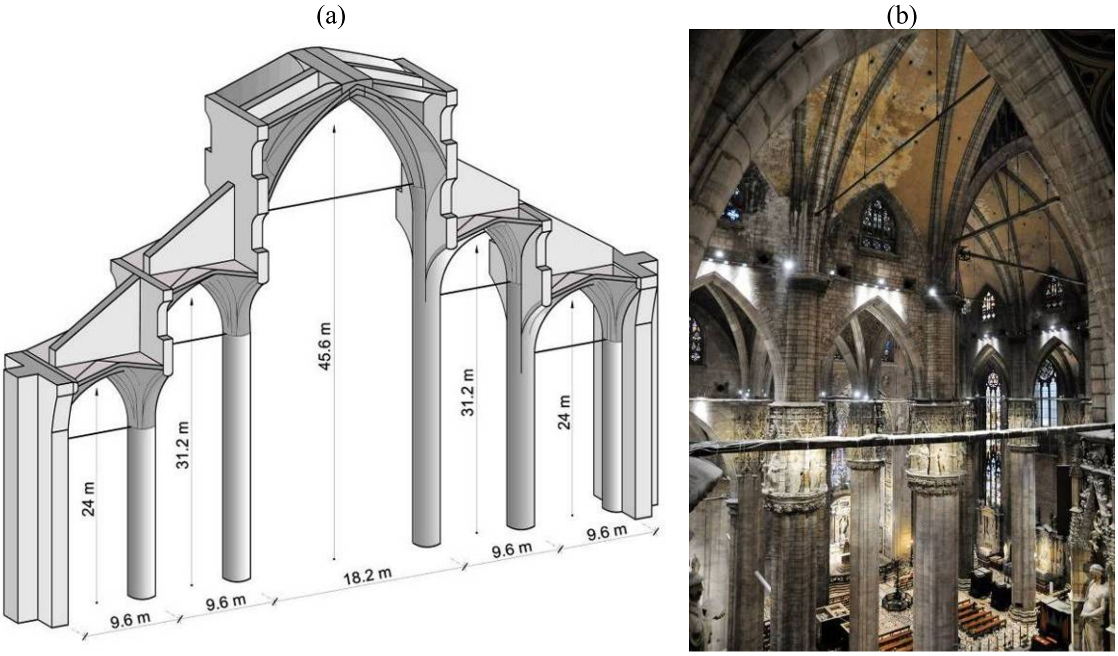


Figure 2: Views of the Milan Cathedral (courtesy of *Veneranda Fabbrica del Duomo di Milano*)


(a)

(b)

Figure 3: (a) Schematic of the structural arrangement exemplified on one bay of the Milan Cathedral; (b) Inside view of arches, vaults and iron tie-rods

The church construction started in 1386 from the half-octagonal apse and East choir, and proceeded with the transept, the main dome, the *tiburio* (i.e., the prismatic structure with octagonal base, which is built around the main dome); subsequently, the five-nave structure over eight bays was built, whereas the main spire and the neo-Gothic façade dates back to 1774 and 1814, respectively.

The structural arrangement of the main limb is exemplified in Fig. 3a, illustrating the distinctive elements of the structural schematic, such as double masonry vaults (i.e., cross vaults and barrel vaults) and permanent metallic tie-rods (Fig. 3b) placed under each arch. It is worth mentioning that the adoption of 122 iron tie-rods, still exerting an active role in resisting the lateral thrusts [5], is one of the main characteristics of the Milan Cathedral: the construction Masters decided to connect the capitals of all adjacent piers by means of metallic elements to reduce the thrust on the slender lateral buttresses and in response to the critical comments raised by the French Architect Jean de Mignot [1]. This peculiar structural arrangement is unique in Gothic cathedrals, where wooden or metallic ties were used as provisional elements and removed at the end of the construction.

The Cathedral has a Latin cross shape in plan (Fig. 4a), with the overall dimensions being about 66 m × 158 m; it should be noticed that the longitudinal limb points the East-West direction, whereas the transversal transept is oriented in the North-South direction.

3 DESCRIPTION OF THE MONITORING SYSTEM

The knowledge of the monument, along with targeted documentary research in the archives of the *Fabbrica* and recent experimental tests [5], allowed to identify the sub-structures to be initially involved in the monitoring: (a) the structural elements subjected to past important strengthening interventions, such as the main spire [7] and the 4 piers [3] supporting the *tiburio*; (b) the piers of the apse (as those elements are not stiffened by buttresses in Gothic cathedrals); (c) selected piers, which are placed in key areas of the church (i.e., transepts, main naves and façade) and (d) selected tie-rods, exhibiting tensile stress of the order of 100 MPa or higher [5].

Since the monitoring system includes a relatively high number of different sensors and the sensing devices are widespread over a large area, a distributed sensor network was implemented to minimize wiring inside the church, with the network being fully computer based and allowing on-site data acquisition and real-time data transfer to remote site. In short, the sensor network inside the Milan Cathedral [6] includes: (a) 12 bi-axial tilt-meters on the capital of selected piers, each with integrated temperature sensor; (b) 12 extensometers on selected tie-rods; (c) 12 hygrometers inside the church; (d) 27 seismometers. Furthermore, one weather station, 3 bi-axial tilt-meters (with integrated temperature sensors) and 9 seismometers are installed in the main spire [6].

Data acquisition (and data analysis) is continuous, even if different sampling rates are adopted for quasi-static and dynamic time series: strains, rotations and environmental data are collected at a rate of two samples per hour, whereas the dynamic monitoring is performed at a sampling frequency of 100 Hz.

A complete description of the static and dynamic monitoring systems can be found in [6], whereas only a brief overview of the static monitoring devices is herein presented. A schematic of the extensometers and tilt-meters installed in the Cathedral is shown in Fig. 4.

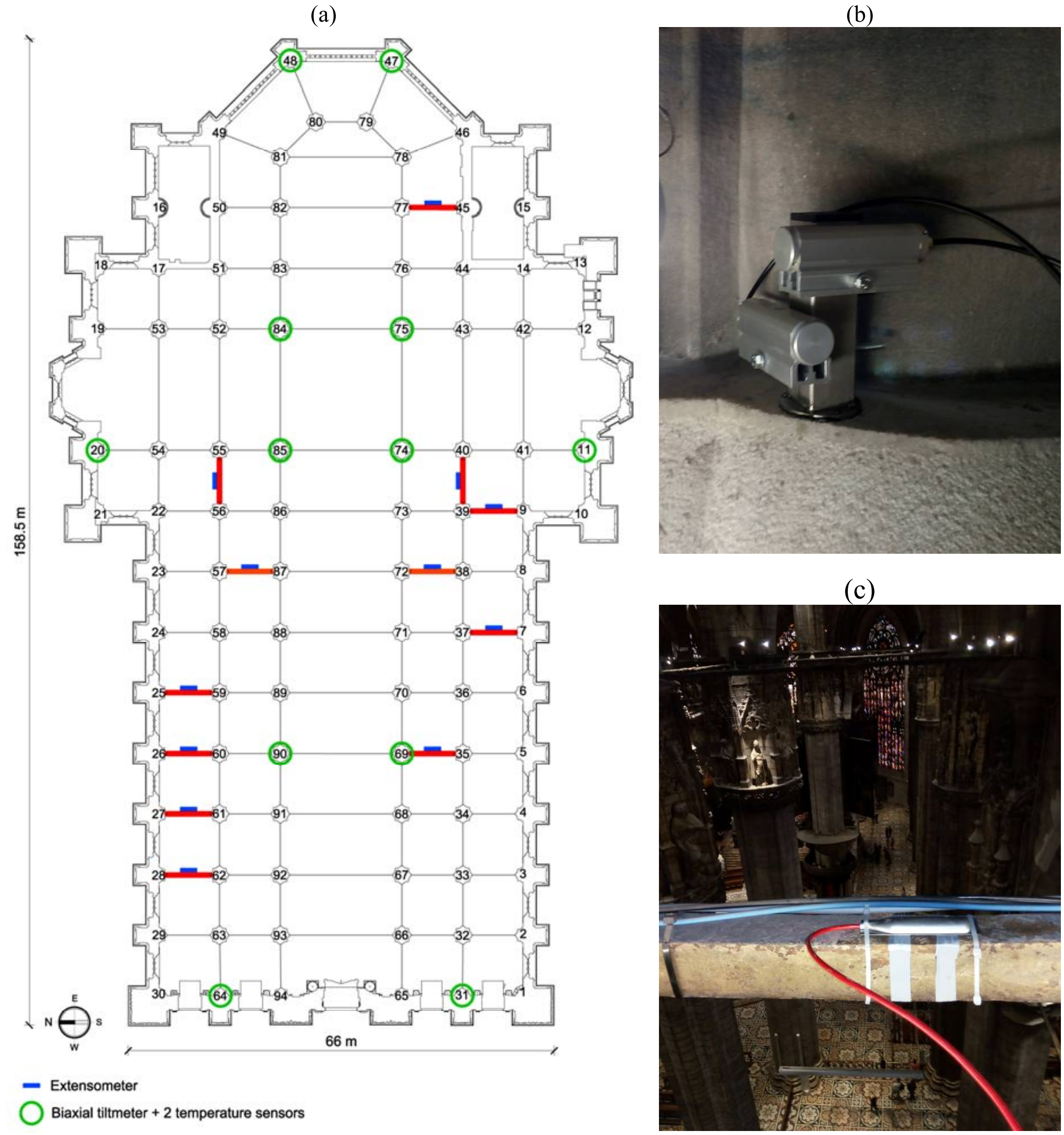


Figure 4: (a) General layout of the static monitoring system installed in the Cathedral (dimensions in m); (b) Bi-axial tilt meter mounted on one capital; (c) Extensometer installed on one tie-rod

In more details: (a) the bi-axial tilt-meters (Fig. 4b, measurement range of ±0.5° and resolution of ±0.5 mm/m) are placed on the capital of piers 31 and 64 (façade), 69 and 90, 11 and 20 (transept), 74-75 and 84-85 (*tiburio*), and 47-48 (apse); (b) the vibrating wire extensometers (Fig. 4c, measurement range of ±3000 με and resolution of 1 με) measure the axial strain of metallic tie-rods with high tensile stress (marked in red in Fig. 4a) or affected by slight damage (marked in orange in Fig. 4a) [5].

As previously pointed out, the indoor and outdoor environmental conditions are extensively measured also to evaluate the risks for the conservation of the main artifacts present in the church [8] and not only for establishing correlations with the structural parameters changes. The indoor and outdoor temperature sensors, with temperature range being between –20 °C and +60 °C and resolution of 0.2 °C, are integrated with each tilt-meter (Fig. 4a); the hygrometers, with measurement range 0-100% and resolution of 1%, are mounted in the neighborhood of the extensometers.

The data transfer of the static devices inside the Cathedral is wireless and each sensor is wired to high capacity batteries, which are placed in walkways over the vaults, quite easy to access for maintenance and substitution. Static and environmental sensors are grouped together (with the number of the sensors in each group being dependent on the relative distances) and are managed by local nodes. The data collected by neighboring nodes are transmitted to routers and those routers, in turn, transmit the information to a local workstation managed by the *Fabbrica* technical staff. The local workstation is equipped with appropriate software codes aimed at the remote management of the different devices, the transformation of raw data and the storage in digital archives. Furthermore, through the Internet, the data might be post-processed by authorized users (such as Politecnico di Milano) and results come back to the *Fabbrica* workstation for being included in digital archives. Typical post-processing includes the removal of environmental effects, which will be exemplified in the forthcoming sections.

4 SELECTED RESULTS FROM THE CONTINUOUS STATIC MONITORING

The static monitoring of the Milan Cathedral is fully active since October 19th, 2018. This section summarizes selected results from the static monitoring over the first year of monitoring (from 19/10/2018 to 18/10/2019) and, for the sake of consistency, only the experimental results collected in the Cathedral are presented and discussed (with no comments being provided on the data measured on the main spire).

As usual for masonry buildings, the evolution in time of environmental parameters is firstly presented in order to understand the effects of changing environment on the variations observed in the quasi-static measurements (strain of the tie-rods and tilt of the columns).

4.1 Environmental parameters

As previously pointed out, a quite extended grid of temperature sensors and hygrometers has been installed inside the church, with the objective of supporting both the SHM program and the preservation of statues, paintings and decorative elements, which are kept inside the monument. The variation in time of the average indoor temperature and the outdoor temperature (measured by the weather station) is shown in Fig. 5a, whereas Fig. 5b refers to the average indoor humidity.

The orange line in Fig. 5a presents the evolution of the outdoor temperature and highlights changes between −1.7°C and +35.4°C, with remarkable daily variations in sunny days. The corresponding variation of the average indoor temperature is represented by the red line in Fig. 5a and ranges between +8.8°C and +30.6°C: it is further noticed that the availability of a large number of temperature sensors in the church allows to verify [6] a low temperature gradient in space, with the difference between the extreme values not exceeding 0.5°C.

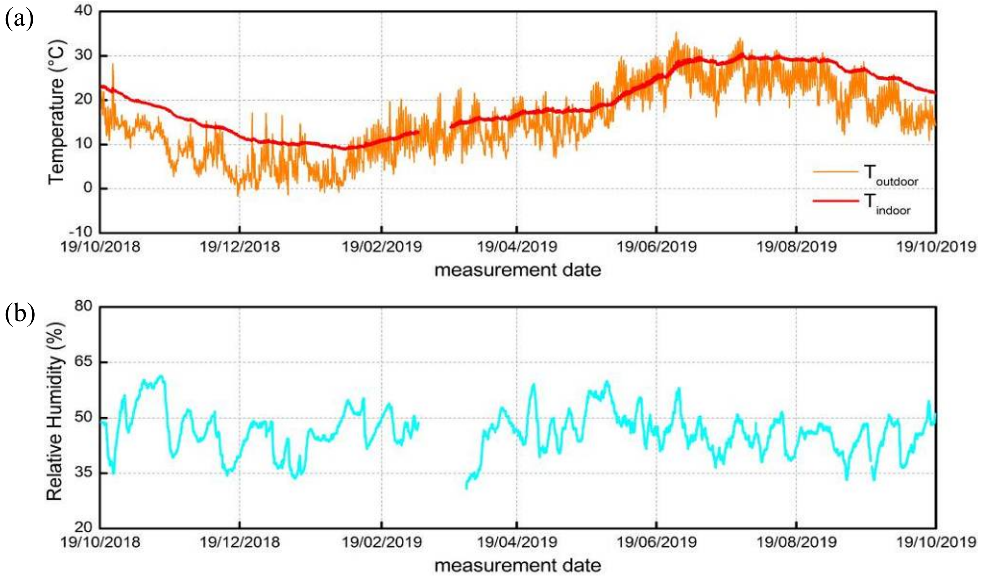


Figure 5: Evolution in time of: (a) average indoor temperature and outdoor temperature; (b) average indoor relative humidity.

Consequently, the low temperature gradient and the correlation coefficients (always larger than 0.99) between the measured temperatures allow to assume the average indoor temperature (Fig. 5a) as a representative quantity for the SHM correlations. A similar conclusion is drawn for the relative humidity, whose time series are highly correlated [6], [8] and exhibit correlation coefficients of the order of 0.90 or larger.

4.2 Static behavior and environmental effects

The time series of measured strain on tie-rods 28-62, 39-09 and 39-40 are plotted in Figs. 6a, 7a and 8a, with a sampling time of 60 min. It should be observed that, although the tension bars 28-62, 39-09 and 39-40are located in the north and south side aisle of the limb (Fig. 4a), the strain variation trend is very similar. The inspection of Figs. 6a, 7a and 8a shows that: (a) the tensile strain increases in winter and the maximum increment is attained on all tie-rods on February 2019, in correspondence with the minimum values of both outdoor and indoor temperature; (b) the strain condition at the beginning of the monitoring (i.e., zero strain increase) is recovered almost simultaneously in all instrumented ties at the end of June 2019 and approximately at the end of the first year of monitoring (Figs. 6a, 7a and 8a).

Figures 6b, 7b and 8b reveals a high correlation between measured strains and (average) indoor temperature, with the coefficient of determination R^2 being larger than 0.90 for tie-rods 28-62 and 39-09. Trends and correlation values similar to the ones exemplified in Figs. 6-8 are observed for all instrumented tie-rods, whose long-tem behavior is significantly affected by the indoor temperature. Furthermore, the strain-temperature plots (Figs. 6b, 7b and 8b) highlight a fairly regular trend with slight deviation of the regression line from linearity. Concerning this aspect, it is worth mentioning that the outdoor temperature also affects the strain variation, whereas almost negligible effects are due to the (average) relative humidity. In addition, the observed non-linear correlations might depend on delayed temperature-induced effects, caused by thermal inertia of the massive masonry church.

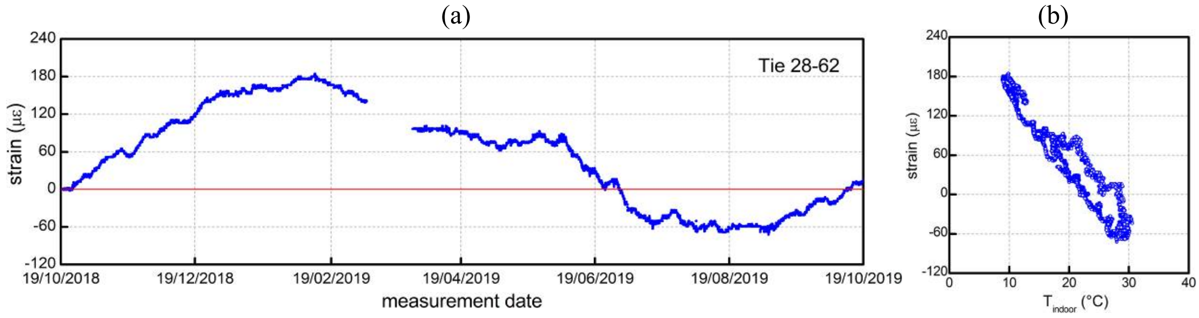


Figure 6: Tie-rod 28-62: (a) Evolution in time of measured strain; (b) Strain vs. indoor temperature.

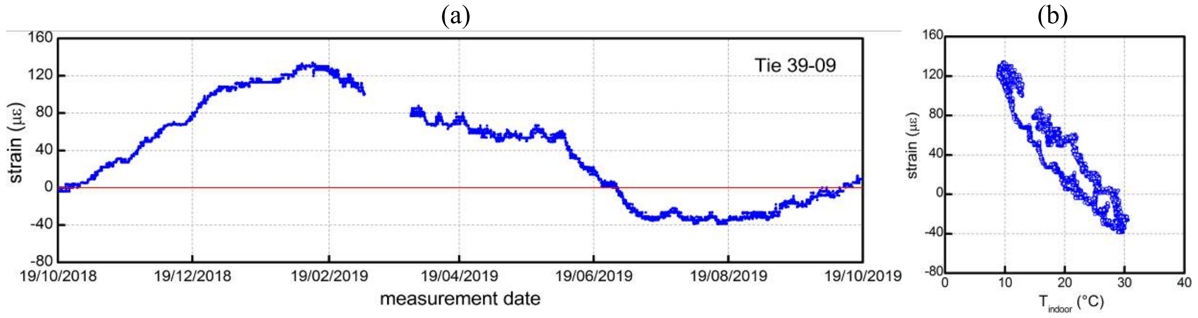


Figure 7: Tie-rod 39-09: (a) Evolution in time of measured strain; (b) Strain vs. indoor temperature.

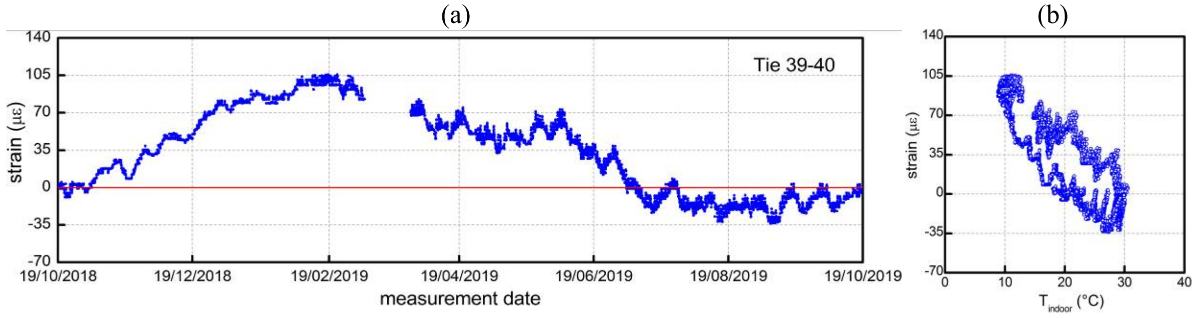


Figure 8: Tie-rod 39-40: (a) Evolution in time of measured strain; (b) Strain vs. indoor temperature.

Deeper investigation of the correlation between indoor/outdoor temperature and strain variations reveals that the currently measured strains exhibit: (a) high correlation coefficients with the indoor temperature measured in the preceding days (until 2-3 weeks before); (b) a remarkable dependence on the outdoor temperature measured in the preceding 12-24 hours.

The effects of environmental changes can be removed from measured strains (or from any other measured quantity) using statistical techniques [9-11]. Among these techniques, multiple linear regressive (MLR) models are often adopted, where linear correlations between a dependent variable (i.e., the strain) and a set of *p* independent variables (i.e, the indoor and outdoor temperatures) are exploited. The above observation on the effects of delayed temperature suggests the use of a "dynamic" model [10-11], involving the use of past observations to re-construct the independent variables (rather than a "static" model, where dependent and independent quantities are sampled at current time).

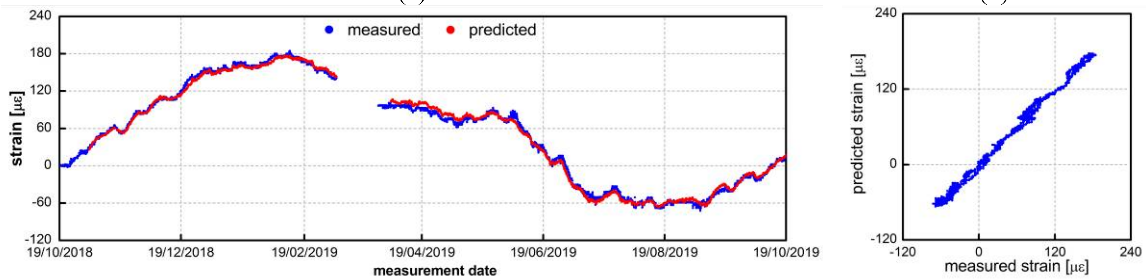

(a) (b)

Figure 9: Tie-rod 28-62: (a) Statistical reconstruction of the measured strain; (b) Correlation between measured and predicted strain.

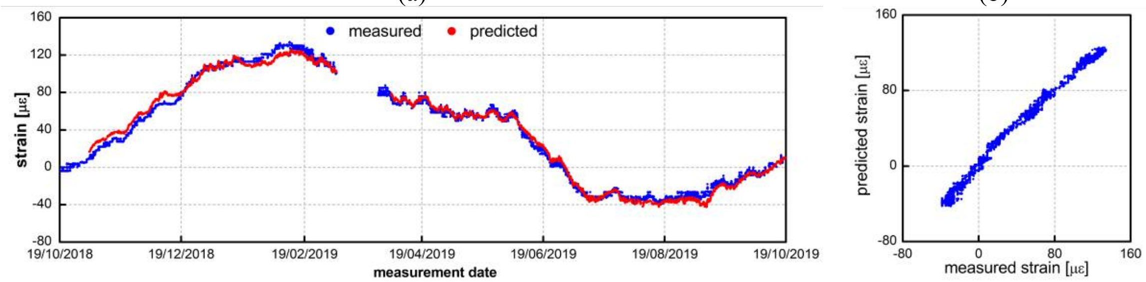

(a) (b)

Figure 10: Tie-rod 39-09: (a) Statistical reconstruction of the measured strain; (b) Correlation between measured and predicted strain.

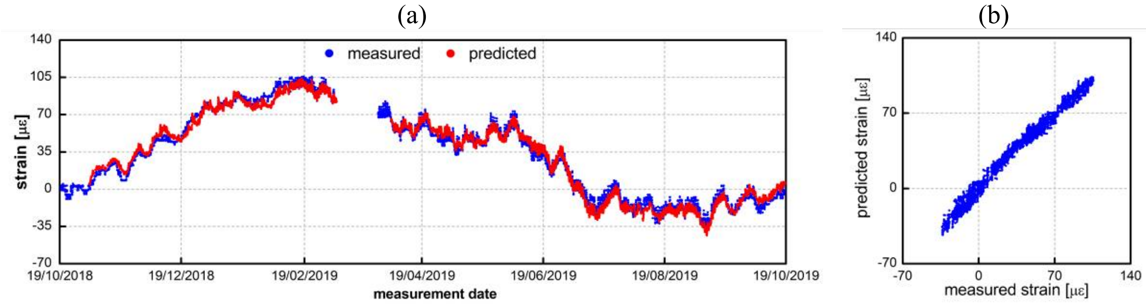

(a) (b)

Figure 11: Tie-rod 39-40: (a) Statistical reconstruction of the measured strain; (b) Correlation between measured and predicted strain.

In the present case, a satisfactory statistical reconstruction of the measured strains (Figs. 9-11) was obtained by using: (a) the current indoor temperature and observations of the preceding 2 weeks, sampled at 36 hours; (b) the current outdoor temperature and a varying number (12-24) of past observations sampled at 1 hours; (c) the current relative humidity.

To exemplify the quality of the dynamic regression predictive models, Figs. 9a, 10a and 11a shows the time series of measured and predicted strains, considering the entire period of monitoring as training period. Furthermore, Figs. 9b, 10b and 11b show the correlation between measured identified and predicted observations. It is worth noting that Figs. 9-11 clearly demonstrate that the adopted statistical technique is capable of re-constructing both daily and long-term variations and, hence, to remove the environmental effects from monitoring data so that damage sensitive features are defined.

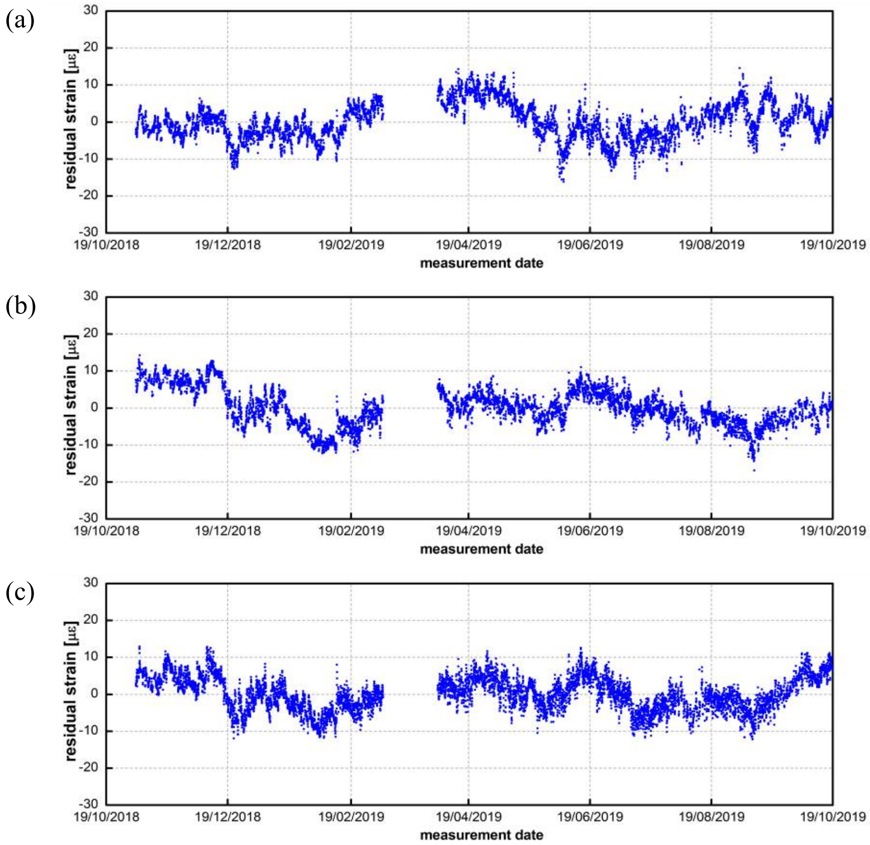


Figure 12: Evolution in time of residual strain in tie-rods: (a) 28-62; (b) 39-09; (c) 39-40.

Figure 12 shows the temporal evolution of the (residual) strains in tie-rods 28-62, 39-09 and 39-40 after the elimination of the environmental effects performed by using the dynamic regression. It can be observed that the variation of the residuals is reduced to a small range: any residual variation exceeding the range established in the training period could imply the occurrence of a potential damage (see e.g. [10]).

The indoor temperature turns out to be the main driver of the changes observed in the piers rotation as well. Fig. 13 shows the evolution of the E-W rotation of selected piers: inspecting the tilt data shows that pier 64 (façade) tends to lean towards east (positive direction) from October to June, whereas all other piers are leaning towards west in the same period, with pier 85 (*tiburio*) exhibiting the maximum tilt. As previously observed for the strain variation in the tie-rods, the rotation cumulated during Winter and Springs tend to be recovered (zero crossing) after mid June.

The correlation between E-W tilt and indoor (average) temperature for piers 64 (façade), 74 (*tiburio*) and 47 (apse) is shown in Figs. 14a-c. The correlation is approximately linear for most piers (Figs. 14a and 14c) but a non-linear correlation between E-W rotation and indoor temperature is observed for pier 74.

Also in the case of strain in tie-rods, the dynamic MLR technique might be adopted for removing the temperature effects from tilt data. It is further noticed that the availability of dynamic data (natural frequencies and mode shapes are automatically identified every hour

[8]) should conceivably be exploited in a data fusion framework for an enhanced program of condition-based structural maintenance.

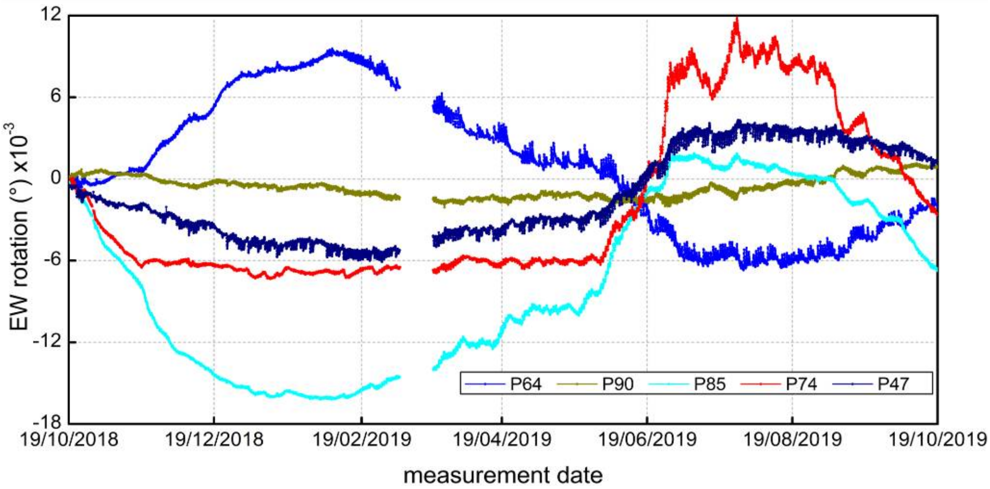


Figure 13: (a) Variation of E-W rotation of selected piers from 19/10/2018 to 18/10/2019.

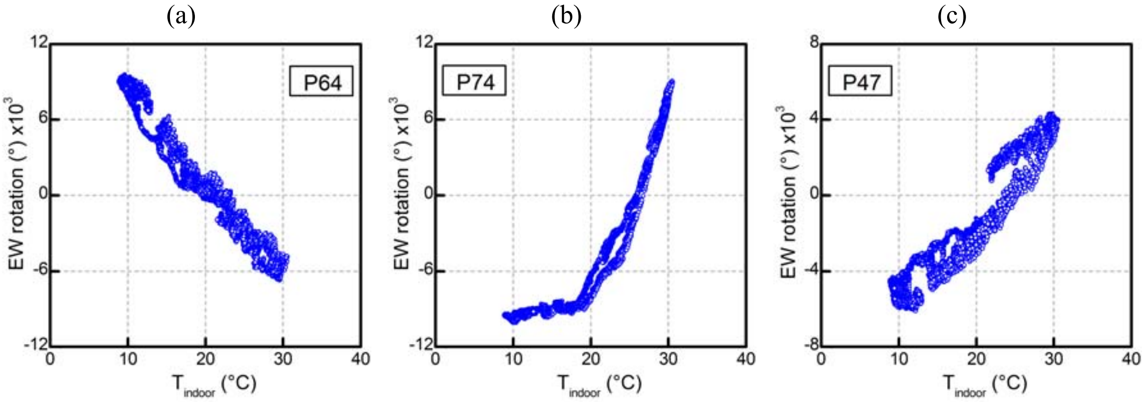


Figure 14: Rotation-temperature correlation for: (a) pier 64 (façade); (b) pier 74 (*tiburio*); (c) pier 47 (apse).

5 CONCLUSIONS

The paper focuses on the description of the monitoring system recently designed and installed in the Milan Cathedral. The monitoring system [6], aimed at enhancing the knowledge and assisting the condition-based structural maintenance of the historic building, includes more than 120 sensors belonging to different classes (i.e., a network of 12 extensometers, 15 bi-axial tilt-meters, 36 seismometers, 30 temperature sensors, 12 hygrometers and 1 weather station) and is fully computer based and characterized by distributed architecture.

Selected results are presented from the first year of the static measurements. Based on those results, the following main conclusions can be drawn:

- The (outdoor and indoor) temperature turned out to be a dominant driver of the variations observed in the quasi-static measurements (strain of the tie-rods and tilt of the columns). The relative humidity seems to slightly affects only the strain variation in the tie-rods;

- The temporal evolution of measured strains and the strain-temperature correlations highlight a fairly regular behavior of the instrumented tie-rods;
- The dynamic multiple linear regression turns out to be an effective tool to remove the environmental effects from measured data and to derive damage sensitive features.

As a final remark, the simultaneous availability of several quasi-static measurements and of the automatically identified modal parameters (resonant frequencies, mode shapes and modal damping ratios) should conceivably provide a data fusion framework for an enhanced SHM program.

Acknowledgements. The support of *Veneranda Fabbrica del Duomo di Milano* and the co-operation of Francesco Canali in the design of the monitoring system is gratefully acknowledged. The authors would like to thank the technical staff of AgisCo and *Veneranda Fabbrica del Duomo di Milano* for the installation of all static monitoring devices.

REFERENCES

[1] *Annali della Fabbrica del Duomo di Milano. Dall'origine fino al presente* (in Italian). Veneranda Fabbrica del Duomo di Milano (1885).

[2] Ferrari da Passano, C. *Storia della Veneranda Fabbrica* (in Italian). Cassa di Risparmio delle Province Lombarde (1973).

[3] Ferrari da Passano, C. *Il Duomo rinato* (in Italian). Veneranda Fabbrica del Duomo di Milano (Diakronia) (1988).

[4] Vicentini, G. *Il pendolo registratore dei movimenti dell'aguglia maggiore del Duomo di Milano* (in Italian). Hoepli (1906).

[5] Gentile, C., Poggi, C., Ruccolo, A. and Vasic, M. Vibration-based assessment of the tensile force in the tie-rods of the Milan Cathedral. *Int. J. Archit. Herit.* (2019) 13(3): 402-415.

[6] Gentile, C., Ruccolo, A. and Canali, F. Long-term monitoring for the condition-based structural maintenance of the Milan Cathedral. *Constr. Build. Mater.* (2019) **228**:117101.

[7] Zacchi, A. *Private communication* (in Italian). Archives of Veneranda Fabbrica del Duomo di Milano (1941).

[8] Aste, N., Adhikari, R.S., Buzzetti, M., Della Torre, S., Del Pero, C., Huerto, H.E. and Leonforte, C.F. Microclimatic monitoring of the Duomo (Milan Cathedral): risks-based analysis for the conservation of its cultural heritage. *Build. Environ.* (2019) **148**: 240-257.

[9] Mason, R.L., Gunst, R.F. and Hess, J.L. Statistical design and analysis of experiments with applications to engineering and science. John Wiley & Sons (2003).

[10] Gentile, C., Guidobaldi, M. and Saisi, A. One-year dynamic monitoring of a historic tower: damage detection under changing environment. *Meccanica* (2016) **51**: 2873-89.

[11] Kita, A., Cavalagli, N. and Ubertini F. Temperature effects on static and dynamic behavior of Consoli Palace in Gubbio, Italy. *Mech. Syst. Signal Pr.* (2019) 120: 180-202.