IL NUOVO CIMENTO Vol. 37 C, N. 4 Luglio-Agosto 2014
DOI 10.1393/ncc/i2014-11806-3

Communications: SIF Congress 2013

Stability monitoring of a historical building by means of cosmic ray tracking

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ricevuto il 31 Gennaio 2014; approvato il 23 Aprile 2014

Summary. — A stability monitoring system based on cosmic ray tracking for applications in the field of civil engineering is presented. The system is applied to the stability monitoring of historical buildings, where conservation constraints are more severe and the time evolution of the deformation phenomena under study may be of the order of months or years. As a significant case study, the stability monitoring of the wooden vaulted roof of the "Palazzo della Loggia" in the town of Brescia, Italy, has been considered. The feasibility as well as the performances and limitations of the muon stability monitoring system have been studied by Monte Carlo simulations.

PACS `06.60.Sx` – Positioning and alignment; manipulating, remote handling.
PACS `07.05.Tp` – Computer modeling and simulation.
PACS `07.07.Df` – Sensors (chemical, optical, electrical, movement, gas, etc.); remote sensing.
PACS `96.50.S-` – Cosmic rays.

1. – Introduction

Cosmic ray radiation at sea level comprises primarily positive and negative muons. The flux is greatest at the zenith and falls approximately as $\cos^2\theta$, where θ is the plane angle from the vertical. The overall muon rate is about $10000\,\mu/(\text{min m}^2)$ for horizontal detectors. The mean muon energy is 3–4 GeV, sufficient to penetrate several meters of rock [1].

Cosmic rays have been utilized since their discovery to investigate the intimate structure of matter and are currently used for particle detector test and calibration [2]. The ubiquitous presence at the Earth surface and the high penetration capability have motivated their use in fields beyond particle physics, to study the composition of large and dense structures [3-9] or for applications in the civil security domain [10, 11]. Recently,

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Fig. 1. – The "Palazzo della Loggia" of the town of Brescia (1574).

cosmic ray muon detection techniques were assessed for measurement applications in civil and industrial engineering, for monitoring alignment and stability of large mechanical and civil structures [12].

In the present work, a stability monitoring system based on the detection of cosmic ray muons is proposed for application to the case of a historical civil building, the "Palazzo della Loggia", seat of the municipal hall in the town of Brescia, Italy. Since the first years after its construction, in 1574, the building suffered from a multitude of structural problems. Recently, from 1990 to 2001, a campaign of measurements has been performed to monitor the stability and progressive deformation of its wooden vaulted roof, completely reconstructed in 1914, by means of a mechanical monitoring system based on the elongation of metallic wires [13, 14].

The possible application of the method of muon stability monitoring to the case of the wooden vaulted roof of the "Palazzo della Loggia" is studied in detail by means of a Monte Carlo simulation. The performances of the proposed measurement system are compared with the performances of the mechanical method actually adopted.

2. – Monitoring system of static anomalies of the wooden vaulted roof of the "Palazzo della Loggia"

Since its completion in 1574, the "Palazzo della Loggia" has cumulated a long sequence of injuries, transformations, repairing interventions, some of which have generated considerable problems of structural stability of the building. The grandiose wooden vaulted roof was completely reconstructed in 1914, with the same architectural shape and construction techniques of the original one, destroyed by a fire one year after the completion of the building. The shape of the dome is like an upside down ship, which reaches in elevation a maximum of 16 m, having the planar rectangular sides of about 25 and 50 m respectively. The structural architecture of the vault consists of principal truss wooden arches and simple secondary arches, both connected at the top by a truss made wooden beam.

Immediately after its construction, the present wooden vaulted roof structure exhibited a progressive deformation of the longitudinal top beam and of the key points of the connected arches. The progressive deflection of the top beam was measured to be 190 mm in 1923, 520 mm in 1945, 800 mm in 1980 and is visible on the top of the roof in fig. 1. Starting from 1990, a systematic campaign of investigation and monitoring of the

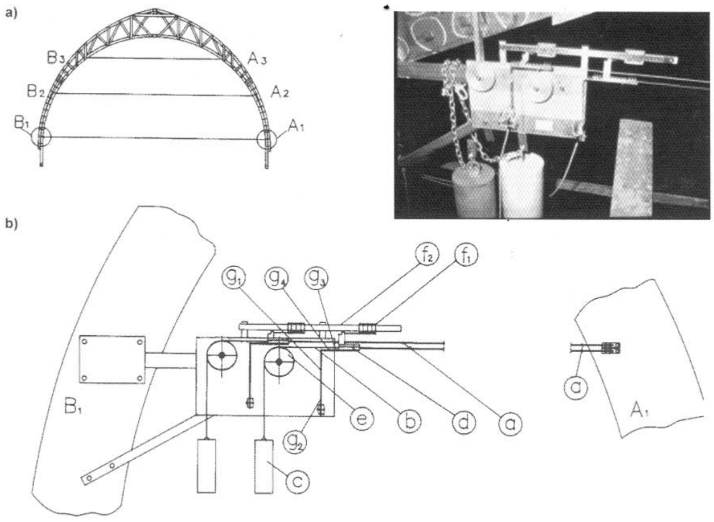

Fig. 2. – Monitoring system of the wooden vaulted roof of the“Palazzo della Loggia”: representation of the stretched wires and details of the measurement system [13, 14].

different stability problems of the Palace has been committed by the Brescia municipality to the *“Centro di studio e ricerca per la conservazione e il recupero dei beni architettonici e ambientali dell'Università di Brescia”* [13, 14]. In particular, the progressive deformations of the principal arches of the wooden vault have been studied with a specifically designed measurement system, some details of which are shown in fig. 2.

On four out of the seven principal truss wooden arches, three couples of wires 2 mm in diameter, one made of ordinary steel and the other made of invar, were stretched between symmetric points at three different levels: A1-B1, at the point of connection of the arches with the building structure, A2-B2 and A3-B3 on the arch reins. The wire tension was maintained by means of a system of pulleys and balance weights, as shown in fig. 2.

The relative displacements of the symmetric points were continuously monitored through the differential elongation of the two wires; the different thermal dilatation coefficients of the two materials made possible to depurate the deformation of the monitoring system itself, subject to the considerable daily and seasonal thermal variations under the roof covered by lead plates. The elongation of the two wires was measured by an electronic system based on clip-gages, with a sensitivity of 1/100 mm, and recorded every six hours. Besides the electronic system, a mechanical measurement system was also employed based on a vernier with a sensitivity of 1/10 mm, as a check of reliability of the electronic system and recovery for possible failures.

In fig. 3 the elongation of the ordinary steel wire (1), of the invar wire (2) and the effective deformation of the structure depurated by the thermal elongation of the wires (3) are shown as a function of the monitoring time in days, for the couple of wires connecting the arch reins at middle height (points A2-B2). The effective deformation is practically coincident with the elongation of the invar wire. The general trend (4) shows a progressive collapse of the wooden structure of the arch of about 1 mm per year.

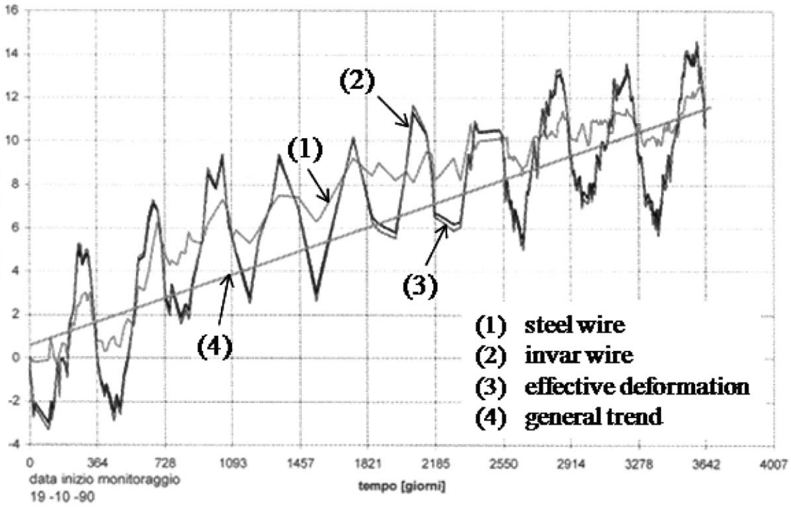

Fig. 3. – Seasonal relative displacements of the points A2-B2 (middle height) measured for eleven years from 1990 to 2001 [14].

3. – Application of the muon stability monitoring system to the case of "Palazzo della Loggia"

The main component of the proposed monitoring system is the "muon telescope", shown schematically in fig. 4(a). It is constituted of a set of three muon detector modules supported by an appropriate mechanical structure and axially aligned at distance of 50 cm one from the other. Each module is composed by two orthogonal layers of 120 scintillating optical fibers with 3 mm × 3 mm cross section and 400 mm length, as shown in fig. 4(b).

The two planes of orthogonal scintillating fibers provide the measurement of the crossing position of an incident muon in the x and y coordinates, with a pitch of 3 mm. Considering a flat detection efficiency over the entire surface of the scintillating fiber, the expected spatial resolution on the hit coordinate is about 0.9 mm.

The "muon telescope" is mechanically fixed to a structural element of the building, that constitutes the reference system, with its axis aligned in the direction corresponding to the part of the structure whose displacements should be monitored: points B1, B2 or B3 of the wooden arches in the case considered. A fourth muon detector module, with the same geometry and structure of the previous ones, is positioned as "muon target" on the point to be monitored.

Thanks to their high penetrability, cosmic ray muons are able to cross the system of four detectors as well as the interposed building structures and make possible to continuously monitor the horizontal relative displacements of the "muon target" relative to the "muon telescope" fixed on the masonry structure of the building.

Indeed, the trajectory of a cosmic ray muon crossing the system of four detectors can be extrapolated from the "muon telescope" to the plane of the "muon target" detector, in the hypothesis that it is a perfect straight line. The difference between the muon crossing point on the "muon target" and the extrapolated one from the "muon telescope" allows the position of the "muon target" relative to the "muon telescope" to be measured. Possible displacements of the position of the "muon target" relative to a reference position previously determined can be inferred.

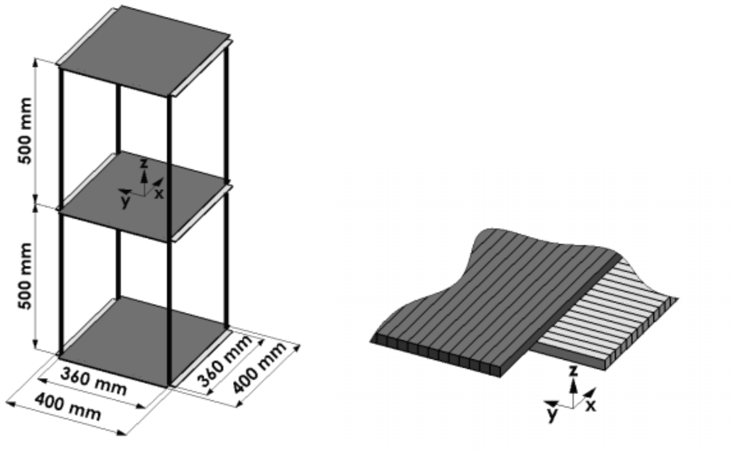

Fig. 4. – (a) Structure of the "muon telescope" formed by three muon detector modules axially aligned at a distance of 50 cm to each other. (b) Sensitive volume of the muon detector module formed by two orthogonal layers of 120 scintillating fibers 3 mm × 3 mm cross section and 400 mm length.

In crossing the interposed materials, the trajectories of cosmic ray muons suffer multiple scattering angular deviations. At fixed momentum and at low deviation angles, these deviations follow a Gaussian law with variance depending on the inverse square of the muon momentum [15, 16]. Being these stochastic effects largely dominant over intrinsic detector resolution, statistical distributions of the difference between measured crossing coordinates in the "muon target" and the predicted crossing coordinates determined by extrapolation from the "muon telescope" are therefore necessary, in order to reduce the stochastic effects by statistical inference methods. As shown in [12], efficient unbiased estimators of the systematic displacement can be extracted from these distributions.

4. – Simulation of the muon stability monitoring system in the "Palazzo della Loggia"

The features and expected performances of the proposed measurement system were studied by Monte Carlo simulations using the GEANT4 package [17], a C++ toolkit for the simulation of the passage of particles through matter largely utilized in the design of nuclear and particle physics experiments. A cosmic ray muon generator based on experimental data was implemented in the code in order to simulate as realistically as possible the momentum, the angular distribution and the charge composition of the cosmic ray radiation at the sea level [18].

In order to study the performances of the proposed monitoring system, the structure and composing materials of the "muon telescope" and "muon target" were modeled as well as the relevant structures of the "Palazzo della Loggia" building.

Three configurations were considered: the first with the "muon target" in position B1 of fig. 2, located 0.50 m above the wooden ceiling of the "Salone Vanvitelliano", at the first floor of the Palace; the second with the "muon target" in position B2, located 5.8 m above the wooden ceiling; the third with the "muon target" in position B3, located

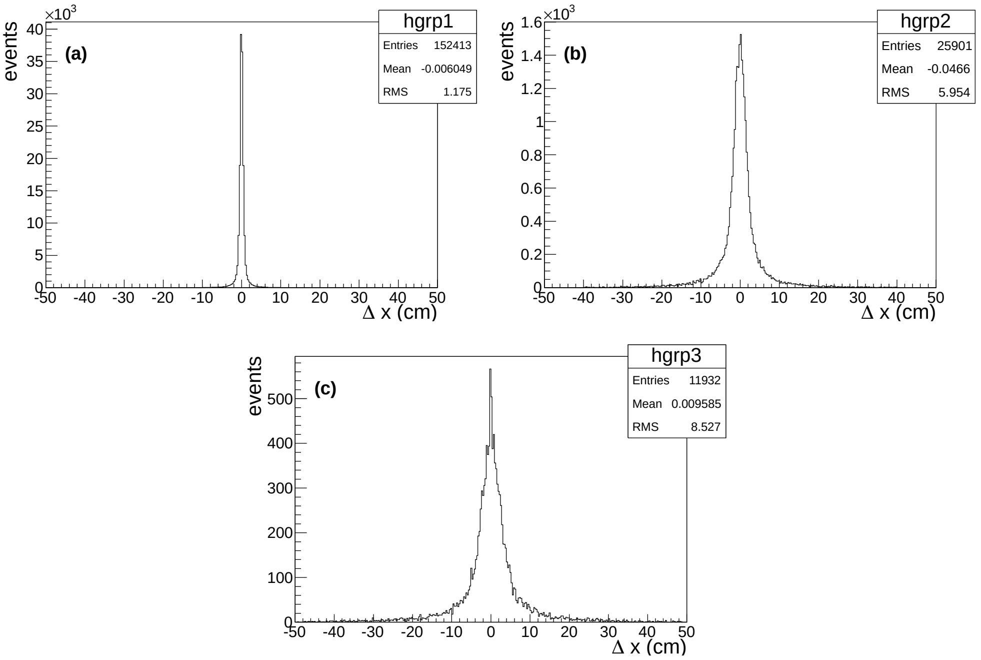

Fig. 5. – Distributions of the differences Δx between the crossing point coordinates measured on the "muon target" in position B1 (a), B2 (b) and B3 (c), and the crossing point coordinates of the extrapolated muon trajectory measured by the "muon telescope", in 15 days data-taking time.

10.0 m above the wooden ceiling. In the tree different conditions, the "muon telescope" was located on the vertical of the corresponding "muon target", 3.0 m below the wooden ceiling. The ceiling of the large "Salone Vanvitelliano" was modeled as a bulky 15.0 cm thick wooden layer.

4·1. *Position measurement uncertainty of the stability monitoring system versus data taking time.* – Simulation campaigns of populations of cosmic ray muons crossing the measurement system were performed for the three configurations described above. The distributions of the differences Δx and Δy between the crossing point coordinates measured by the "muon target" and the crossing point coordinates extrapolated from the "muon telescope" were calculated.

In figs. 5, sample distributions Δx for the three configurations are shown, for an elapsed data taking time of 15 days, corresponding to about $31.7 \cdot 10^6$ cosmic ray muons crossing the "muon target" surface at the rate of $170\,\mu/(\mathrm{s\ m}^2)$ [1]. The number of events in each distribution is coherent with the number of cosmic ray muons entering the geometrical acceptance of the measurement system, which depends on the surfaces of the "muon target" and of the lowest "muon telescope" modules and on their distance. The Δy distributions are not shown, since they are statistically identical to the Δx distributions.

As the "muon target" and the "muon telescope" are exactly coaxial in the simulation, the Δx distributions are symmetric and centered at zero. The shape of the distributions exhibits a central narrow peak with very long tails on both sides. This shape is due both

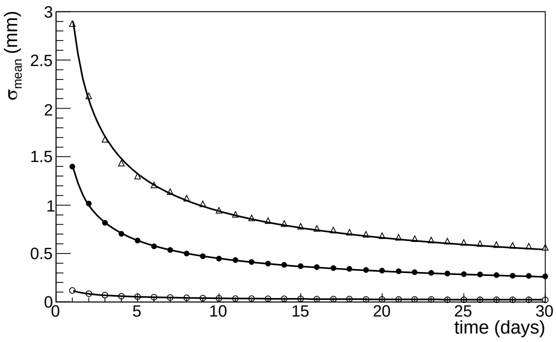

Fig. 6. – Relation between the standard uncertainty on the mean value of the sample distribution and the data-taking time, for the “muon target” in position B1 (○), B2 (●) and B3 (△). Each plot is fitted with the function (2).

to the intrinsic uncertainty of the “muon telescope” in measuring the direction of the cosmic ray muon and to multiple scattering angular deviations of the muon trajectories traversing the interposed materials. The latter effect dominates for large distances of the “muon target” from the “muon telescope”.

The long tails of the distributions are due in part to low momentum muons, suffering larger deviations, and, in part, to spurious events corresponding to emission of delta rays, most of which can be discarded with a more refined data analysis. At present, the only selection applied to these bad quality events is an arbitrary cut of both tails in the three distributions, discarding about 1.0% of the total events.

The mean value of the sample distributions represents an unbiased estimator of the position of the “muon target” relative to the “muon telescope” axis. The root mean square of the sample distribution represents the uncertainty in the measurement of the position of the “muon target” relative to the “muon telescope”.

The uncertainty on the mean value is given by the well-known relation:

$$\sigma_{mean} = \sigma_{distr}/\sqrt{N_{ev}}, \tag{1}$$

where N_{ev} is the number of events in the distribution. Since in the same geometrical conditions the number of events in the sample distribution is proportional to the data taking time, the measurement standard uncertainty depends only on the inverse of the square root of the data taking time. In fig. 6 the relation of the position measurement standard uncertainty and the data taking time for the three examined conditions is plotted up to a data taking time of one month.

As time increases, the measurement standard uncertainty decreases. By fitting the plots with the general relation:

$$\sigma_{mean} = C/\sqrt{t}, \tag{2}$$

where C is a constant depending on the geometry and materials interposed and t is the data taking time expressed in days, the following values for the constant C are obtained in the three conditions considered: $0.12\,\text{mm day}^{1/2}$, $1.42\,\text{mm day}^{1/2}$, $2.96\,\text{mm day}^{1/2}$; the errors from the fit procedure are below 1%.

For example, in one month of data taking in position B3, where "muon target" and "muon telescope" are positioned 13.0 m far apart, a measurement standard uncertainty of the order of 0.5 mm may be achieved. The same value may be achieved in a week of data taking in position B2, whereas a 0.1 mm standard uncertainty may be obtained in just one day in the position B1.

As expected, the standard uncertainty of the measurement system depends on the geometrical configuration considered, since both the root mean square of the distributions and the rate of useful events collected are strongly dependent on the geometry of the system and on the amount of materials interposed. Nevertheless, although requesting different data taking times, the position monitoring of all the three inspected points by a cosmic ray tracking system could provide performances compatible with the requested precisions and with the time scale characteristic of the inspected deformation phenomenon. Typical time scales, in the case of "Palazzo della Loggia" and, in general, for historical buildings, may span over several years. Furthermore, as demonstrated in this case and unlike other monitoring systems, a stability monitoring system based on tracking of cosmic ray muons can efficiently operate also when the building parts whose relative positions must be monitored are not reciprocally visible and are separated by solid masonry structures.

4·2. *Measurement of seasonal deformations of the wooden vaulted roof of the "Palazzo della Loggia"*. – Due to the low cosmic ray rate, a monitoring system based on cosmic ray muon tracking can not provide high precision results in short time. Therefore, it can be competitive with other monitoring techniques only when the deformation under study develops over periods of months or years and the requirements for the monitoring system is to track the slow deformation with time.

This is the case of the cyclic seasonal deformations of the wooden vaulted roof of the "Palazzo della Loggia", which have been simulated with the Monte Carlo program for points B1, B2 and B3 of the roof structure. As a realistic model of the seasonal deformation, the measured displacement in point B2 on the arch reins, reported in fig. 3, was adopted.

In fig. 7 the curve corresponding to the assumed seasonal deformation (the same for the three points) is shown as a continuous line. The results of the simulated measurements of the position of the "muon target", displaced following the assumed structure deformation, are shown; sampling rates of one week, two weeks and one month respectively for points B1, B2 and B3 have been used. It is evident the ability of the proposed measurement system to follow seasonal structural displacements of few millimeters and, even more so, also systematic ones.

5. – Conclusions and prospects

Cosmic ray muon detection techniques for stability monitoring of historical buildings have to deal with the low rate of muon events and with the stochastic nature of the deviations of the muon trajectories due to multiple scattering in crossing materials.

However, due to the very slow evolution of the deformation phenomena that may characterize the behavior of historical building structures, as in the case illustrated in the present work, these constraints do not really constitute a severe limitation for the employment of the proposed method.

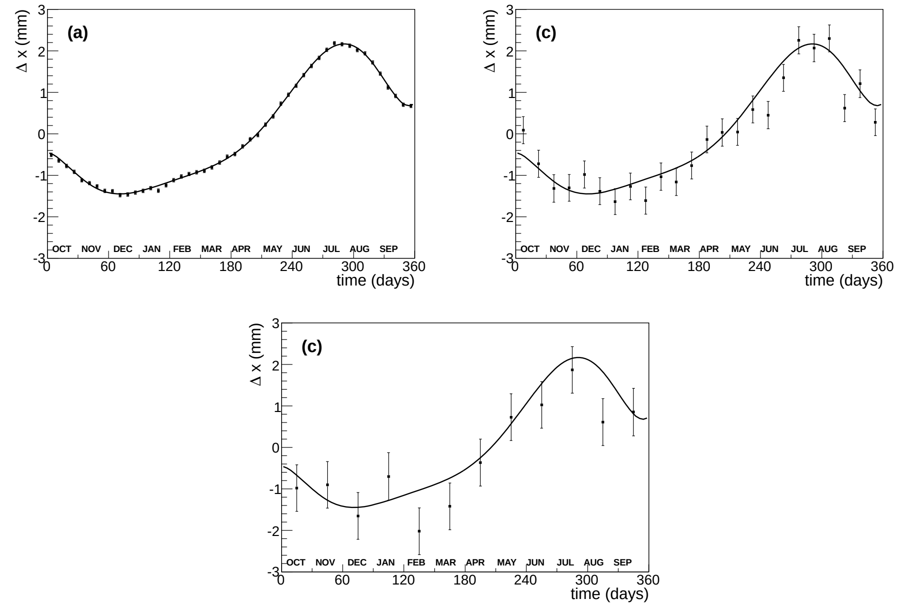

Fig. 7. – Continuous line: Seasonal deformation corresponding to the first year of data taking in fig. 3. Dots with error bars: results of the simulated measurements of the position of the "muon target", displaced following the assumed structure deformation. Sampling rate is one week for position B1 (a), two weeks for position B2 (b) and one month for position B3 (c).

Conversely, the ability of muons to penetrate large thicknesses of material suffering only small deviations of the trajectories offers a new possibility to perform the stability monitoring of parts of the building physically and optically separated from the reference position by solid structures, as walls or floors.

For particular applications these performances may be competitive in respect to the ones of monitoring systems today widely employed as laser scanner and theodolites, which make use of visible light, or as global-position-system–based methods, hardly applicable to monitor with high-resolution internal parts of buildings. In addition, whereas the performances of monitoring techniques based on pendulums, inclinometers and extensometers provide measurements of deformation or strain in specific point positions, a global and simultaneous muon monitoring system may be constituted exploiting compact muon detectors distributed in different positions inside the building.

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This work was supported by a special project of the Department of Mechanical and Industrial Engineering of the Brescia University. The author is grateful to A. Zenoni, G. Bonomi and G. Baronio of the Department of Mechanical and Industrial Engineering of the Brescia University for their help in the preparation of the present work. Special thanks go to Profs. Ezio Giuriani and Alessandra Marini of the Department of Civil, Architectural, Land and Environmental Engineering and Mathematics of the Brescia University for the information provided on the long-lasting study performed on the "Palazzo della Loggia" and for the invaluable advice concerning the problem of historical building monitoring.

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