A Methodology of Analysis for a Critique Interpretation of the Data Acquired from Monitoring Systems of Historical Buildings

Simonetta Baraccani, Tomaso Trombetti, Michele Palermo, Giada Gasparini, Stefano Silvestri, Antoine Dib

A METHODOLOGY OF ANALYSIS FOR A CRITIQUE INTERPRETATION OF THE DATA ACQUIRED FROM MONITORING SYSTEM OF HISTORICAL BUILDINGS

Simonetta Baraccani[1], Tomaso Trombetti [1], Michele Palermo[1], Giada Gasparini[1], Stefano Silvestri[1], Antoine Dib[1]

[1] *DICAM, University of Bologna, 2 viale Risorgimento, 40136 Italy*

simonetta.baraccani2@unibo.it

ABSTRACT

Preserving historical buildings is essential in the safeguard of the cultural heritage of any country. The need to carry out structural analysis with non-destructive methods gave structural monitoring a widespread fame in the world of diagnosis and control of historical buildings. The aim of this study is to introduce a standardized approach for the analysis of the data acquired from a monitoring system of an historical building, through the definition of specific reference quantities (extrapolated from the recorded time series) able to characterize the main features of the structural response and the preliminary identification of the order of magnitudes of these quantities. It is assumed that the recorded time series may be decomposed into two fundamental components: the first one related with the natural actions and characterized, in absence of extreme events, by a substantial periodic behavior, the second one related to the other factors such as the evolution of the state of the structure due to material degradation, soil settlements and others. Exploiting the properties of periodic functions, one may identify these reference quantities, which are based on the year and the day variability and allow to monitor the evolution of the phenomena under observation. These reference quantities may be collected in a database and may become fundamental for comparing the response of similar buildings. This methodology has been applied to the data obtained from the monitoring system of the Cathedral of Modena.

KEYWORDS : *structural health monitoring, data analysis, reference quantities, historic buildings*

INTRODUCTION

In the last recent years, structural monitoring has acquired an increasing importance in the diagnosis and control of buildings, in particular for historical buildings. The main target of a monitoring system is the evaluation of the building “structural health”. The engineering discipline dealing with this topic is called “Structural Health Monitoring” (SHM) [1]. An SHM strategy requires that the building should be monitored in a determined span of time, during which measurements are taken in order to infer the presence of potential structural criticalities and/or incoming damages. Therefore, structural monitoring allows to get a diagnosis of the building through a non-destructive assessment. The SHM involves the installation of several devices that permit to monitor the time evolution of parameters concerning the structural behavior of buildings - like the strain and stress state of structural elements, the development of specific existing cracks, the inclination at specific critical points of the structure …. The obtained data need to be analyzed in order to gather some useful information on the condition of the building under observation. Analyses carried out on these data can have multiple purposes.

The present paper is aimed to introduce a standardized approach for the SHM data analysis with a specific reference to historical buildings. The approach is applied to one important Italian monument: the Cathedral of Modena.

1 APPROACH FOR THE DATA ANALYSIS

From theoretical point of view, it should be straightforward, once the structure is idealized by a mathematical model, to determine the response of a structure under a given, or known, set of actions. However, in most cases, and in particular with reference to historical buildings, the structural behavior, and therefore its idealization (the structural model), may be quite uncertain. In these cases, SHM may provide information on the evolution of the structural response. A simplified standardized approach is presented hereafter for the interpretation of the monitored data.
This approach is aimed to:(i) introduce reference quantities based on the identification of the main physical components characterizing the recorded data, (ii) provide order of magnitudes of these physical quantities.

1.1 The main components of the recorded data

SHM systems return discrete time series which can be generally referred to as $x(t_i)$, where x represents the monitored parameter (e.g. displacement, strain stress, angle inclination, crack width, temperature, …) and t_i represents a specific instant of time t. Each parameter time series can be seen as a function of two main factors:

$$x(t) = f\left[F(t), S(t)\right] \tag{1}$$

F(t) are the (time-dependent) forces acting on the structure, and S(t) represent the time evolution of the "state" of the structure, i.e. the condition of the structure due to its geometrical configuration, the materials mechanical properties, its boundary conditions, etc.

The state of the structure can be stationary or variable with time. The variation of the state may due to different factors such as material degradation, incoming coactive states, soil-structure interaction, etc.

The actions occurred on the building, F(t), can be classified into three main groups:

- Dead loads D(t): the permanent forces acting on a structure such as the self-weight of the structure.
- Live loads L(t): the non-permanent forces acting on the structure. In detail, these loads encompass the forces that depend on the weather effects, which are herein referred to as natural forces, N(t), such as wind, temperature, precipitations, etc.
- Accidental loads A(t): the forces depending on rare events, such as earthquakes, hurricanes, explosions, etc.

Thus:

$$F(t) = D(t) + L(t) + A(t) \tag{2}$$

The state of the structure may be seen as:

$$\mathrm{S}(t) = S(t_0) + \Delta S(t_0, \mathrm{t}) = S_0 + \Delta S(t_0, t) \tag{3}$$

where:

- S_0 is the state of the structure at time t_0, which is assumed as a known value.
- $\Delta S(t_0,t)$ represents the variation of the state over the time. If $\Delta S(t_0,t)=0$ and $S(t)=S(t_0)$, then the state is stationary. On the contrary, if $\Delta S(t_0,t)$ differs from zero, then it clearly indicates a variation in the state.

1.2 The assumptions

If the dead and live loads are within their usual ranges, it is expected that the state of the structure will not substantially change and that the recorded data may be characterized by predominant periodical components due to seasonal and daily temperature excursions.

In the absence of rare events inducing accidental actions, A(t) = 0, and assuming that the live loads are predominately due to the natural forces L(t) = N(t), F(t) can be expressed as the sum of the two components D(t) and N(t). Moreover, assuming that the dead loads may be taken as constant, $D(t) = \overline{D}$, Eq. (2) can be specified as follows:

$$\mathrm{F}(t) = \overline{D} + N(\mathrm{t}) \tag{4}$$

Substituting Eqs. (2), (3) and (4) in Eq. (1) leads to:

$$\mathrm{x}(t) = f\left[\overline{D}, N(t), S_0, \Delta S(t_0, t)\right] \tag{5}$$

The natural forces are assumed to be periodic functions with two fundamental contributions:

$$\mathrm{N}(t) = N_1\left(T_1, t\right) + N_2\left(T_2, t\right) \tag{6}$$

A contribution N_1 with period T_1 equal to 365 days (due to the revolution of the earth around the sun) leading to the annual oscillations and a contribution N_2 with a period T_2 equal to 1 day (relative to the earth rotation around its axis) leading to the daily oscillations. The actions on the structure due to the earth motion of revolution are considered periodic functions with constant amplitude. The actions on the structure due to the Earth rotation are considered periodic functions with variable amplitude depending on the season.

Based on the above considerations, it is assumed that the time series x(t) are formed from two components:

$$\mathrm{x}(t) = x_1\left(t\right) + x_2\left(t\right) \tag{7}$$

$x_1(t)$ is the periodic component of x(t) depending on N(t) and $\overline{D}$ actions; $x_2(t)$ is the component of x(t) depending on the state S(t). The component $x_2(t)$ could have some periodicity which characterization generally requires several years of monitoring.

1.3 Analysis of the data

Based on the assumed functional form of the recorded time series $x(t_i)$, the data analysis is conducted introducing the quantities summarized in Table 1.

With reference to the j_{th} generic day, the quantities of interest are the daily amplitude and the mean daily value. With reference to the j_{th} year, the quantities of interest are the annual amplitude and mean annual value. We are also interested in computing the daily residuals at the j_{th} day of the amplitude ($r_{\delta day,i(k-l)}$) and of the mean value between two consecutive years k and l ($r_{\mu day,,j(k-l)}$). These quantities are useful to obtain information on the evolution of the state S(t). Also, the annual residual of the amplitude ($r_{\delta year,i(k-l)}$) and of the mean value ($r_{\mu year,i(k-l)}$) contribute to the knowledge of the evolution of the state S(t).

As illustrative example, a time series x(t) simulating generic data from a SHM system has been generated and displayed in Figure 1. For the sake of clearness, Figure 2 illustrates some reference quantities: daily amplitude (σ), mean daily value (m), annual amplitude (Σ) and mean annual value (M).

Table 1: The reference quantities for the analysis of the recorded data

Reference quantity	Definition	
Daily Amplitude	$\delta_{day,j} = [max\, x(t_i) - min\, x(t_i)] = \sigma$	$\forall\, t_i \in day\, j$
Mean Daily Value	$\mu_{day,j} = \frac{1}{n_j}\sum_{i=1}^{n_j} x(t_i) = m$	$\forall\, t_i \in day\, j$
Annual Amplitude	$\delta_{year,j} = [max\, x(t_i) - min\, x(t_i)] = \Sigma$	$\forall\, t_i \in year\, j$
Mean Annual Value	$\mu_{year,j} = \frac{1}{n_j}\sum_{i=1}^{n_j} x(t_i) = M$	$\forall\, t_i \in year\, j$
Daily residual on σ	$r_{\delta day,j(k-1)} = \delta_{day,j}\rvert_{year\,k} - \delta_{day,j}\rvert_{year\,l} = r_\sigma$	
Daily residual on m	$r_{\mu day,j(k-1)} = \mu_{day,j}\rvert_{year\,k} - \mu_{day,j}\rvert_{year\,l} = r_m$	
Annual residual on Σ	$r_{\delta year,j(k-1)} = \delta_{year,j}\rvert_{year\,k} - \delta_{year,j}\rvert_{year\,l} = R_\Sigma$	
Annual residual on M	$r_{\mu year,j(k-1)} = \mu_{year,j}\rvert_{year\,k} - \mu_{year,j}\rvert_{year\,l} = R_M$	
Drop	Δ	

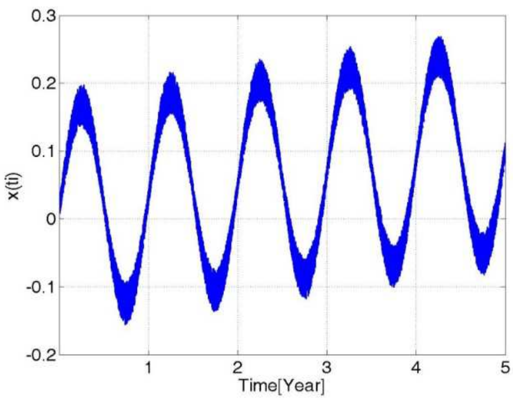
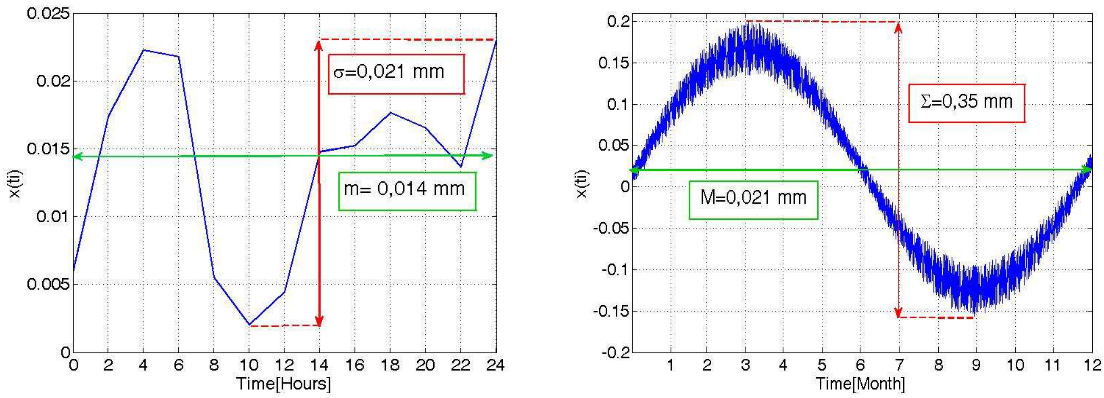


Figure 1:Time series x(t).



a) b)

Figure 2:a) Daily amplitude and mean daily value. b) Annual amplitude and mean annual value.

From the graph of the residual, it is possible to evaluate the trend through linear regression of the data and the histogram of the annual cumulative values curve to extrapolate: (i) linear regression of r_σ and r_m (trend of the residuals), (ii) cumulative of the residuals (stability of the measured event).
In addition to the above described quantities, sudden drops (Δ) may also be present in the recorded time series x(t). These sudden drops may be related either to an instrument malfunctioning, to external factors or to accidental events (earthquakes, hurricanes, …).

The introduction of the reference quantities summarized in Table 1 can be useful in order to collect data in a systematic way and to compare them with those of similar structural buildings. In the following sections, some selected data from SHM related to two important Italian monuments systems are analyzed and preliminary reference values are obtained for the defined quantities.

2 THE CATHEDRAL OF MODENA

The Cathedral of Modena, whose construction began in 1099 through the instrument of architect Lanfranco and finished in 1184, is one of the most important examples of the Romanesque art in Italy (Figure 3). In 1997, it has been declared "UNESCO Cultural Heritage" site. The Cathedral has a basilica plan with three naves culminating in three apses. The cathedral is connected to the contiguous Ghirlandina Tower (a tower of about 86 meters height) through two masonry arches. During the centuries, the monument experienced various interventions and transformations [2, 3]. Recently, a conservation project, which is currently under development, has been planned with the purpose of strengthening the main walls, the vaults and of providing the structure with a box behavior. In the context of this retrofit project, a SHM system was also installed.

Figure 3: The Cathedral of Modena.

2.1 The Monitoring System

The monitoring system allows monitoring the main cracks across the walls and vaults, the relative displacements between the cathedral and the tower, the inclination of the external longitudinal walls, the foundation settlements, the water table level and the temperature. Most of the instruments were installed in 2003, while others (such as the inclinometers) were installed in 2010. Data are acquired at time intervals of 30 minutes. Figure 4 shows the location of the sensors. The symbols indicate: D: deformometer, E: extensimeter, MGB: biaxial joint meter, MGT: triaxial joint meter, FP: inclinometer, T: thermometer.

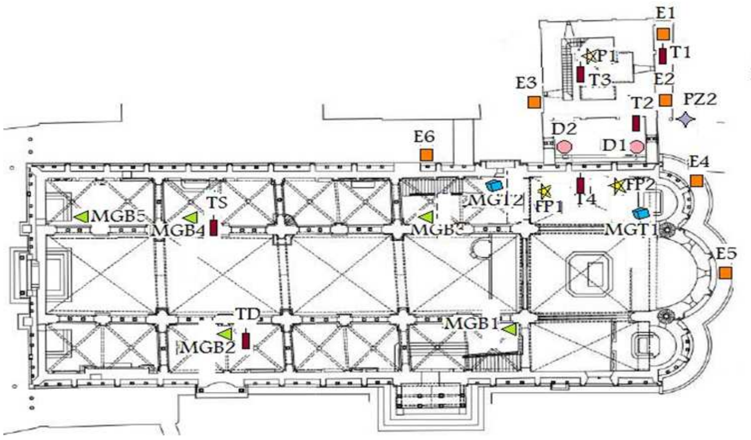


Figure 4: Location of the sensors.

2.2 The data obtained from the SHM

A summary of the reference quantities defined in section 1 is reported in Table 2. Each value refers to a single specific device except for the biaxial joint meter whose value is obtained computing the average of all instruments of that type.

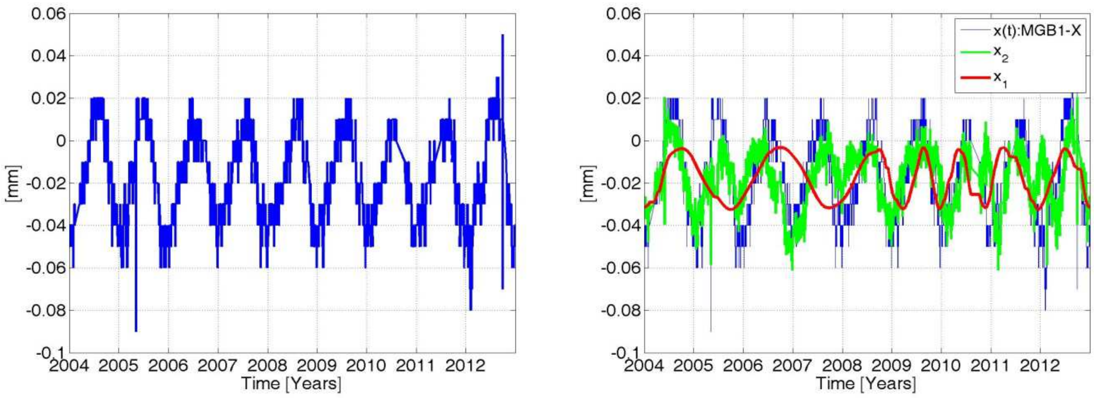
Table 2: Reference values for each kind of instrument

Device			**σ [mm]**	**Σ [mm]**	**r_m [mm]**	**R_M [mm]**
Deformometers			0,02	0,70	0,10	0,30
Exstensimeter	E4		0,16	4,7	-0,25	-1,55
	E5		0,02	1,05	-0,07	-0,04
Biaxial joint meters		Comp.X	0,02	0,35	-0,012	-0,03
		Comp.Y	0,006	0,10	-0,005	-0,01
Triaxial joint meters	MGT1	Comp.X	0,03	0,60	0,02	0,04
		Comp.Y	0,01	0,15	-0,004	-0,006
		Comp.Z	0,01	0,20	0,014	0,020
	MGT2	Comp.X	0,026	0,70	0,034	-0,11
		Comp.Y	0,010	0,50	0,013	0,011
		Comp.Z	0,006	0,22	-0,06	-0,08
Inclinometers	FP1	Comp.X	0,007	1,5	-0,37	-0,70
		Comp.Y	0,008	0,84	-0,50	-1,0
	FP2	Comp.X	0,012	0,90	-0,58	-1,10
		Comp.Y	0,008	0,30	-0,16	-0,31

As illustrative example, a more detailed data analysis following the approach introduced in the previous section is conducted with reference to the biaxial joint meter MGB1 placed on a crack on the south longitudinal wall (Figures 5 to 8).

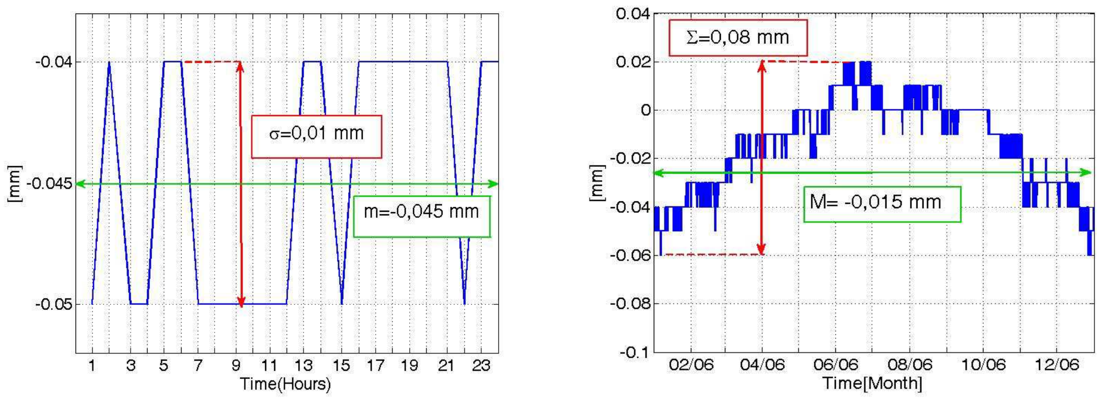
Figure 5a displays the complete time series over years 2004-2012. With the exception of few spikes, this series clearly shows the daily and annual periodicity with an almost constant average value, thus not showing a significant evolution of the state S(t). A more in depth inspection of the time series is provided by the Figure 5b which provides the two main components of the signal x_1 and x_2. For this specific case, the periodic contribution is essentially given by the harmonic with period T_1 = 365 days, whilst the amplitude of the harmonic T_2 = 1 day is order of magnitudes lower. In addition, the signal component x_2 is characterized by a significant periodicity whose fundamental harmonic has a period T of 300 days.

Figure 6a displays the daily amplitude (σ about 1/100 mm) and the mean daily value related to a generic day. Figure 6b represents the annual amplitude (Σ about 1/10 mm) and the mean annual value related to year 2006. Note that the ratio σ/Σ seems to be equal to 1/10.
Figure 7a plots the daily amplitude (σ) and the daily mean value (m) over the entire observation period (9 years). It can be noted that m oscillates around an almost constant value, indicating a stable behavior of the monitored crack (no evolution in time), whilst σ is small and bounded within 0.02 mm, despite isolated spikes. Figure 7b plots the daily residual of the mean daily value r_m. These graphs further confirm that no significant evolution of the state S(t) is observed: the trend regression line is practically horizontal.
Figures 8a and b represents the histograms of the annual residuals R_Σ and R_M, and their cumulative curves. The cumulative curves indicate a quite stable behavior, with compensations along the years (except for year 2012 in R_Σ).



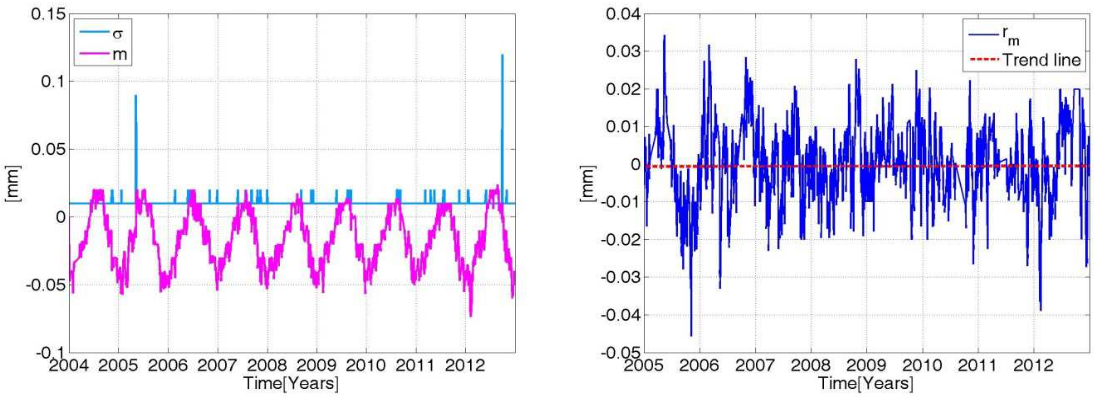
a) b)

Figure 5:a) Overall trend MGB1-X. b) Reconstructed signal with only the harmonics corresponding to T_1=365 day, T_2=1 day, and signal less harmonics corresponding to T_1 and T_2.



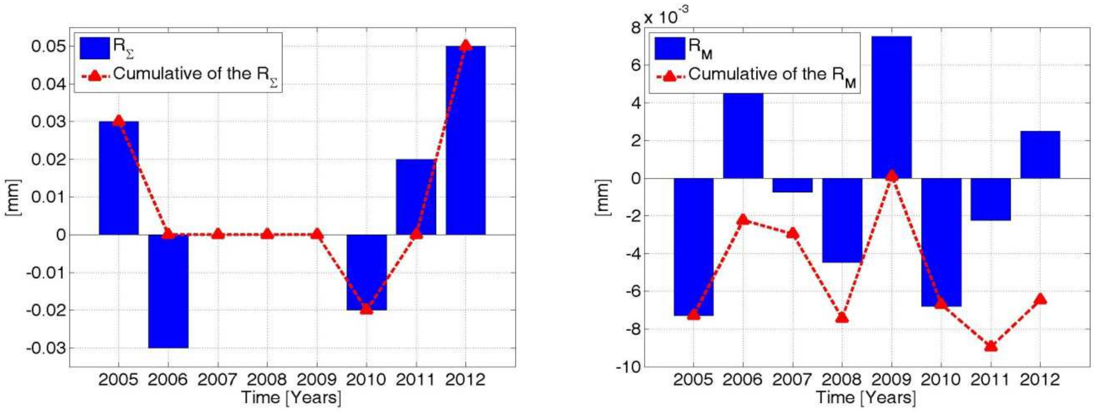
a) b)

Figure 6:a) Daily amplitude and middle value. (b) Annual amplitude and middle value.



a) b)

Figure 7:a) Trend in the year of daily amplitude and middle value. b) Daily residual on m and linear regression line.



a) b)

Figure 8:a) Annual residual on Σ and cumulative curve. b) Annual residual on M, and cumulative curve.

CONCLUSIONS

This paper presents a simple approach for a standardized analysis of the data recorded by a Structural Health Monitoring system installed in an historical building. The main objective is to introduce significant reference quantities from the recorded data in order to detect possible anomalies from the usual structural behavior. This information may be collected in a database and adopted as reference quantities (order of magnitudes) for the analyses of data of similar buildings in order to have reference values leading to a more sound interpretation of the SMH data.

As illustrative example, with reference to masonry displacements, the values of the daily amplitude σ (about 1÷1,3 /100 mm) and the values of the annual amplitude Σ (about 2÷2,2/10 mm) which were detected in the Cathedral of Modena gave us the ratio σ/Σ, which is roughly equal to 1/10.

REFERENCES

[1] H Sohn, C.R. Farrar, F.M. Hemez, D.D. Shunk, D.W. Stinemates, B.R. Nadler, J.J. Czarnecki. A Review of Structural Health Monitoring Literature: 1996–2001. *Los Alamos, NM: Los Alamos National Laboratories,* 2004.

[2] M. Armandi). Lanfranco e Wiligelmo. II Duomo di Modena. 1984

[3] T. Sandonni. Cronaca dei restauri del Duomo di Modena (1897-1925). *Baracchi Giovanardi, O.*, Modena, 1983