Advanced Methodologies and Techniques for Monuments Preservation: the Trajan Arch in Benevento as a Case of Study

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ABSTRACT

An effective assessment of the static and dynamic structural behavior of historical monuments requires the development and validation of suitable adaptive structural models using high quality experimental data acquired with an effective continuous and distributed monitoring. Furthermore, this adaptive strategy allows an effective evaluation of the health status and of the evolution along the time of a historical monument, providing relevant information to plan appropriate actions for its long-term preservation.

The Trajan Arch in Benevento was chosen as a case of study to develop and apply this new adaptive strategy in cultural heritage preservation. The paper, after a description of the innovative monitoring system, based on state-of-the art mechanical sensors, presents and discusses the results of two tests, comparing the measurements with the predictions of an adaptive structural FEM model developed for the dynamical simulation of the Trajan Arch.

Keywords: *monument preservation; monolithic folded pendulum; distributed monitoring system; structural dynamic analysis.*

1 INTRODUCTION

The Trajan Arch in Benevento is one of the most important and well preserved monuments of the roman empire, although along its history of about two thousand years it suffered many damages due to important events, such as earthquakes, wars, and, last but not least, partial reconstructions, and restorations Fig.1. Such important structural changes interested the monument in different periods: most of them on its top section, the Attic, probably already during or just after its construction.

The preservation of the Trajan Arch and its historical value for future generations requires, therefore, a dedicated program of preservation, with conservation actions and safeguarding measures, programmed and optimized along the time [1][2][21]. It is, therefore, very important the acquisition of an effective knowledge of its present health status and of its evolution along the years. This knowledge can be obtained with an optimized design and implementation of a continuous and distributed monitoring of all its important structural elements in connection with a

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careful analysis based on an adaptive structural FEM (Finite Element Method) dynamic model of the arch.

Figure 1- East Facade – Architectural survey. Soprintendenza Archeologica delle Province di Salerno, Avellino e Benevento, 1998.

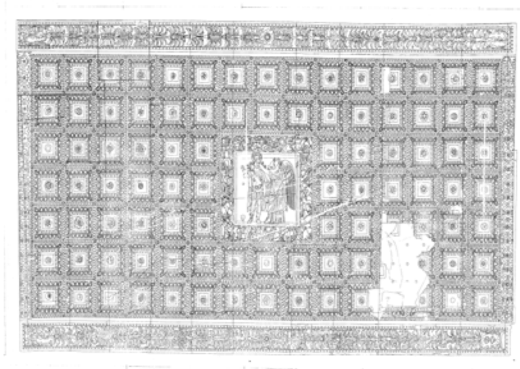


Figure 2 - The Fornice (bottom view) Architectural survey. Soprintendenza Archeologica delle Province di Salerno, Avellino e Benevento, 1998.

This procedure can provide information both on the dynamic and static loads sources (seismic noise, anthropic noise, wind noise, etc.) which affect the monument and on the effects on its sculptures and structural elements, such as to provide reliable description and clarification of the existing damage patterns, like the ones in the Fornice.

2 SEISMIC HISTORY OF BENEVENTO

The Trajan arch rises in an area subjected to a very strong and high seismic events among the most dangerous ones happened along the Apennines. The Apennines are crossed by the Mediterranean fault earthquake which represent the plate boundaries between the African plaque and the Euro-African one. Surely these have affected the territory of Benevento and the structural changes implemented on the arch.

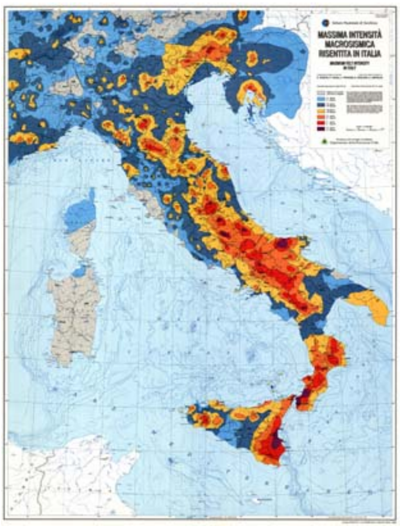


Figure 3 - Map of Maximum Macroseismic intensity observed, the database Macroseismic DBMI11 Italian INGV

The multiple seismic events that have occurred over the years can be defined as the cause of some interventions that were made on the arch and that led to the changes of it. In particular the highest catastrophic events, which have been registered in the last 2000 years, have been characterized by an intensity to the site "Is" greater is equal to 8 are the following:

• *Seismic event 99 AC, in Circello;*

• *Seismic event 375 AC, in Benevento;*

The city was completely destroyed. At that time Benevento was an important cultural and artistic centre. Most of its inhabitants died. All the 15 towers and the important buildings and temples crashed down. So its citizens cared for the rebuilding without any public financing as Simmaco's letter to his father testified.

• *Seismic event 989 AC, in Irpinia;*

The earthquake caused the fall of many buildings in Benevento and 15 towers;

Again some people testify this earthquake as in "Gli Annales Beneventani", Leone Ostiene and "The Chronicon" by Romualdo Salernitano.

• *Seismic event 1456 AC, in Molise;*

This earthquake has affected the city of Benevento, Naples, L'Aquila, just to quote some of the most important cities of South of Italy. But the damages were huge all over this area as written in some of the letters sent by ambassadors living in the Neapolitan court found in the state archives.

• *Seismic event 1688 AC, in Sannio;*

In Benevento 997 buildings over 1607 were totally destroyed; 285 had no damage, 325 had cracks, 1367 people died. Churches were badly damaged such as Santa Sofia's in which the Medioeval adjuncts, the central dome and the Romanesque bell tower collapsed. The only evidence of this have been found in chirographs by Innocenzo XI and Alessandro VIII.

• *Seismic event 1702 AC, in Benevento, Irpinia;*

There were huge damages in the city of Benevento which interested the lower part of the city.

The quakes of the 2nd and of the 6th April caused crashes and cracks at some buildings in the city. 159 people died over 8400. Many new and old buildings crashed, too. The pope sent some technicians to evaluate the damages and to allow extraordinary loans by the city's bishop. All is testified in letters between the vice- governor of Benevento and the secretary of the papal state.

This such of earthquakes, as shown by Petti [19], are characterized by strong directivity effect Petti [20].

3 THE MONITORING SYSTEM

The monitoring system implemented for the Trajan Arch in Benevento is an application of a general adaptive assessment strategy that originates from an innovative monitoring approach based on state-of-the-art broadband high sensitivity mechanical sensors.

This strategy requires the implementation and optimization of a numerical finite element model (FEM) describing the dynamical behaviour of the Trajan Arch on the basis of measurements obtained with an adaptive monitoring system, that acquires data from sensors, whose typology, position and number is defined on the basis of the obtained results [3].

The final goal of this strategy is that of understanding the dynamical behaviour of the Trajan Arch to assess its health status and to foresee its dynamical evolution along the years, necessary for the definition of suitable interventions aimed to its preservation.

For the above quoted reasons, the monitoring system architecture implemented for Trajan Arch is fully modular: the acquisition system is able to integrate sensors, whose number, position, typology (displacement, acceleration, environmental variables like wind speed and direction, temperature, etc.) and characteristics (weights, dimensions, band, sensitivity, etc.) are defined and/or changed on the basis of the experimental results and of the numerical simulations. Furthermore, the data acquisition system ensures wireless connectivity, very low power consumption, fault tolerance and unattended working. For this task, the standard module is based on real-time Compact-RIOs 16 bits DAQ board by National Instruments™, that fully satisfies the above quoted requirements.

The main sensors (displacement and/or acceleration sensors) belong, instead, to the UNISA class of folded pendulum mechanical sensors, an innovative class of broadband high sensitive mechanical sensors developed at the University of Salerno by the Applied Physics Research Group. These sensors, briefly described in the following section, are characterized by large bands, high sensitivities (especially in the low frequency region), dimensions and weights that fully satisfy all the requirements on data accuracy and quality for the Trajan Arch [4][5]. Furthermore, their large band in the low frequency region (a yet unexplored band) allow the possibility to study the effects of many relevant noise sources, that may damage the monument in the long term. Typical examples are the daily and seasonal temperature changes, which may induce relatively large displacements among different sections of the Trajan Arch, or daily anthropic noise (e.g. car traffic).

4 THE UNISA FOLDED PENDULUM

The main element of the monitoring system is a folded pendulum, a mechanical monolithic sensor belonging to the class of broadband high-sensitivity position and/or acceleration sensors based on the Watt's linkage architecture (UNISA Folded Pendulum [4]).

The UNISA Folded pendulum is a mechanical oscillator of remarkable properties, able to resonate at very low frequency, still keeping compact size and weight [4-8]. In fact, taking advantage of the peculiar coupling of the local gravitational acceleration with the folded pendulum mechanics [4] and of the modern machining technologies and techniques (e.g. precision milling ad electro-discharge machining (EDM)), it is possible to design compact, light and stable mechanical oscillators, an effective basis for the implementation of high quality and high sensitivity mechanical seismometers and/or accelerometers, characterized by very low natural resonance frequencies (< 100 mHz), large measurement bands (10^{-7} Hz – 10^{3} Hz) and sensitivities ($<10^{-12}$ m/$Hz^{1/2}$) also in the low frequency region of the seismic spectrum, still keeping light weight (< 200 g), small size (< 10 cm side) and large immunity to environmental noises.

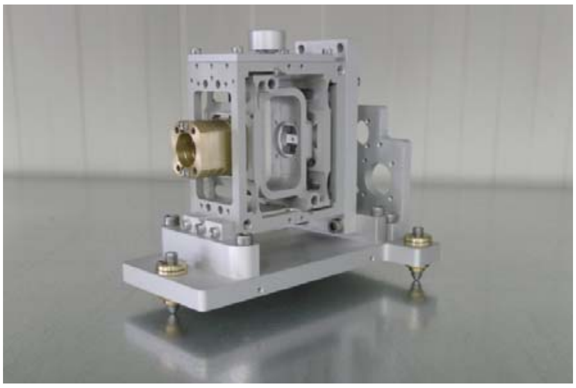


Figure 4 - Uniaxial monolithic UNISA Folded Pendulum (Model GE15).

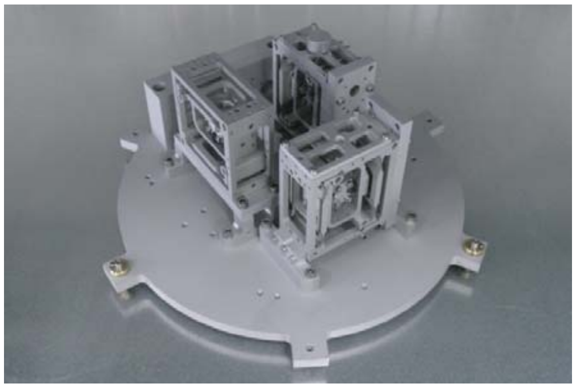


Figure 5 - Triaxial sensor based on monolithic UNISA Folded Pendulum.

Moreover, their mechanical transfer function, and in particular, their natural resonance frequency, can be changed by applying external forces or by introducing calibration masses or suitable external forces, changing, in this way, also their sensitivity curve [4-12].

Fig. 4 shows the mechanics of the Model GE15, a medium size (8 cm side, 0.3 kg weight) UNISA uniaxial monolithic folded pendulum seismometer for low frequency large band measurements used for the test on the Trajan Arch. This sensor is implemented in Ergal (AL7075-T6), anodized for long term environmental applications and designed to host the most common readouts (shadow meters, optical levers, LVDTs, fiber channels, interferometers). Fig. 5. shows, instead, a triaxial sensor obtained with three monolithic UNISA Folded Pendulums (Model GE15) oriented along the three Cartesian axes (x, y, z), allowing the implementation of an effective and stable tridimensional measurement point.

Table 1: UNISA Folded Pendulum Main Characteristics.

Characteristic	Properties
Band	0.1 uHz < B < 1 kHz
Sensitivity	10^{-15} m/Hz$^{1/2}$ < S < 10^{-6} m/Hz$^{1/2}$
Directivity	D > 10^4
Reson. Frequency	50 mHz < f_0 < 1 kHz

Finally, Table 1 synthetizes some of the main characteristics of typical mechanical sensors based on the UNISA Folded Pendulum architecture.

An important advantage of using UNISA folded pendulum monolithic mechanical sensors is that, at least for applications on the Earth surface, their sensitivity and band of this class of sensors are not limited by intrinsic mechanical noises (e.g. thermal noise), but by the noises introduced by the readout and data acquisition system [4]. Therefore, in the case of Trajan Arch the best choice of the mechanics, of the readout and of the data acquisition system is a real compromise among performances, cost, stability along time and, last but not least, power consumption (solar power supply). It is important to underline that the total power consumption of the monitoring system (power consumption of the sensors electronic interfaces, of the acquisition boards, of the local data storage and of the data transmission devices positioned on the Attic) is probably one of the most important constraint for the design and implementation of a reliable and effective monitoring system. To minimize power consumption and to guarantee enough dynamics to the sensor, the readout system is based on commercial LVDTs that still guarantee enough sensitivity (≈ 10^{-9} m/Hz$^{1/2}$. Of course, UNISA mechanical seismometers with better/or worse sensitivities can be designed using different readouts (shadow meters, fiber bundle, LVDT, capacitive, etc.). Just for sake of comparison in Fig. 6 the designed theoretical sensitivity of the UNISA Folded Pendulum sensor with commercial LVDT readout, compared with the typical theoretical sensitivities and bands of UNISA Folded Pendulum sensors equipped with optical lever and interferometric readouts are shown. In the same figure, the sensitivity curves of the STS-2 by Streckeisen [13] and of the Trillium-240 by Nanometrics [14], representing the state-of-the-art of ground-based low frequency seismic sensors, are reported for comparison, together with the Peterson New Low Noise Model (NLNM) [15] and the McNamara and Bouland Noise Model [16], that represents the minimum measured Earth noise evaluated from a collection of seismic data from several sites located around the world: noise levels below this are never - or extremely rarely – observed.

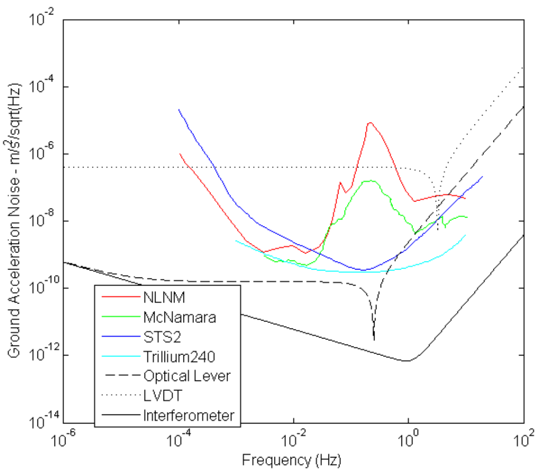


Figure 6 - Sensitivity curves of the UNISA Horizontal Folded Pendulum mechanical sensors, compared with the Peterson Low Noise Model, with the McNamara Noise Model and with two commercial sensors: STS-2 by Streckeisen and Trillium-240 by Nanometrics.

5 THE MEASUREMENTS

Two tests were performed on the top of the Trajan Arch with a limited number of sensors, the first one in July 2015 (few hours) necessary for the definition of the requirements that sensors and monitoring system have to satisfy, the second one in late September 2015 (4 days) performing a simultaneous acquisition of 4 sensors, necessary to understand the optimal placement of the sensors and of the data acquisition system on the Attic. Measurement were performed also at the base of the Arch in order to understand the noise floor level, to correlate the measurements of the sensors on the top of the Arch.

These measurements highlighted the need of an effective and continuous monitoring also of wind speed and direction. In fact, the effect of the wind and car traffic is very relevant for the dynamic behavior of the Trajan Arch. The first test was performed during a windy day in Benevento. Fig. 7 shows the displacement spectral density of three sensors positioned on the top of the Arch (the first two sensors on the Arch center, the third one on the corner) in the band 100 mHz – 100 Hz). It is evident the strong effect of the wind on the whole band, in particular in the central part of the Arch.

The second test was longer (4 days), with very low wind. In Fig. 8 the central transverse measurement point is shown for comparison, but on a larger band (10 mHz – 100 Hz). The sensitivity of the sensor (10^{-9} m/sqrt(Hz) is the one predicted by the theoretical model.

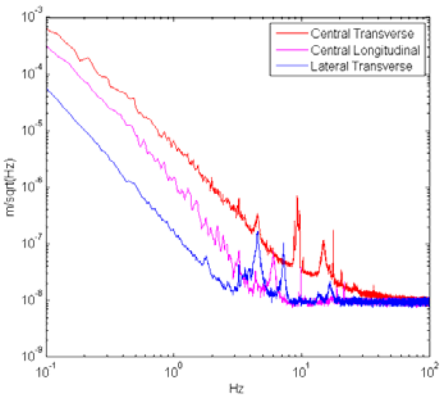


Figure7- Displacement spectral density of selected measurement points on the top of Trajan Arch (I test).

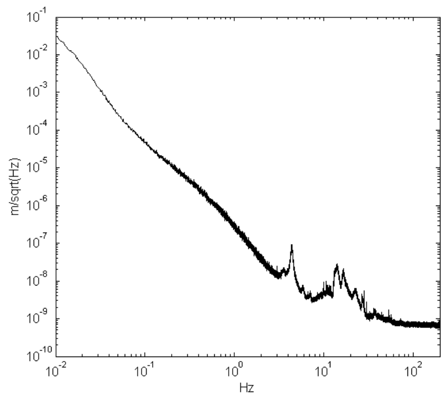


Figure 8- Displacement spectral density of the central transverse measurement point on the top of Trajan Arch (II test).

Finally, the effects of the anthropic noise (mainly car traffic) during the daily course is shown in Fig.9, reporting the time course of the signal acquired by the lateral transverse sensor of Fig. 8. This figure clearly shows the different amplitudes of the top of the arch displacement during the day with respect to the night.

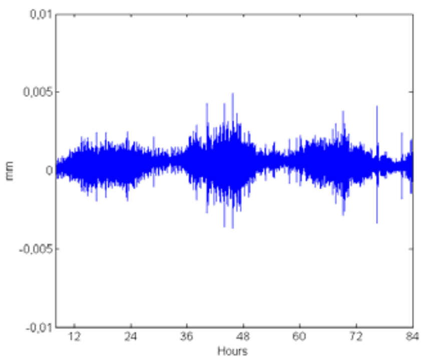


Figure 9 - Displacement time course of the lateral transverse measurement point on the top of Trajan Arch (II test).

6 FEM MODEL DESCRIPTION

For the study of the Arch has been modeled by linear finite 3D elements (fig. 10) by using the *"SAP2000 Advanced v17.3.0"* [18] software developed by CSI (Computers and Structures Inc.) di Berkeley.

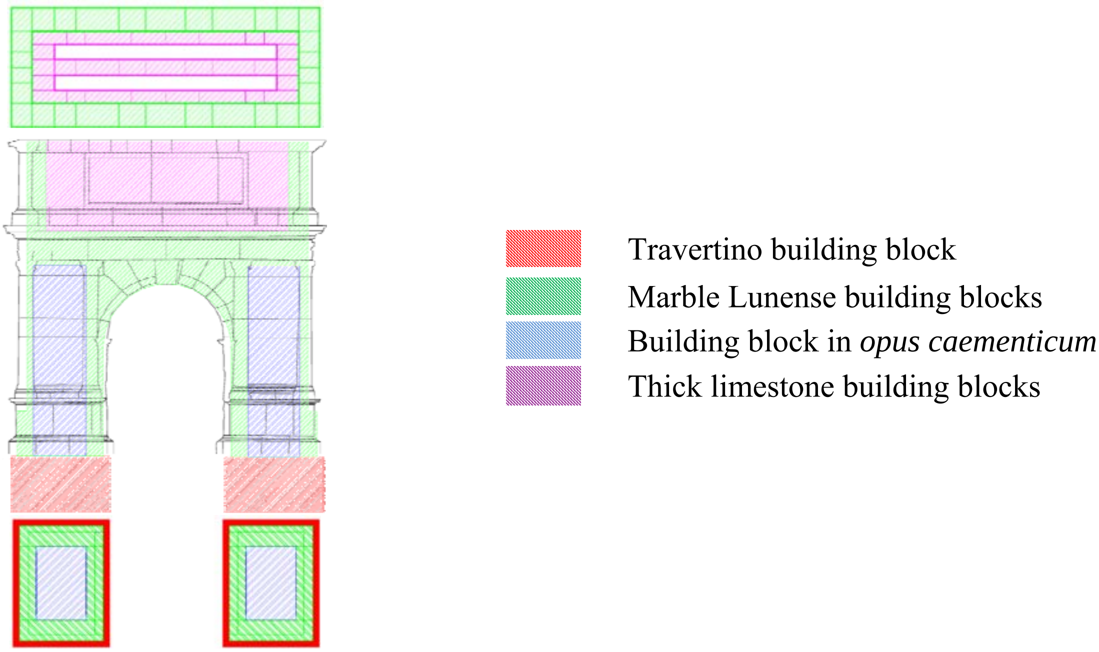


Figure 10 - Macro-elements subdivision of the Arch, with breakdown by material.

The FEM model involves the use of macro-elements solid, able to describe three-dimensional stress states. The Arch has been divided in several FEM macro-elements and subsequently automatic discretized by an appropriate meshing, which allowed to carry out more refined analysis in section variations. At the base the model has fixed constraints, being the dynamic recorded response modest. In particular, the macro-elements, which describe the blocks groups of limestone, have been modeled assuming an equivalent compact section as described in Fig.10.

The macro-elements thus defined have been then meshed assuming a reference maximum length of 0,40m. The particular shape of the attic of the is formed by an internal and an external parameters. In this way the FEM system realized until now has been refined with the splitting of the last top block as shown in the picture.

The model has subjected at a further improvement through research into triumphal arches built in the history. In fact it has been found a close relationship between the triumphal arches and the Traiano one in Rome. The similarity between the two arches is either in the architectonic shape or in the dimensions. It has been possible to make assumptions according to the information acquired from the Arch of Tito as regards the material used to build the Trajan arch.

Above all it is thought that the building blocks at its basis were in travertino marble. The pylons were made of a central nucleus of '*opus caementicium*' concrete, plated with building blocks Lunense marble and the internal cover of the attic was made of thick limestone blocks. Thus the FEM pattern has further been refined.

The mechanical properties for the reference FEM model have been researched by adaptive recursive analysis, having considered for the first model the mechanical properties as described in the the report of the prof. Salvatore D'Agostino (1991), who wrote also "..It is constituted by a core wall in limestone boulders covered with marble slabs lunense…".

The results of the adaptive recursive analysis has been leaded at the end to the following equivalent mechanical parameters for each considered materials (Tab. 2):

Table 2: Mechanical properties adopted for the reference FEM model

Materials	Weight (kN/m^3)	Modulus of Elasticity E (GPa)
Travertine building block	24,00	8,50
Marble Lunense building blocks	28,17	10,00
Building block in *opus caementicum*	19,00	4,00
Thick limestone building blocks	26,00	10,00

7 ASSESMENT PROCEDURE AND RESULTS

The reference FEM model has been obtained by varying the elastic properties of the materials by means of an adaptive recursive procedure. The tables 3 and 4 describe the main modal analysis results carried out in the first and in the last steps.

Table 3: Modal analysis results, Case 1

Material	Modulus of Young
Travertino building block	40.0 GPa
Marble Lunense building blocks	50.0 GPa
Building block in *opus caementicum*	8.0 GPa
Thick limestone building blocks	50.0 GPa

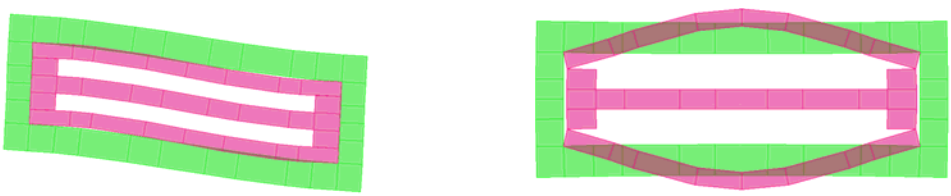
Modes	Frequency [Hz]	Period [s]
1^{st}	9.28	0.107
2^{nd}	14.85	0.067
3^{rd}	17.80	0.056
4^{th}	24.01	0.041
5^{th}	24.54	0.040
6^{th}	35.27	0.028

Table 4: Modal analysis results, Reference Case

Material	Modulus of Young
Travertino building block	8.5 GPa
Marble Lunense building blocks	10.0 GPa
Building block in *opus caementicum*	4.0 GPa
Thick limestone building blocks	10.0 GPa

Modes	Frequency [Hz]	Period [s]
1^{st}	4.33	0.230
2^{nd}	7.14	0.140
3^{rd}	8.38	0.119
4^{th}	10.76	0.092
5^{th}	10.98	0.091
6^{th}	15.97	0.062

The first three modal shapes respectively show transversal, longitudinal and rotation motion of the top side. The upper modal shapes involve deformations in the walls of the Attic. In Fig.11 the 3^{rd} and 5^{th} are described as examples.



3^{rd} modal shape T=0.119 sec F= 8.38 Hz 5^{th} modal shape T=0.091 sec F= 10.98 Hz

Figure 11 - Modal Shapes

The Table 5 describes the activated displacement components in correspondence of the recording stations for each investigated modal shape.

Table 5. Modal shapes displacement components

	External Zone			Internal Zone		
Modes	**Shift X**	**Shift Y**	**Rotation ϕ**	**Shift X**	**Shift Y**	**Rotation ϕ**
1°	-	all point	-	-	all point	-
2°	all point	-	-	all point	-	-
3°	-	-	all point	-	-	all point
4°	-	-	-	-	middle point	-
5°	-	-	-	-	middle point	-
6°	-	-	-	-	middle point	-

Fig.12 describes the comparison between the evaluated main modal periods (frequencies) and the Fourier Spectrum of the recorded signals of the first FEM model. It is possible to observe that the numerical evaluated modal periods do not fit the processed field test data with regard both the transverse (Y) and longitudinal (X) behavior. The observed shift on the frequencies between the modal and the signal analysis shows a stiffer behavior of the Arch FEM model. The result appears consistent, observing that the Arch was built as a superposition of blocks and that the external Attic walls were realized by coupling a thin stone wall not rigidly linked, while the FEM model considers the Arch as unique stone block.

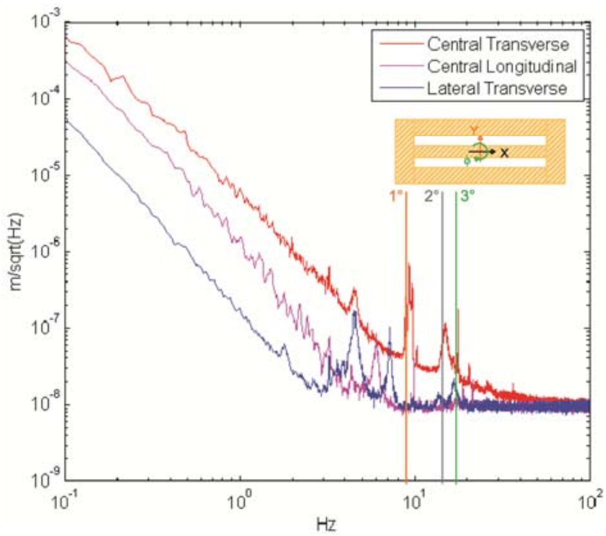


Figure 12 - Comparison between numerical and signals data analyses. Case 1

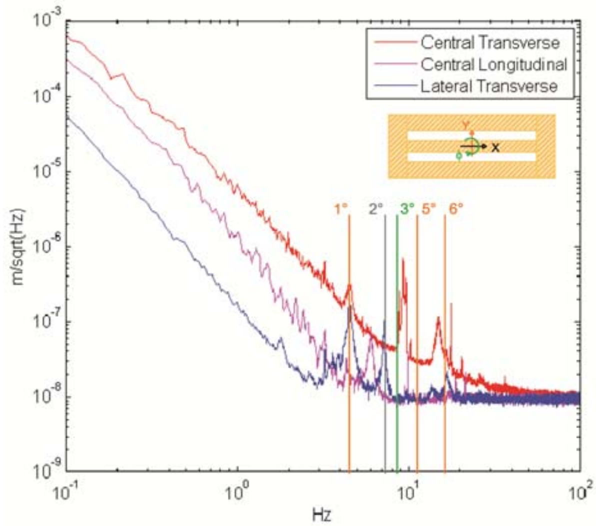


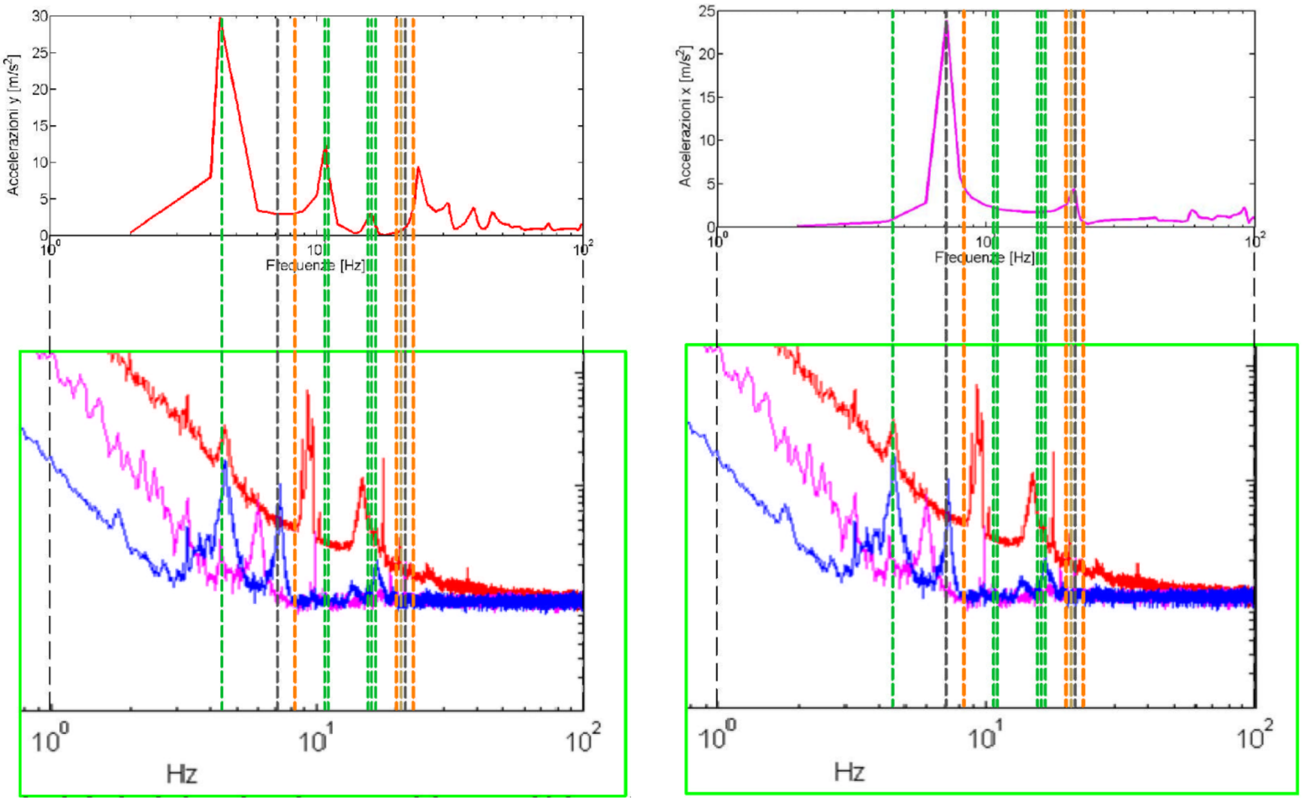
Figure 13 - Comparison between numerical and signals data analyses. Reference Case

The Fig. 13 show instead the comparison between the frequency description of the recorded signals and the numerical vibration main for the reference FEM models. Results show a quite good agreement between the numerical modal analysis and the Fourier Spectrum of the acquired signals. In correspondence of the first mode (transversal displacement of all the top side of the Arch) both the signals recorded in the center (red) and lateral (blue) of the external wall present resonance peaks. For the second shape mode a resonance peak could be read only on the recorded longitudinal signals (magenta) and, last, for the third shape mode only the lateral recorded signal (blue) present a resonance peak. The fifth modal shape presents resonance peaks on both central (red) and lateral (blue) recorded signals. In this case, there is a greater shift from the recorded signals results and the numerical ones. The Fourier Spectrum shows also a peak on the central recorded signal around 9 Hz that could not be explained by the linear analysis carried out. The latter observations could be explained by considering local behavior due to the real composition of the external walls in correspondence of the Arch. Finally, it is interesting to observe that equivalent Young modulus is considerably lower of that describing the blocks material.

Similar results have been obtained through the steady-state analysis, which relates the dynamic response in the frequency domain of a reference point to the loads. The case study has been investigate by considering the following loads patterns:

- Ground acceleration in the transverse direction y of the arc;
- Ground acceleration in the longitudinal direction x of the arc;
- Load applied in the transverse direction over the entire facade, due to the wind.

For each load, the state steady analysis has been carried out considering the frequencies range 0-100 Hz and step of 2 Hz, investigating the transversal and longitudinal acceleration of the corner and central nodes of the arch. Figures 14 and 15 describe the comparison between the amplification functions carried out by the FEM models and the frequency responses obtained from the on field tests in the center node.



Figures 14-15 – Amplification function comparison for longitudinal and transversal direction– central node

Fig.16 describe the same comparison for the corner node in the transversal direction.

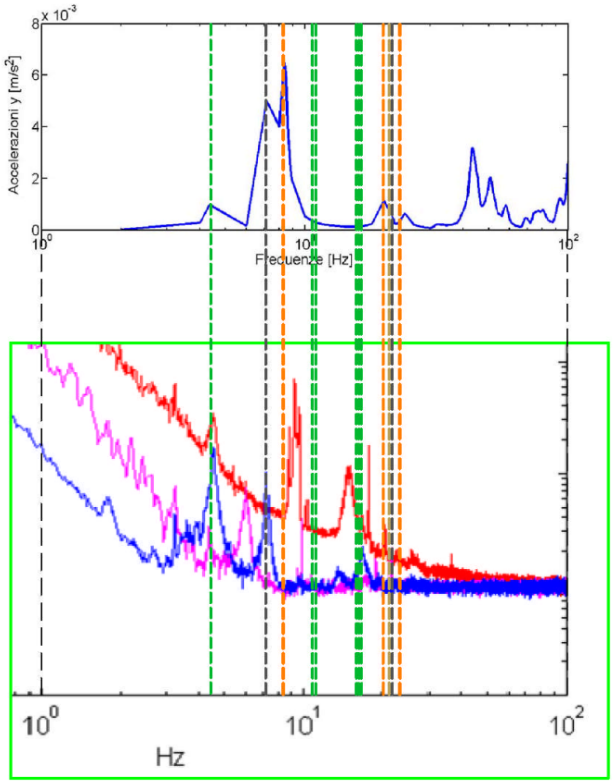


Fig.16 Amplification function comparison for transversal direction – corner node

8   CONCLUSION

The paper describe an adaptive recursive procedure able to describe a dynamic behaviour of a monumental construction by using innovative monitoring system, based on state-of-the art of mechanical sensors. The described procedure is profitable to both in deep analyse complex structural systems and monitor the evolution of static behaviour over time.

The presented results, obtained by comparing a reference FEM model behaviour with the on site recorded signals, show a very good agreement and demonstrate the effectiveness of the adaptive procedure to assess complex structures like the monumental one.

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