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DESIGN AND INSTALLATION OF A PERMANENT MONITORING SYSTEM FOR PALAZZO LOMBARDIA IN MILANO, ITALY

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Abstract. *This work describes the design and installation of a permanent system for the structural monitoring of Palazzo Lombardia Building in Milano. This is one of the high rise buildings (162 m tall) built in Milano in the last few years and is actually the seat for the regional government. A dynamic testing of the building was performed during the construction, highlighting the main vibration frequencies and the associated mode shapes. Now that the building is fully operational the public administration asked for the installation of a monitoring system in order to satisfy the following requirements: (i) monitoring the evolution of the dynamic parameters identified during the previous testing phase, (ii)monitoring the vibration to assess comfort and serviceability against the wind, (iii) monitoring the static behavior of Core 1 (tallest tower), (iv) having a continuous monitoring to capture exceptional events*

To this aim a continuous monitoring system was developed relying on high sensitivity piezo-accelerometers, low-noise high stability clinometers and a wind measurement station. The system has been installed and is fully operational since the end of October 2015. The system is described in details in this paper and the first results in terms of vibration and static behavior evolution are presented. Starting from these data a continuous modal parameter extraction will be developed and implemented.

1 INTRODUCTION

In the last few years a number of high rise buildings have been built in the center of the Italian city of Milano completely changing the city skyline. Among them the Palazzo Lombardia was the first to be built and is the current seat for the regional government.

Due to the building strategic relevance, a number of dynamic tests have been performed at the end of the construction phase in order to assess the structure dynamic behavior and update the FE model to seismic resistance purposes [1,2,3]. After these tests the first principal vibration modes and their associated mode shapes are known and set the base for the planned long term monitoring of the structure.

As other important buildings in town [4,5,6], the public administration asked for a continuous monitoring system in order to be able to detect and prevent possible problems in terms of comfort and structural failures, and to be able to assess the structural status after exceptional events such as earthquakes.

In order to fulfill the request, and after all the bureaucratic issues were accomplished, a permanent monitoring system has been designed, installed and is now running in the building. The main aims of the system are:

- Monitoring the evolution of the dynamic parameters identified during the previous testing phase
- Monitoring the vibration to assess comfort and serviceability against the wind
- Monitoring the static behavior of Core 1 (tallest tower)
- Having a continuous monitoring to capture exceptional events

The idea is to exploit the data that will be available to set-up a health monitoring procedure of the core 1 structure [7,8].

In this paper, after a brief description of the building structure is shown, the monitoring system layout is presented in terms of sensors and data acquisition/storage devices. In the last section the first results coming from the monitoring system are presented.

2 STRUCTURE DESCRIPTION

The “Palazzo Lombardia” building is the first in a series of high rise buildings which have been built in Milano in the last years. It is the current seat for the Regional Government and offices and therefore considered of strategic relevance. The complex is made up of five lower buildings (about 40m high, called Cores 2, 3, 4, 5 and 6), surrounding the high-rise Tower (Core 1), which scored, at the time of construction, the new height record in Italy. The complex sinuous interweaving strands recall the mountains, valleys, and rivers of the Lombardia region.

The curvilinear shapes of the buildings, while having a very strong aesthetical impact, are also strongly reflected in the irregular plan-wise configuration of the complex, which, at its center, defines an inner covered public ‘plaza’(Piazza Lombardia), having an area of about 4200 m^2, covered by a steel truss system supporting transparent Texlon ETFE (ethylene-co-tetrafluoroethylene) cushions. In Figure 1, the six buildings, or Cores (1-6), making up the complex are visible.

Figure 1 Palazzo Lombardia: the whole complex

The structural system is entirely made up of reinforced concrete load bearing elements, except for the Auditorium area in Core 4 and the 'Velarium' on top of Core 1, a three-storey high belvedere area to be used for official public purposes and rented for private events. For these two parts structural steel was employed. The monitoring system will be dedicated to the Core 1 structure (tallest tower) in the initial phase with the idea of possibly expanding it to the remaining sub-structures.

3 GENERAL SPECIFICATIONS OF THE MONITORING SYSTEM

As stated in the introduction, the monitoring system should be capable of handling both dynamic vibration signals and static variables, as well as of the wind conditions. To this aim, high reliable low noise sensors have been selected and a well-known already tested and employed solution has been implemented for data acquisition[5].

3.1 Selected sensors

The chosen sensors had to fulfill all the requirements which were proposed to Regione Lombardia, formerly the work committer. In order to be able to monitor vibration comfort levels against wind serviceability [11][12] and perform operational modal analysis identifications [9][10] very high sensitivity low noise accelerometers had to be employed. Moreover, the building first natural frequency is around 0.3 Hz [1][3], thus posing problems both on the sensor choice and the data acquisition hardware.

On the other hand, the selected tilt sensors had to provide long term stability and a certified temperature sensitivity in order to guarantee reliability to the static measurements.

As a cabled solutions have been chosen (synchronized wireless measurements were not considered affordable on such a high building) the sensor types were chosen in order to minimize the needed cabling.

According to all the above stated needs, the following sensors were chosen:

- Accelerometers: PCB 393B31 Piezo units, which have proven to have a very low noise floor level and guarantee good frequency response down to 0.1 Hz, having a 0.5 g full scale value.

- Clinometers: ±5° Singer TS servo clinometers with extended temperature calibration. High reliability sensors with a frequency response up to 3 Hz, which is enough to cover the building first frequencies
- Wind speed/direction: Anemometer NESA ANS-VV1-A + ANS-DVE-A (potentiometric wind direction), with a 50 m/s full scale value.

Al the installed sensors are connected through custom built connection boxes and multipolar shielded cables to the data acquisition device. Sensor positions are described in the next section.

3.2 Sensor positioning

To the aim of identifying at least the first three vibration modes of the structure (2 bending modes and the 3rd torsional one [1][3]) and according to the commitment request, a total number of 24 piezo accelerometers have been installed at five different levels of the Core 1 tower.

Figure 2 shows the instrumented floors and the different sensors that are installed.

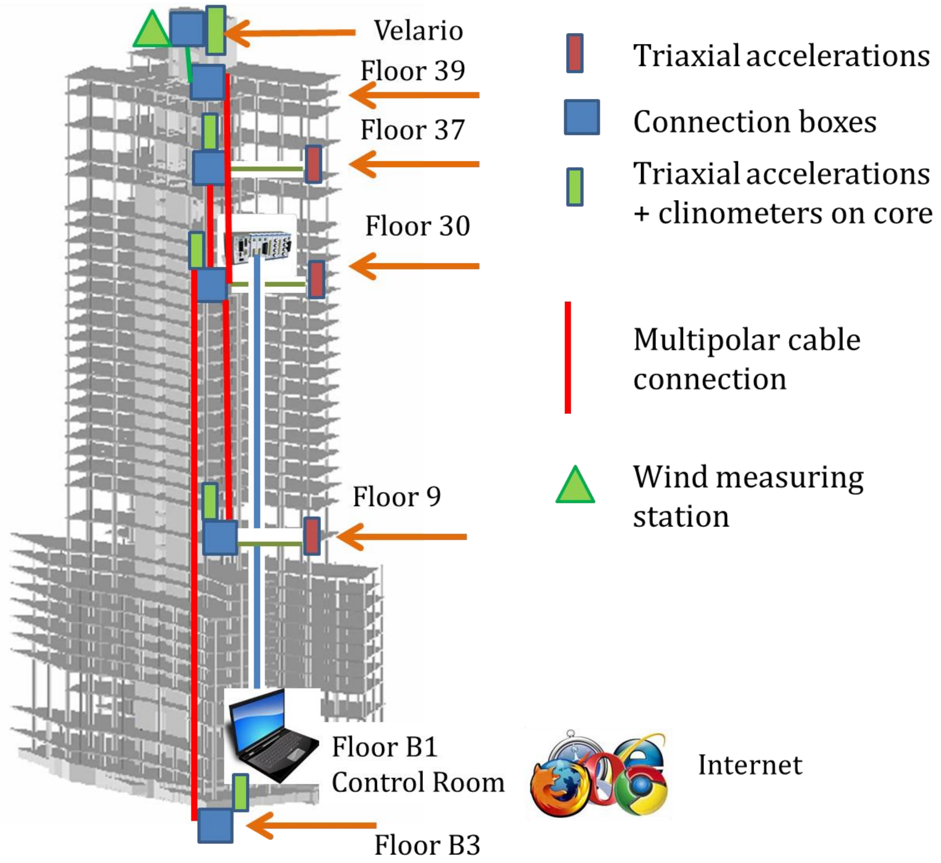


Figure 2 Sensor positions in the building

As can be noticed in Figure 2, sensors are placed starting from the top steel structure “Velario”, to the last underground basement (B3 floor). Floor 39 has no sensors and only a couple of connection boxes are installed there in order to facilitate system maintenance.

Sensor position at each flor is depicted in Figure 3 for floors 37/30/09. The B3 and Velario floors are instrumented with sensors in the core area.

Clinometers are placed at all instrumented levels on the concrete core in order to detect rotations around the X and Y axes.

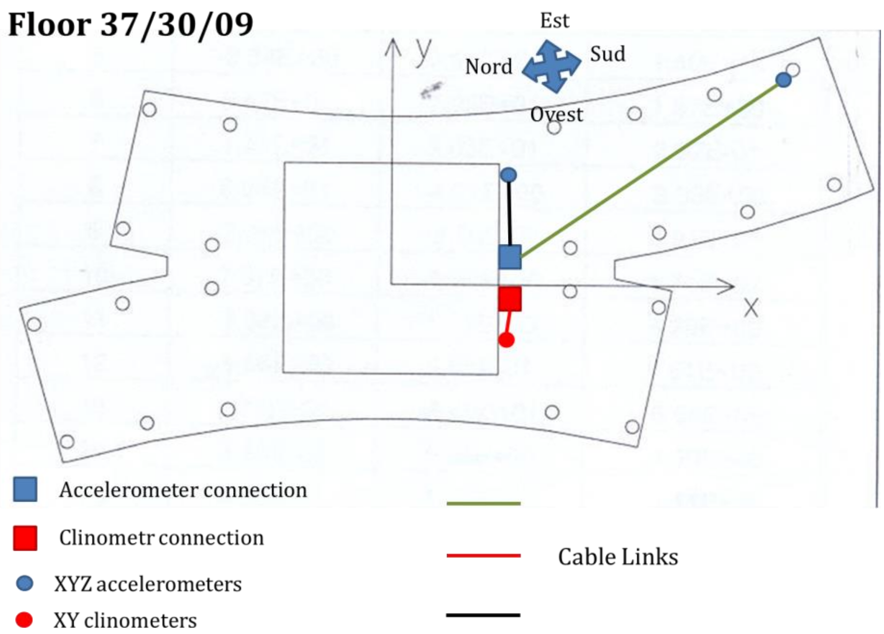


Figure 3 Sensor positions on floor 37/30/09, on floor B3 and on the "Velario" only the Core sensors are installed.

According to the sensor positions illustrated in Figure 3, it is possible to identify and distinguish the two principal bending modes and the first torsional one. It will also be possible to study the higher modes and compare them with what was identified during the validation testing at the end of the construction phase [1][3].

Accelerometers at level B3 will provide information in case of seismic events on the earthquake strength at the building foundations and therefore to evaluate the overall structural amplification. Clinometers at the same level will be used to track deformations on the building foundations.

All sensors are directly cabled to the data acquisition system described in the next section.

3.3 Data acquisition and storage

The data acquisition and storage system was designed in order to guarantee continuous functioning 24hours/7days-per-week . In order to fulfill the design needs the system is split into 2 independent units:

- Data acquisition unit with a local storage capability on floor 30
- Data storage and visualization on floor B1

The data acquisition device is a National Instrument C-RIO unit, in charge of measuring the acceleration and inclination signals together with the wind information and assemble them in 10-minutes-long data files which are then stored locally. The accelerometers are powered and conditioned using PCB ICP power units able to guarantee a low cut-off frequency below 0.1 Hz.

All accelerometers signals are converted using 24 bits simultaneous conversion and built-in anti-aliasing filters. Clinometers and wind data are sampled using 16 bit converters. The analog to digital sampling frequency is 2000 Hz, which is then digitally down-sampled 8 times to 250 Hz.

In Figure 4 it is possible to see some pictures of the data acquisition cabinet placed at the 30th floor.

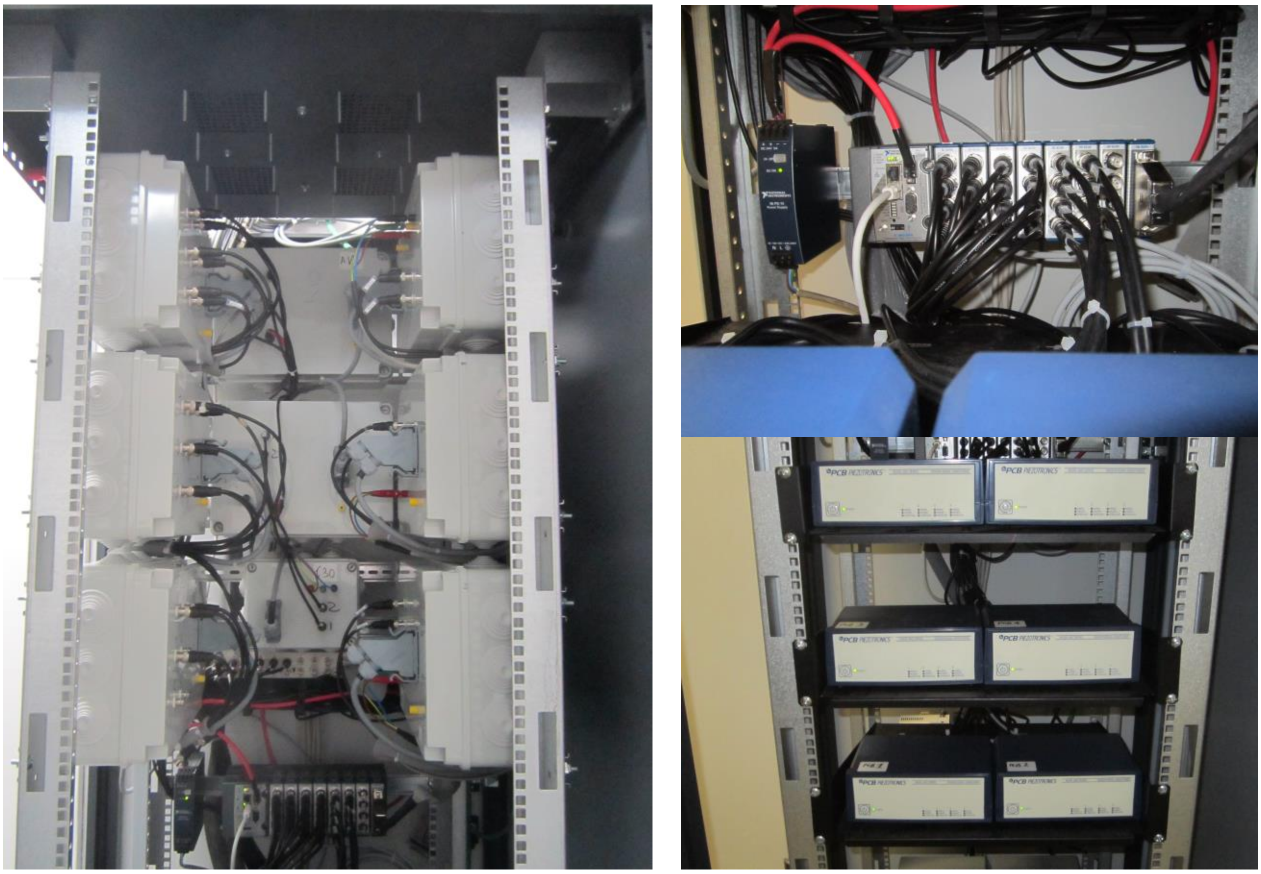
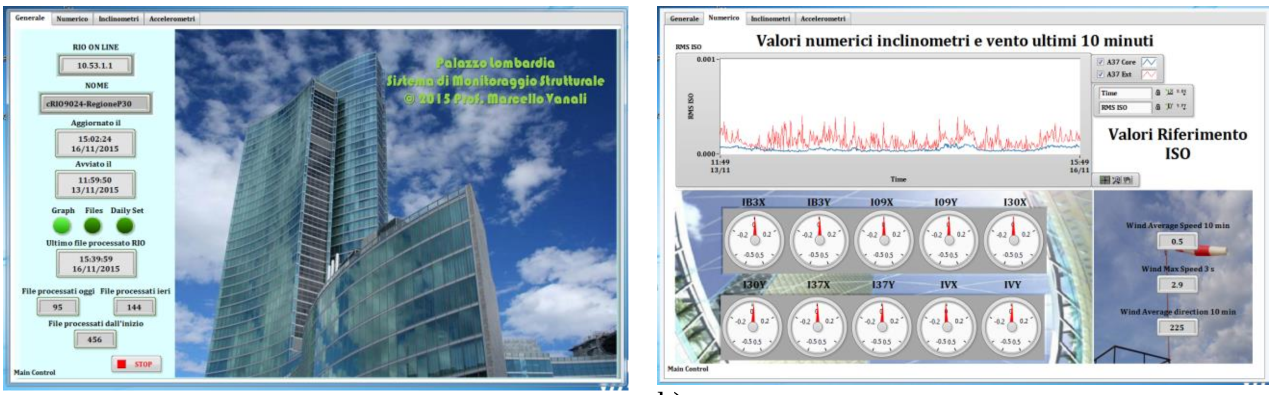


Figure 4 Data acquisition cabinet at floor 30: whole view (left), CRIO and IEPE conditioner (right)

Every time a new data file is stored on the local unit, the system automatically transfers it via Ethernet to the storage unit at floor B3. In case of an Ethernet failure, the local system can store up to two days of data in order not to lose any critical event. System power is assured by the building preferential line that guarantees continuous power supply to all critical systems.

The storage unit at floor B1 is a common server grade PC with raid data storage and a software that periodically check system functionality and, every time a new data file is found, process it to extract some synthetic data. At the moment, all raw data are stored on the B1 floor unit, but in the future a selection of the raw data to be stored is planned based on the acceleration RMS values and wind speed values.



a) b)

Figure 5 Screenshot of the data storage and visualization Software. a) Main Screen, b) Resume of the last ten minutes and wind induced vibrations

Among the synthetic information given by the software, it is worth citing a the vibration RMS magnitude of floor 37 in the frequency range of wind induced vibrations [11] that gives an immediate feedback of possible wind serviceability problems, and the average value of all clinometers sensors in the last ten minutes and their evolution in the last 48 hours.

The system is running since 19 October 2015 and the first data together with some analysis are presented in the next section.

4 FIRST DATA

As previously stated, the system was started on the 19th of October 2015 and is running continuously since then. The first data coming from the system are shown here.

Figure 6 shows the average value evolution of all clinometers since October 19th (the zero value was set at the first valid file that was measured).

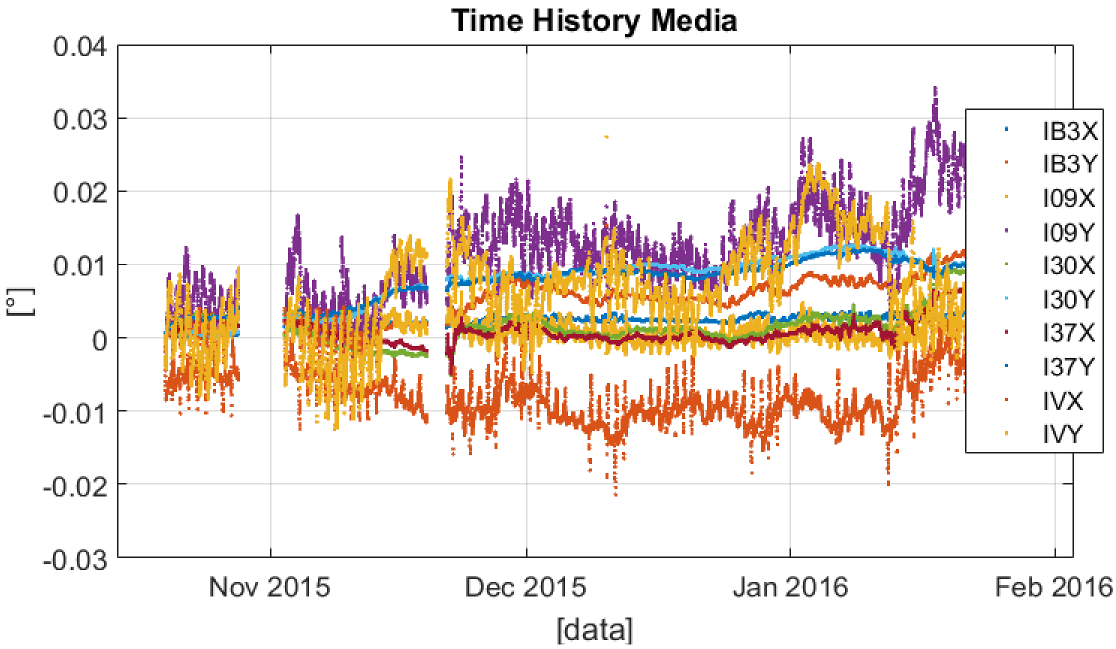


Figure 6 Clinometers average values up to 31/01/2016

As can be noticed in Figure 6 two main signal family are present. The first one (IB3,I30, I37) which shows few oscillations and a constant trend, the second one (I09, IV) that shows wide intraday oscillations.

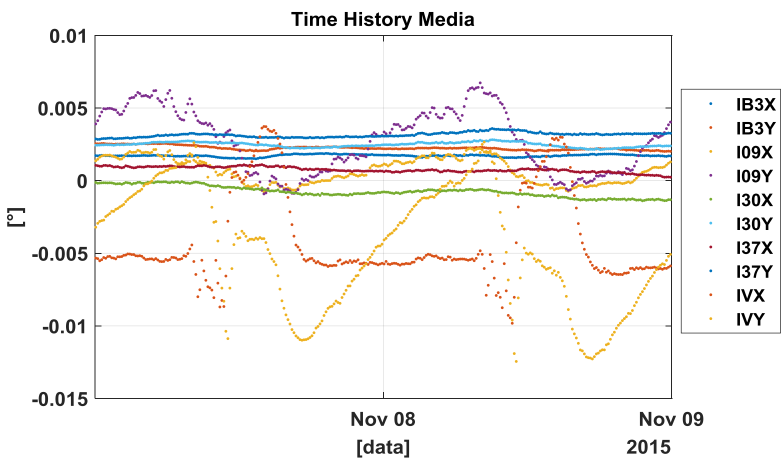


Figure 7 Two-days zoom of clinometers average value

The difference is highlighted in Figure 7 where the clinometers average value evolution over two days is shown. In order to verify and understand this behavior, a temperature sensor has been installed at floors 09 and 30, close to the clinometers. Measurements showed that the higher oscillations experienced at floor 09 are strictly linked to the local temperature and the same applies for clinometers at the “Velario” level, which are outside the building.

The overall variability is around 0.01 ° and the trend will be kept under observation in order to quantify the one-year thermal cycle of the building.

According to what was stated at the beginning, acceleration measurement are taken to the aim of identifying continuously the building modal parameters and to provide information on the vibration serviceability against the wind induced vibrations.

Figure 8 shows the power spectral densities (PSD) measured during a windy day at level 37. The three main vibration modes (1 weak axis flexural, 2 Strong axis flexural, 3 Torsion) are put into evidence by the blue arrows.

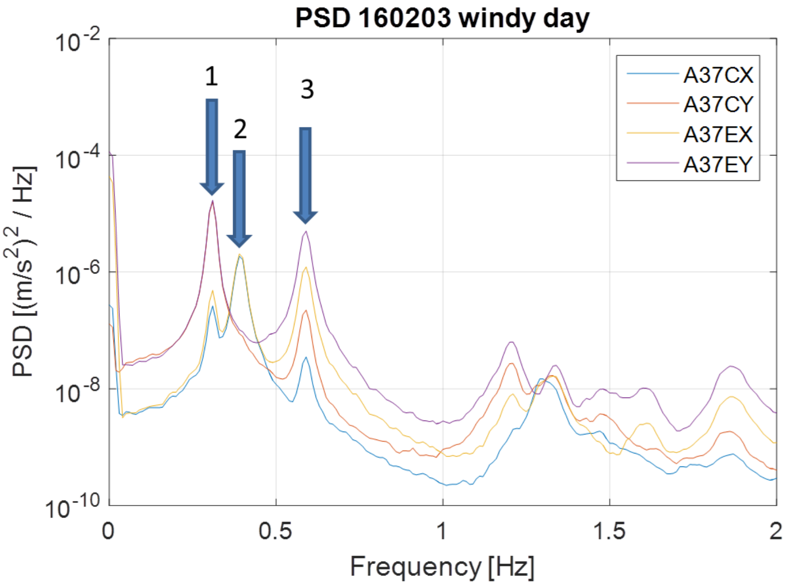


Figure 8 Power Spectral densities at floor 37, 37CXY core accelerations, 37EXY extremity accelerations

The main frequency values and the associated mode shapes are in a very good agreement to the ones found during forced testing [1][3]. Figure 9 shows the same day PSDs in Y direction at different levels on the core.

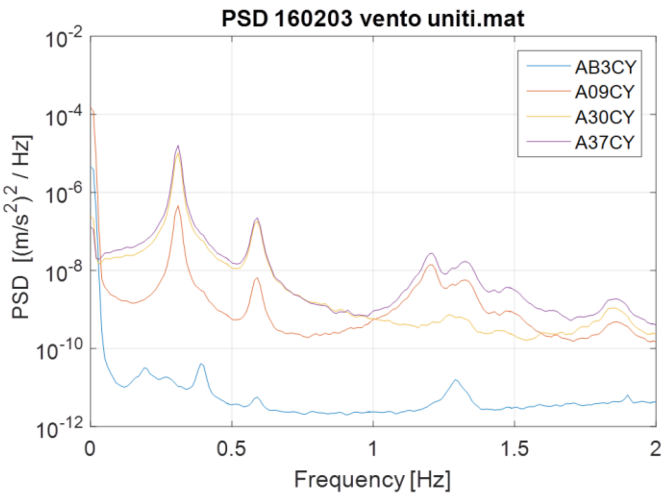


Figure 9 PSD core accelerations at different levels

Vibration levels shown in Figure 9 are increasing from level B3 (bottom) to level 37 (top) of the building in accordance to the expected mode shapes. This measurement will be the input data to an automated modal extraction procedure which will provide synthetic information on the building dynamics [13].

As for the wind induced vibrations, the most critical levels are the highest ones. In Figure 10 the RMS accelerations measured at floor 37 and B3 on the core are shown together with the wind speed. It is noticed that the measured accelerations increase as the wind speed raises even if the reached levels are far below the comfort limits [11][12].

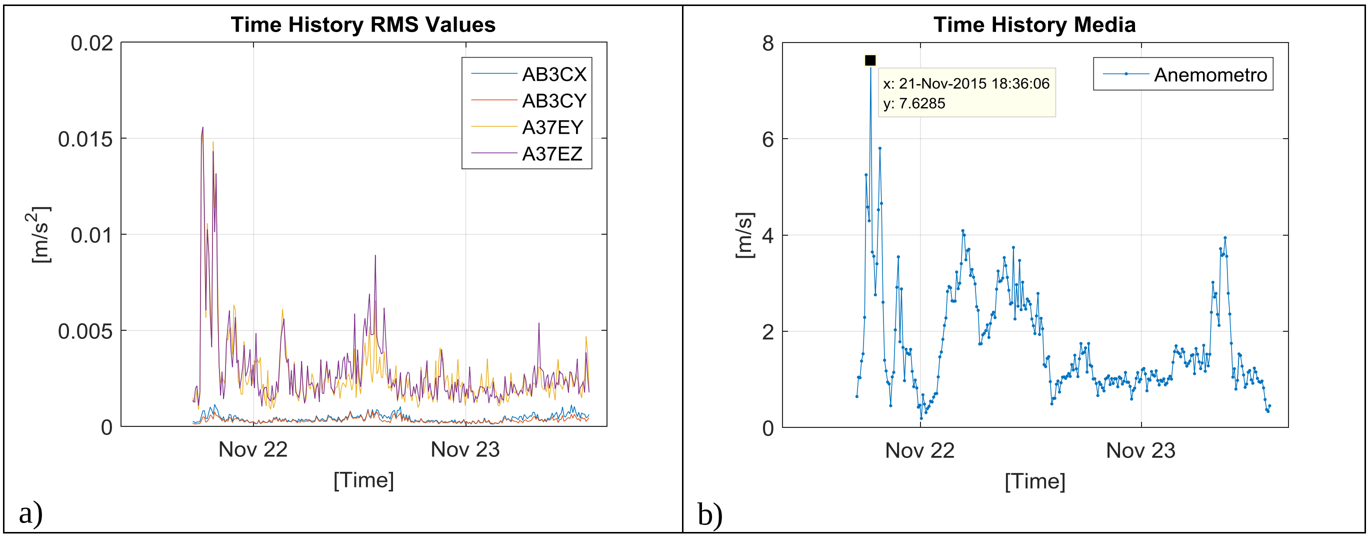


Figure 10 Windy day, a) RMS accelerations on floor 37, b) “Anemometro”, measuring the wind speed

The filtered RMS value, averaged on 10 minutes and in the 0.1-1 Hz frequency band, at floor 37 is continuously computed and displayed as one of the synthetic data from the program running on the PC at floor B1 (Figure 11), so that any increase in this level is immediately evident.

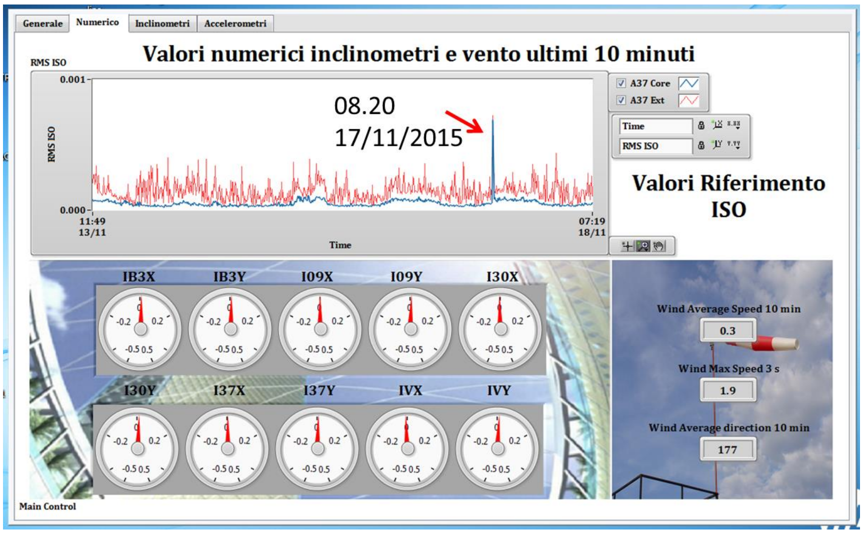


Figure 11 Singular event on November 17th 2015

Figure 11 also shows an anomalous increment in the structural vibration measured at floor 37, occurred on November 17th 2015 around 08.20am hours. This event was not related to the wind or other specific local episodes (e.g. works and/or maintenance operations at the floor).

It was then decided to investigate better this RMS peak. At first it was found that the same peak could be experienced in the structural frequency range at all building levels, including the B3 (basement level). The only remarkable event that happened in that time frame was the earthquake in the Greek Ionic coast as can be seen in Figure 12, where the web page of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) reports the event (green arrow).

Figure 12 Web page of INGV reporting the Greek Earthquake on Novembre 17th.

We contacted the INGV in the person of Dr. Paolo Augliera and he confirmed that very low frequency shock waves travel very far during earthquakes and they are used to seismic prediction purposes [14].

We computed the acceleration PSD during the event and compared it to the usual one; the results are shown in Figure 13. A noticeable increase in the vibration levels below 1 Hz is experienced during the earthquake (terremoto).

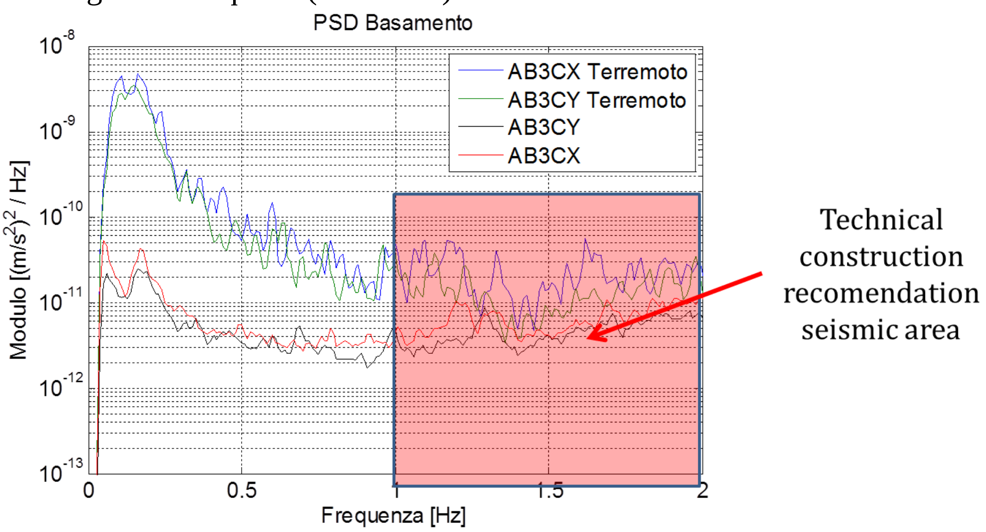


Figure 13 PSD at level B3, normal activity VS Terremoto (Earthquake) of November 17th.

It is noticed that the frequency range involved in this activity is completely out of those considered in NTC08 (technical construction recommendation) [15] for the Milano area which is highlighted in red in Figure 13.

Other similar events have been experienced and recorded since then, proving the system capability to evidence any peculiar situation occurring to the building.

5 CONCLUSION

In this paper the permanent monitoring system for “Palazzo Lombardia” design an installation has been described. The system aims have been illustrated and explained and the instruments chosen to fulfill them have been described. The data acquisition set-up that was designed to guarantee continuous measurements and analysis of the data was presented and finally a first glance to measured data has been given.

First results showed the system capability to follow the building static and dynamic evolution and therefore to provide a valid database for future health monitoring. Moreover, the system proved to be capable to put into evidence a number of unusual events linked to earthquakes which occurred far away from the building location.

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