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CC2015-24: Monitoring for Damage Detection, Vulnerability Assessment, Forecast and Protection Of Structures and Continua

A new tool for monitoring and assessing the structural health of ancient masonry constructions

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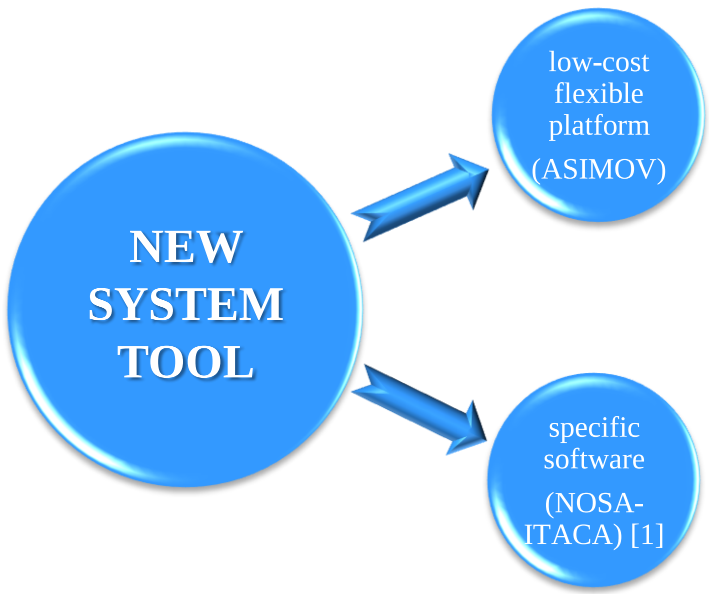
- **S**tructural **H**ealth **M**onitoring refers to technologies used both to measure specific parameters and physical quantities that provide information about a building's structural behavior and to aid in choosing appropriate interventions of consolidation and seismic retrofitting.
- **MONSTER project** was set up to develop an integrated set of technologies to perform more sophisticated assessments of the conservation status of masonry constructions and to monitor their behavior over time.

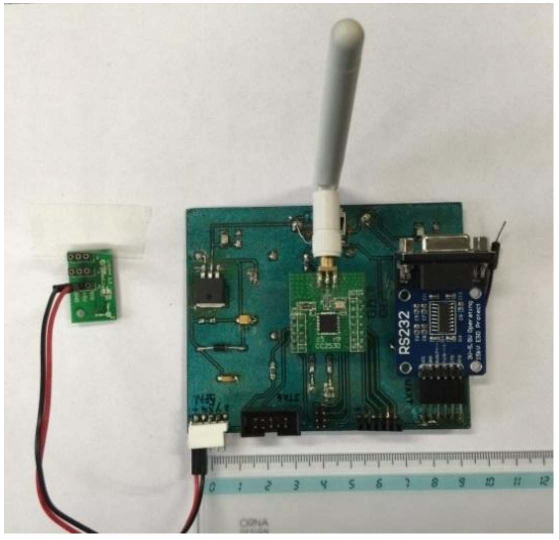


- Ability to gather data through different types of sensors installed on buildings

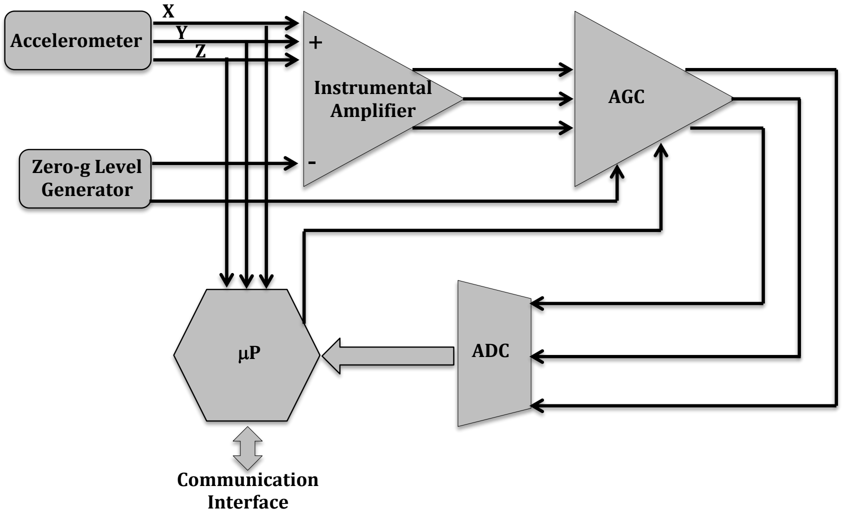
- Ability to monitor and model the mechanical behavior of the structure under study

[1] www.nosaitaca.it

- **ASIMOV** (Acquisition System for low-Intensity MOnument Vibration) has been designed and built at ISTI-CNR . It is based on a 3-axis accelerometer, whose native resolution settings have been adapted to suit the specific needs of structural monitoring. The system has been designed so that it can automatically adapt to variations in acceleration within the range of 10^{-3} m/sec^2 to 20 m/sec^2.



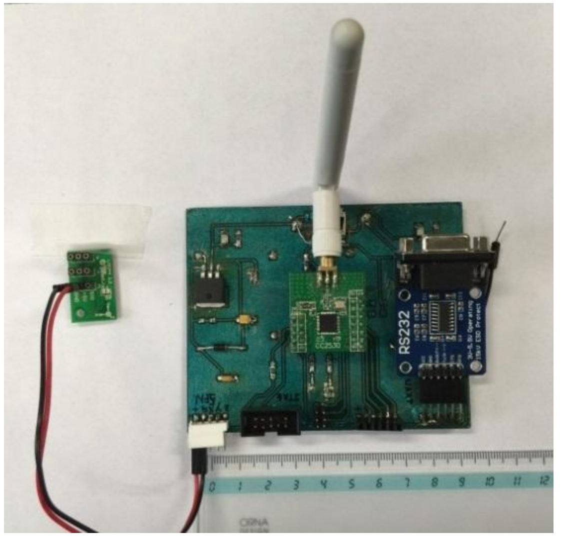
The acquisition system (length in cm)



Block diagram of the system

- The system has a sampling frequency of 100 Hz. It is equipped with a 16 bit analogue-to-digital converter (ADC) and a serial interface to communicate with external devices. The system can communicate via most commercial data transmission interfaces.

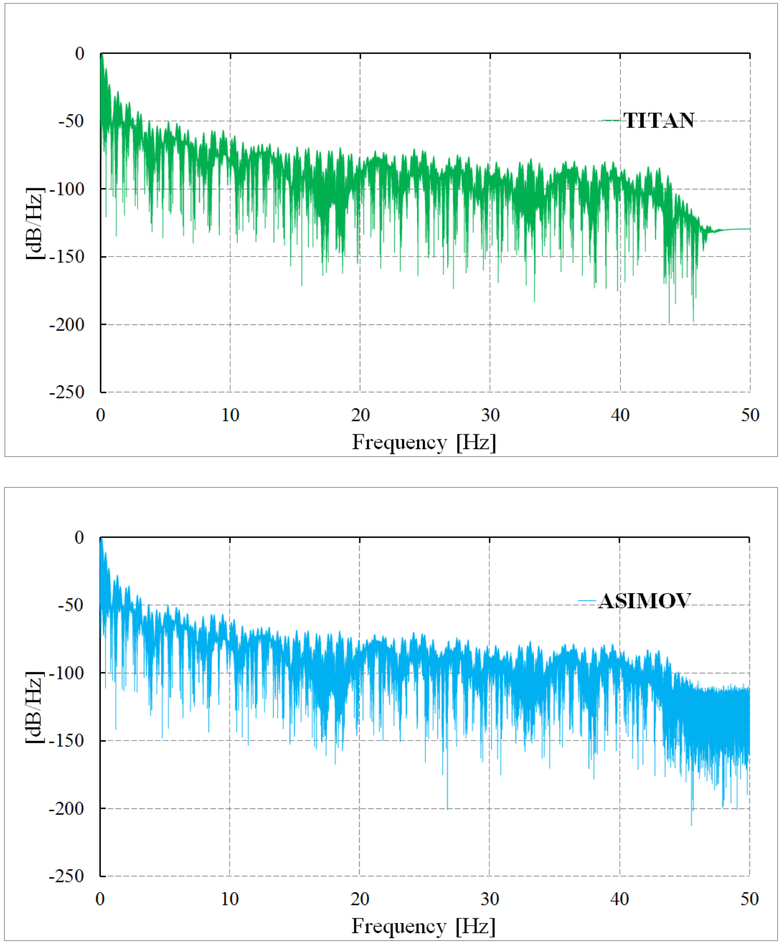
- **Calibration** of the system plays a crucial role in developing an effective and reliable WSN accelerometer. In order to calibrate the accelerometer, comparisons have been carried out between ASIMOV and TITAN, a 3-axis accelerometer made available by the Italian Institute of Geophysics and Vulcanology (the INGV-Istituto Italiano di Geofisica e Vulcanologia).



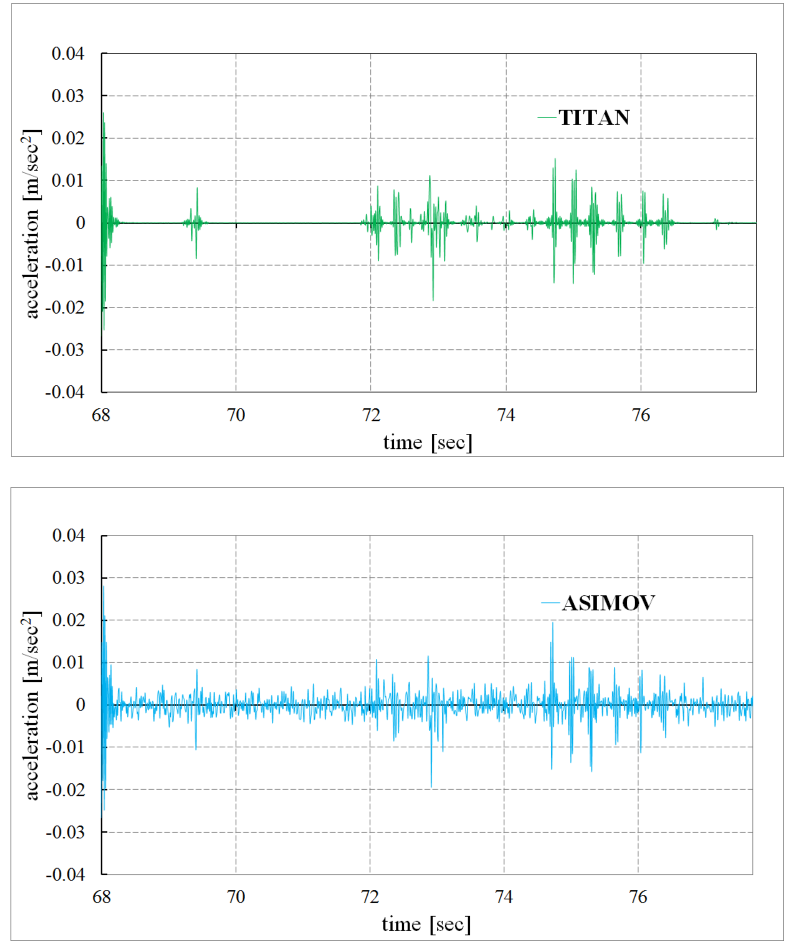
The acquisition system (length in cm)

TITAN

- **Calibration:** comparisons in terms of time-history and PSD (Power Spectral Density) between ASIMOV and TITAN:



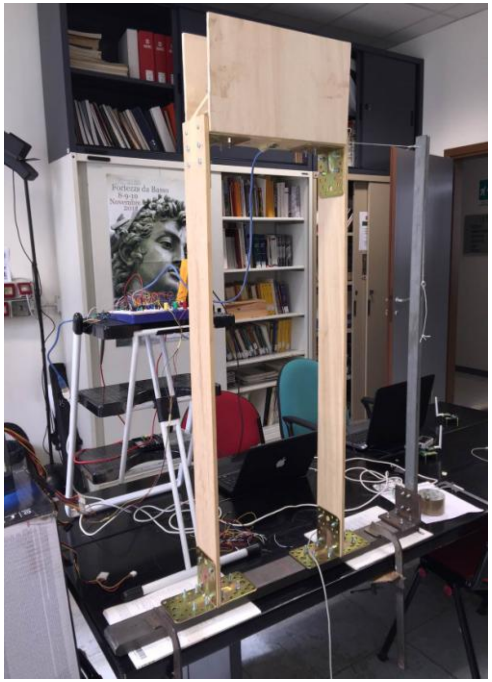
Power Spectral Density



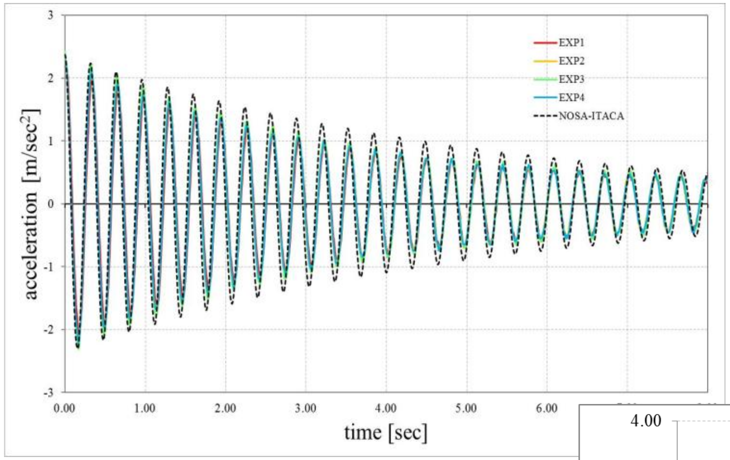
Acceleration versus time

- **Calibration** via ambient vibration tests using the wooden frame structure shown in the figure.

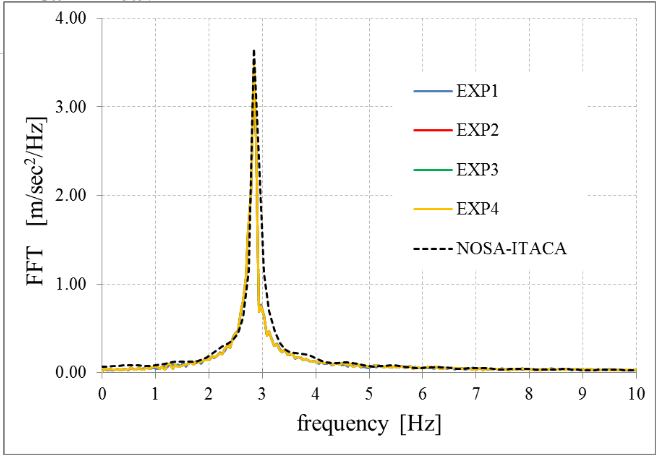
Initial displacements u_0 were assigned to the top of the frame for different values of the mass *m* applied to the structure, and the acceleration of the freely vibrating system measured; each experiment was repeated four times. The collected data were then compared with the results of the numerical simulations conducted via the NOSA-ITACA code.



The calibration device



Acceleration versus time

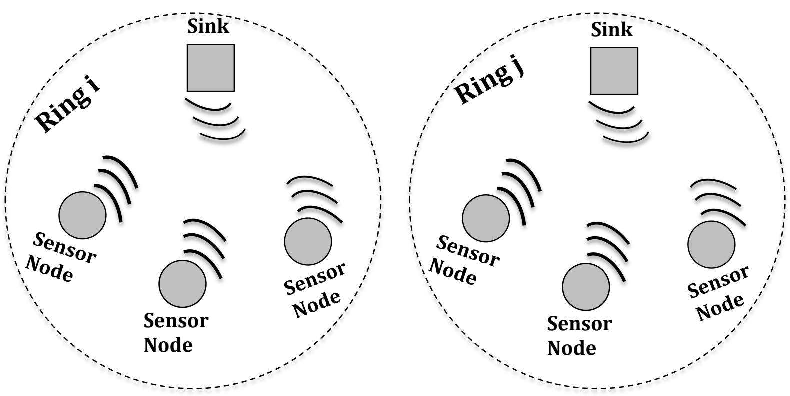


Discrete Fourier Transform

- **Wireless sensor network** (under development).

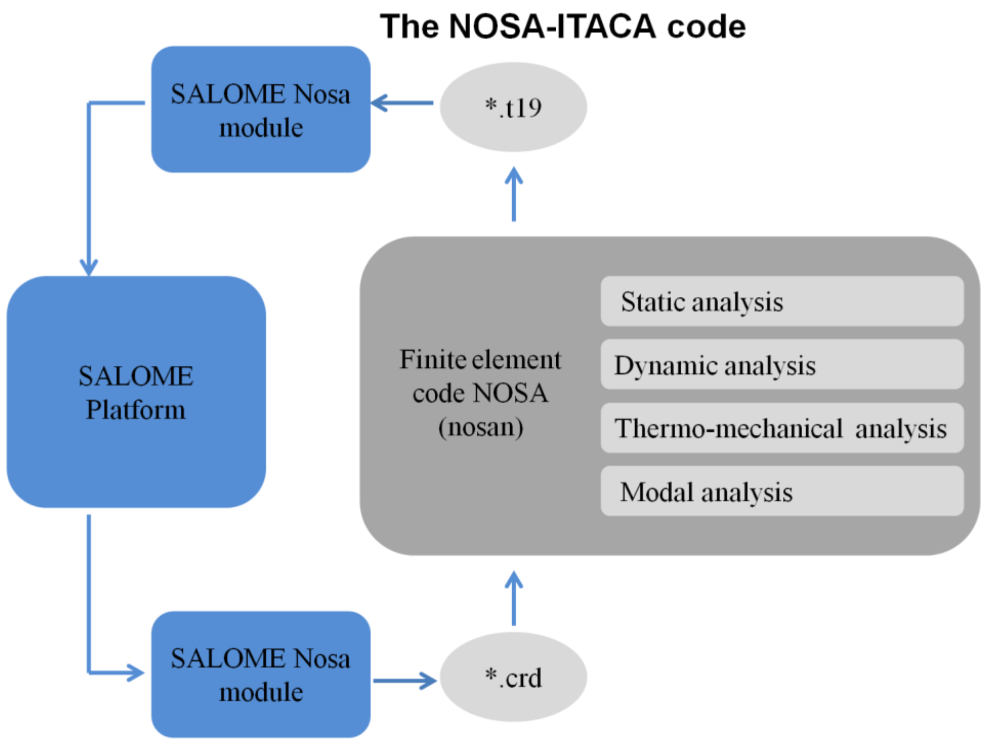
Two basic requirements must be fulfilled: **reliability and scalability** of the data transmission. Reliability means reducing any potential data loss to a minimum, while scalability involves the ability to install a large number of sensors within the network without compromising data transmission performance. The network is made up of various "rings", each of which includes a commander node, called the "sink" (the core of the ring), and a sufficient number of sensor nodes (e.g., accelerometers) to ensure the necessary amount of transmitted data. Each sink receives the sampled data from the sensor nodes either continuously, or following a prescheduled sampling sequence, depending on how it is programmed. The firmware of the node enables point-to-multipoint communication between the sink and its subset of nodes, as well as point-to-point communication between any node and the sink. **Through the point-to-multipoint communication, a sink can start acquisition on the sensor nodes simultaneously, as well as perform synchronization of the acquisitions**. When the acquisition window has ended, all sensor nodes can send their data to the sink through the point-to-point communication link.

The sink can perform proper synchronization of its subset of nodes through a Real-Time Clock system.



The WSN topology

- **NOSA-ITACA code (http://www.nosaitaca.it/en/download).** Freeware/open-source software for computational mechanics distributed with the aim of disseminating the use of mathematical models and numerical tools in the field of Cultural Heritage (constitutive equation of masonry-like materials).

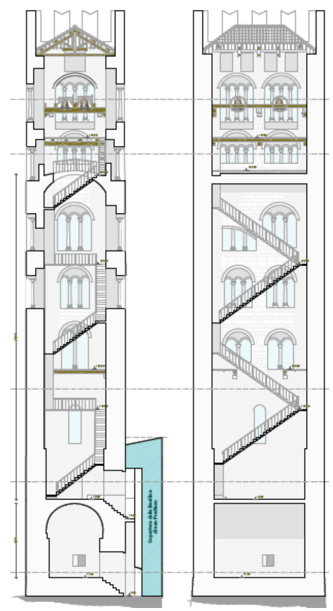


- **Case study:** the San Frediano bell tower in Lucca (dating back to the 11th century).

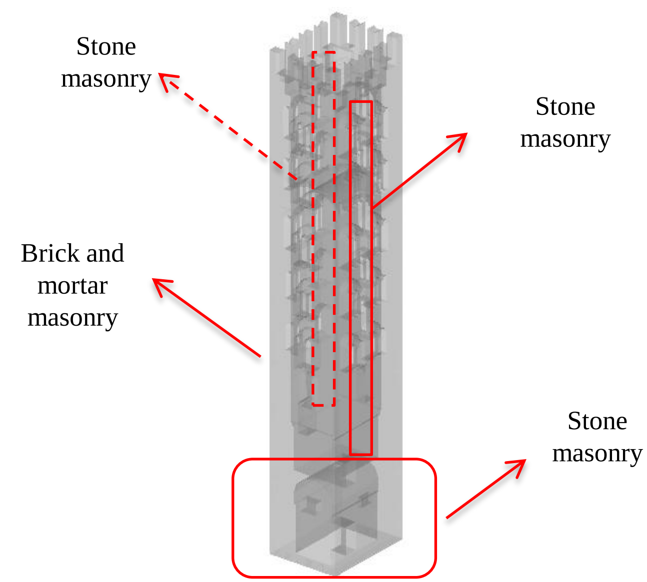
The bell tower of San Frediano

Characteristics of the tower:

- Height 52 m;
- Walls thickness varies from ~ 2.1 m at the base, to 1.6 m at the top;
- Two masonry vaults (at about 9 m and 38 m);
- Hip roof with wooden trusses and rafters;
- Different types of masonry as indicated in the scheme.

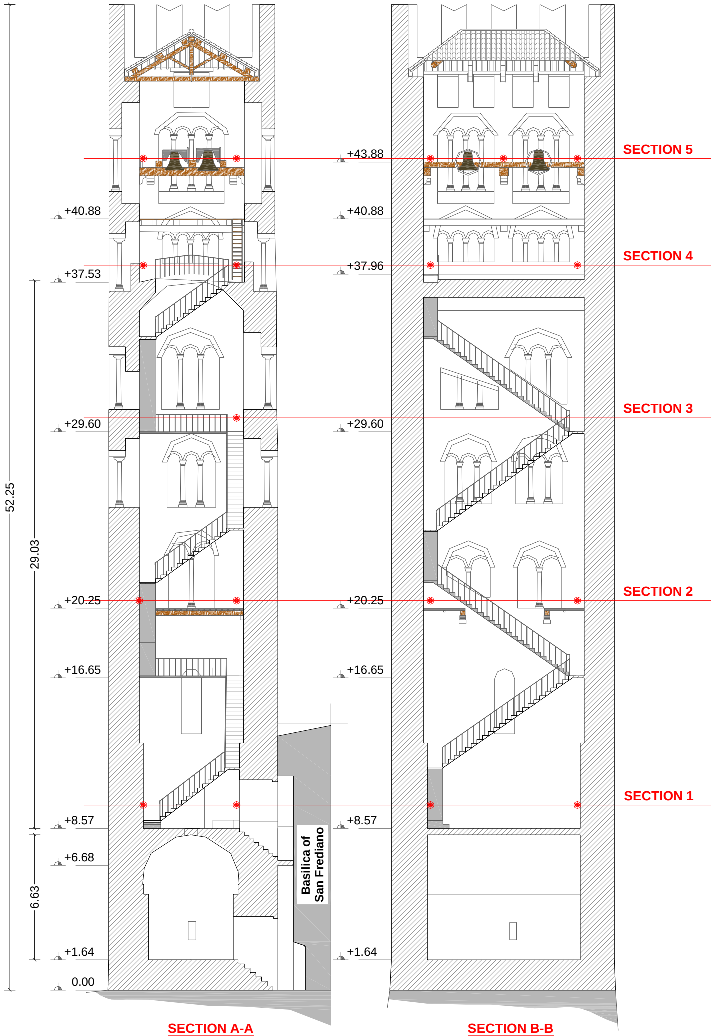


Survey of the bell tower

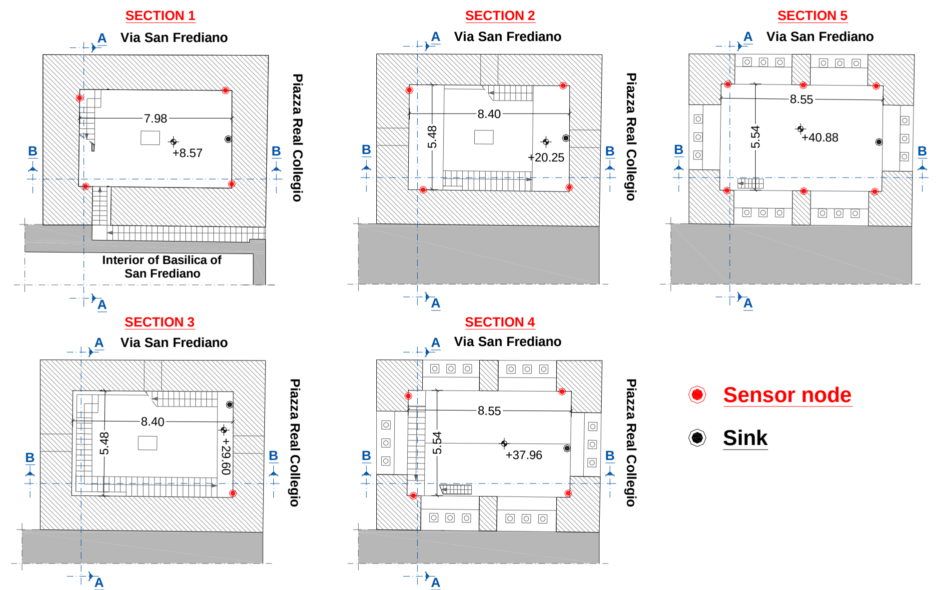


Scheme of the tower materials composition

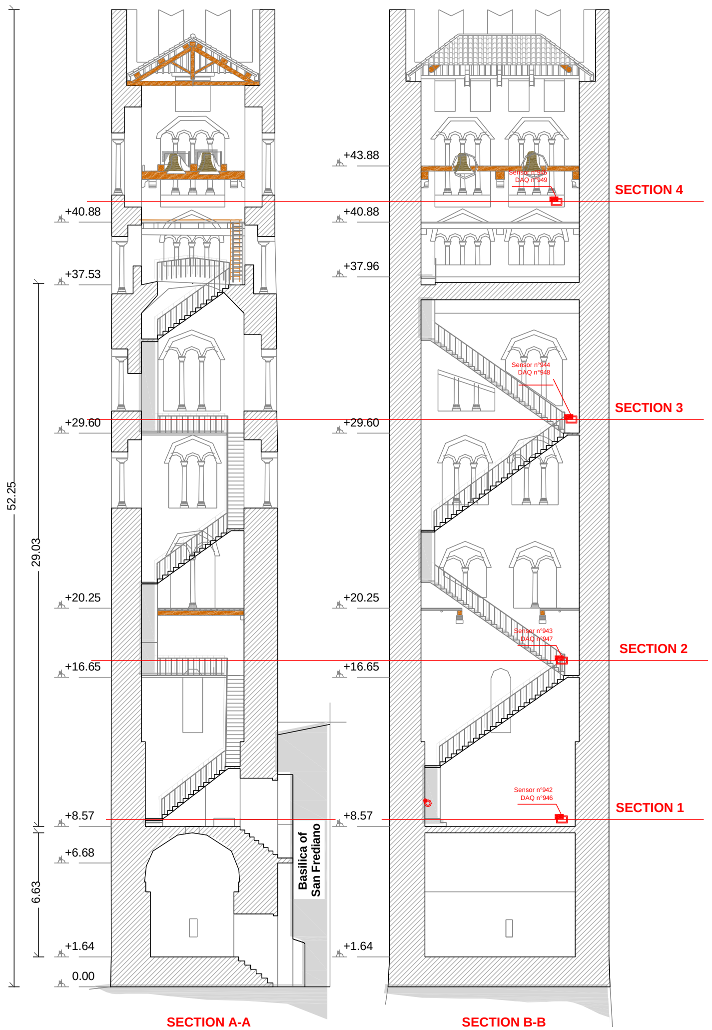
- **The sensor network on the case study**

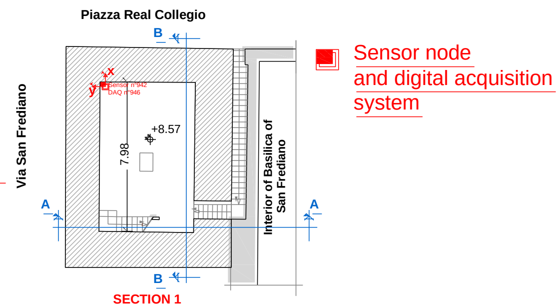


A sensor network will be installed on the interior surface of the tower's walls. The positions of the accelerometers to be placed on 5 levels inside the tower are illustrated in the figure. When installed and tested, the network will enable comparisons of the frequencies and modal shapes calculated via the NOSA-ITACA code and the same quantities calculated via suitable dynamic identification techniques on the accelerations recorded.



- **Preliminary monitoring:** data acquisition from 1 pm May 29th , until 8 am June 3rd of this year (ambient vibration).





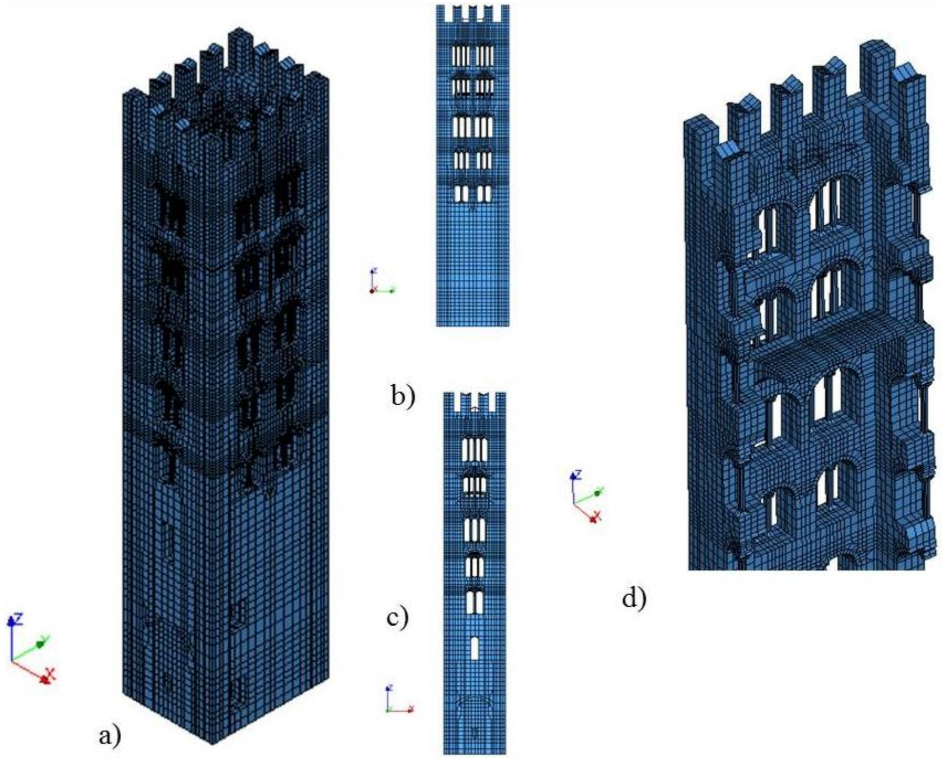
Seismic station

Four Seismic stations (SARA) placed along a vertical line:

- Digital acquisition system SL06;
- Seismometer SS20;
- Sampling frequency 100Hz.

- **FEM analysis**

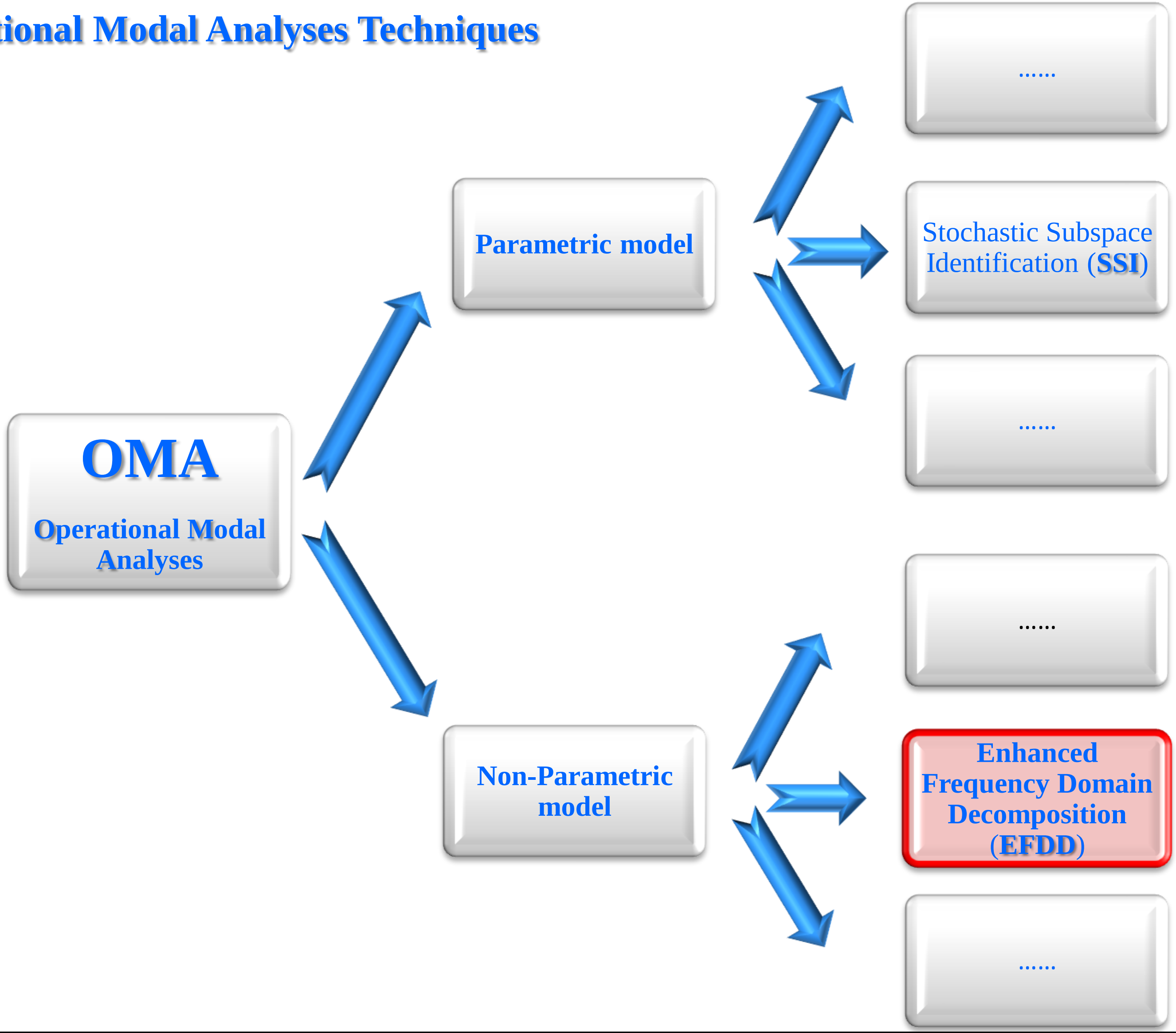
In order to perform a preliminary modal analysis, the tower's structure has been discretized into **45641 brick elements** (element n°. 8 of the NOSA-ITACA code element library) with **136923 degrees of freedom**. The steel tie rods and wooden elements of the roof have been discretized using beam elements (n°. 9 of the NOSA-ITACA code element library). As a first attempt the masonry has been modeled as a homogeneous material with Young's modulus E = 4000 MPa, Poisson's ratio $\nu = 0.2$ and mass density $\rho = 1800$ kg/m^3.



FEM model: a) overview; b) west side; c) south side; d) cross-section and magnification of the model

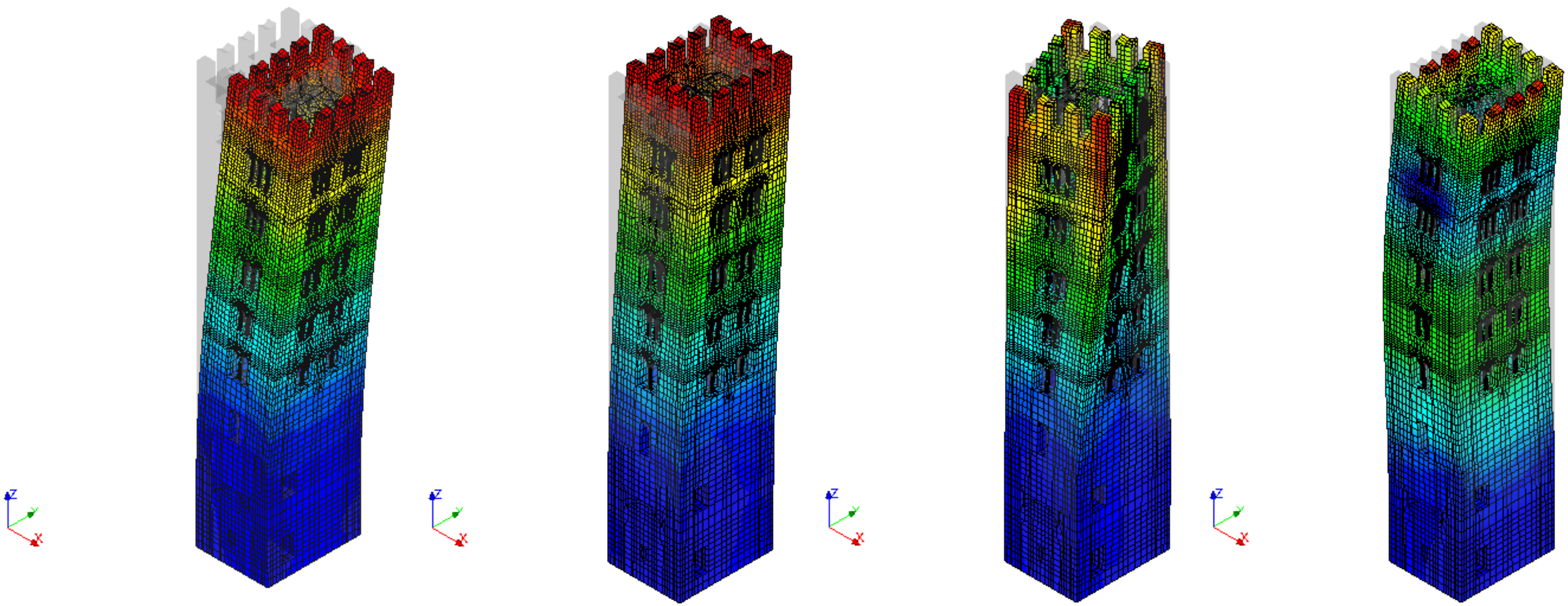
The structure is assumed to be clamped at the base, and additional boundary conditions have been imposed 12.50m above the base to account for the church's walls.

- **Operational Modal Analyses Techniques**



- **Data processing results versus FEM analysis results**

OMA technique used: Enhanced Frequency Domain Decomposition via the **TruDI** software (s**Tru**ctural **D**ynamic **I**dentification) developed within the project.



Mode 1 (along X):

f_{FEM} = 1.177 Hz

f_{EFDD} = 1.116 Hz

ξ_{EFDD} = 0.81 %

Mode 2 (along Y):

f_{FEM} = 1.367 Hz

f_{EFDD} = 1.385 Hz

ξ_{EFDD} = 0.85%

Mode3 (torsional mode):

f_{FEM} = 3.341 Hz

f_{EFDD} = 3.485 Hz

ξ_{EFDD} = 0.29 %

Mode 4 (along X):

f_{FEM} = 5.053 Hz

f_{EFDD} = 4.606 Hz

ξ_{EFDD} = 0.22%

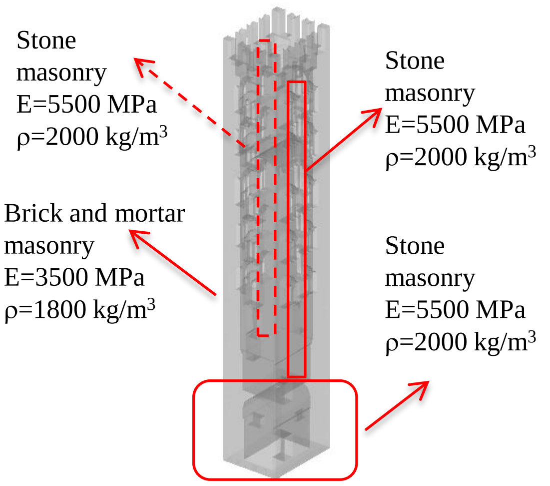
- **Updating the FEM model** by varying the physical and mechanical characteristics of the materials

	Mode 1		Mode 2		Mode 3		Mode 4	
Experimental Frequency	**1.116 Hz**		**1.385 Hz**		**3.485 Hz**		**4.606 Hz**	
Finite Element Model	Freq. [Hz]	MAC	Freq. [Hz]	MAC	Freq. [Hz]	MAC	Freq. [Hz]	MAC
Model 1	1.117	0.921	1.367	0.952	3.341	0.315	5.053	0.703
Model 2	1.152	0.918	1.349	0.955	3.204	0.312	4.833	0.704

- Model 1: frequencies yielded by FEM modal analysis considering homogeneous elastic material with Young's modulus E = 4000 MPa and mass density ρ = 1800 kg/m^3;
- Model 2: frequencies yielded by FEM modal analysis considering 3 different materials (see figure).
- $$\mathrm{MAC}(\phi_{EXP},\psi_{FEM}) = \frac{\left|\phi^{H}_{EXP}\,\psi_{FEM}\right|^2}{\phi^{H}_{EXP}\,\phi_{EXP}\,\psi^{H}_{EXP}\,\psi_{EXP}}$$

ϕ_{EXP}, experimental modal vector; ψ_{FEM}, numerical modal vector

^{H}, complex conjugate transpose (Hermitian)



Conclusion

- The presentation has illustrated the progress and some preliminary results of the **MONSTER project**, whose aim is to develop an integrated monitoring and simulation system for age-old masonry constructions based on wireless sensor networks and the **NOSA-ITACA code** (http://www.nosaitaca.it/en/download).
- A small, inexpensive wireless sensor has been developed based on a 3-axis MEMS accelerometer whose native resolution settings have been adapted to enable structural monitoring of historical buildings.
- Preliminary laboratory results show the reliability of the proposed systems in terms of both measured accelerations and sample frequencies.
- Some prototypes are in the process of being produced and will be installed on the San Frediano bell tower in Lucca in order to estimate the acceleration levels.
- A finite element model of the tower has been built via the NOSA-ITACA code, and a preliminary modal analysis of the tower performed shows good agreement between the experimental and numerical results.

Thank you for your kind attention

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