COMPDYN 2017
6th International Conference on
Computational Methods in Structural Dynamics
and Earthquake Engineering
15-17 June 2017 – Rhodes Island, Greece

A new numerical procedure for assessing the dynamic behaviour of ancient masonry towers

D. Pellegrini[1], M. Girardi[1], C. Padovani[1] and R.M. Azzara[2]

[1] Institute of Information Science and Technologies, Italian National Research Council, Pisa, Italy
[2] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Osservatorio Sismologico di Arezzo, Italy

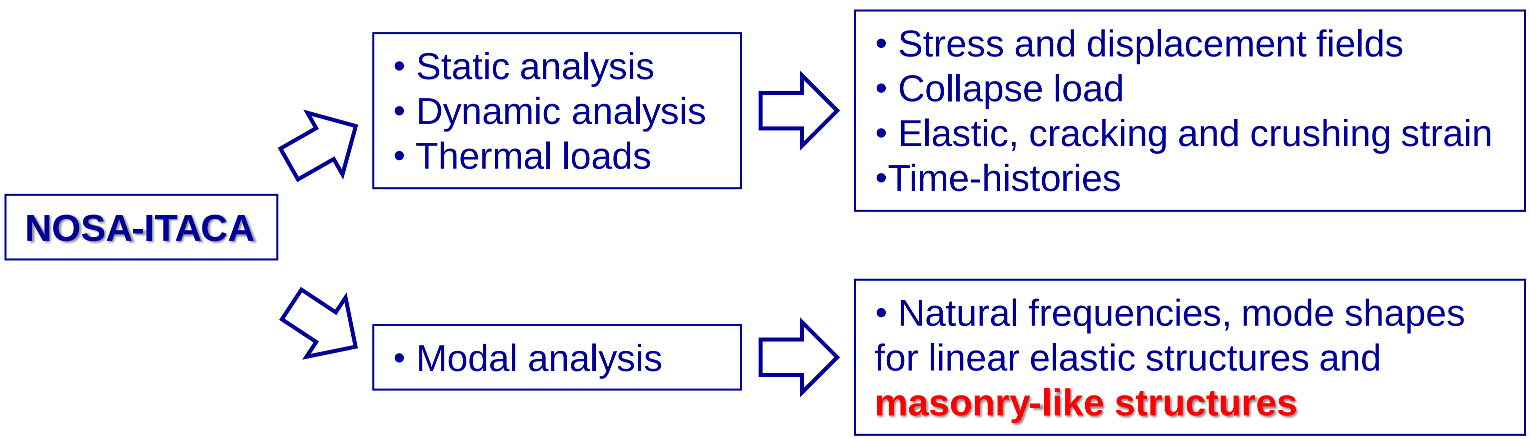
Summary :

1. The NOSA-ITACA software
2. The case study: The “Clock Tower” in Lucca
3. The finite element model of the tower
4. Model Updating
5. Conclusion

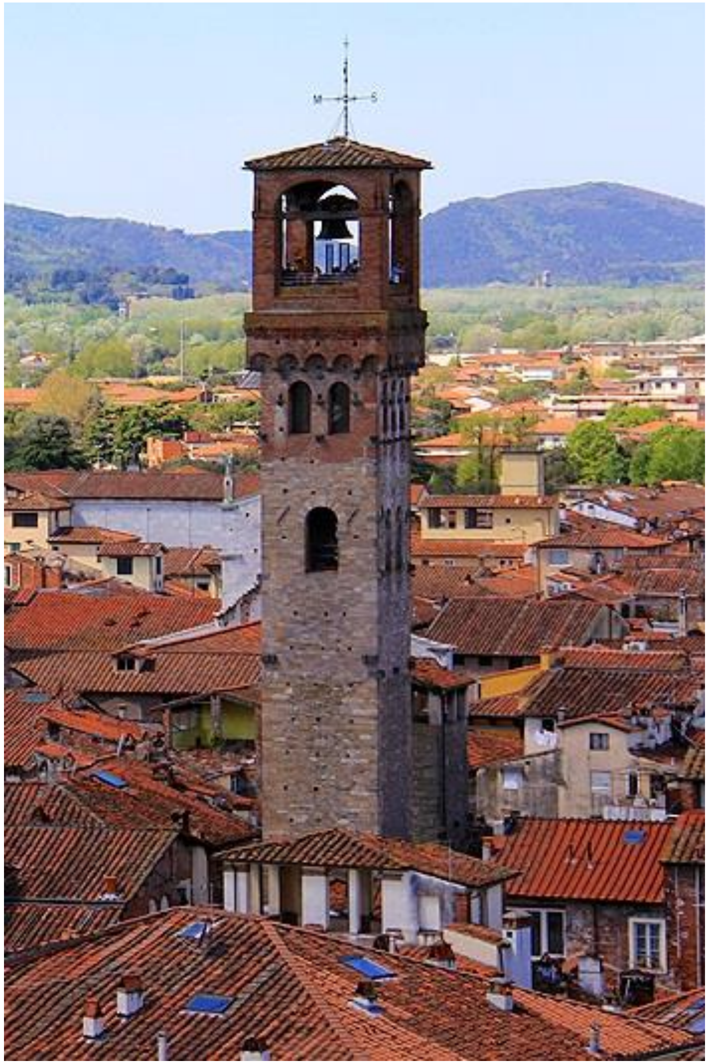
1. The NOSA-ITACA software (last release-version 1.1)

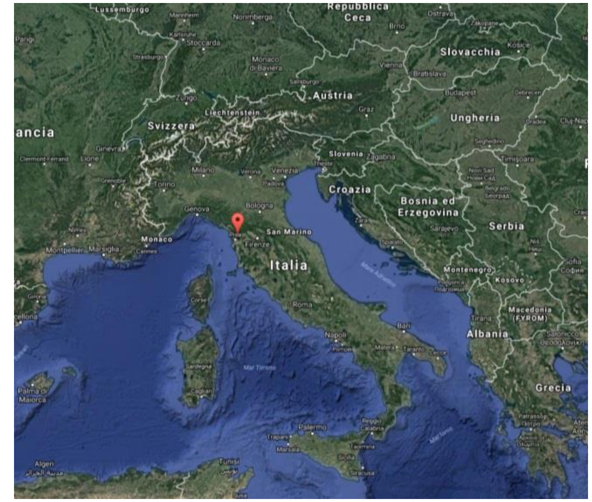
- **NOSA-ITACA** is a **freeware** software package developed by ISTI-CNR. It is a finite element code that combines NOSA with the open source graphic platform SALOME. It is used to study the static and dynamic behavior of masonry constructions.

- **Masonry** is described as a nonlinear elastic material with zero tensile strength and infinite or bounded compressive strength.



2. The case study: The "Clock Tower" in Lucca





<u>Characteristics of the tower</u>

- Height 48.4m;
- Rectangular cross section of about 5.1x7.1m;
- Walls of variable thickness from about 1.77 m at the base to 0.85 m at the top;
- Two barrel vaults set at heights of about 12.5 and 42.3 m, respectively;
- Adjacent buildings on two sides for a height of about 13 m (asymmetric boundary condition);
- Masonry of stone blocks and thin mortar joints and/or regular stone blocks and bricks, also with thin joints (no experimental information is available to date).

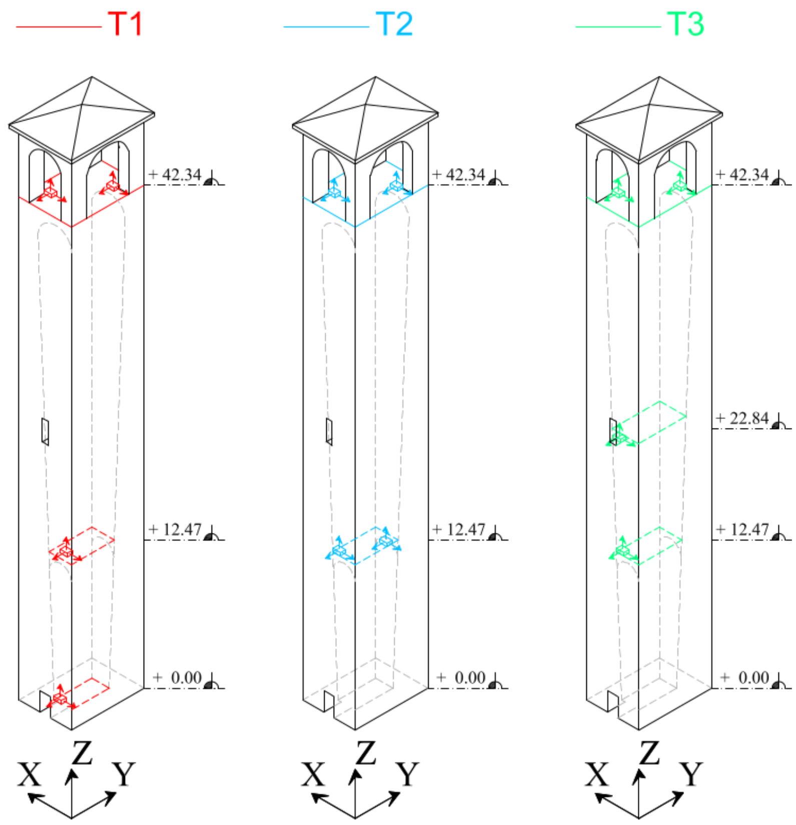
2. The case study: The “Clock Tower” in Lucca

Dynamic behaviour of the tower: experimental campaign

Strumentation employed: SARA Seismic Station; sampling frequency 100Hz.

	Frequency [Hz]	Mode	MPC
Mode 1	1.05	X direction	0.98
Mode 2	1.30	Y direction	0.97
Mode 3	4.20	torsional	0.96
Mode 4	4.50	torsional	0.92

First four mode shapes and the relative frequencies obtained by EFDD method.



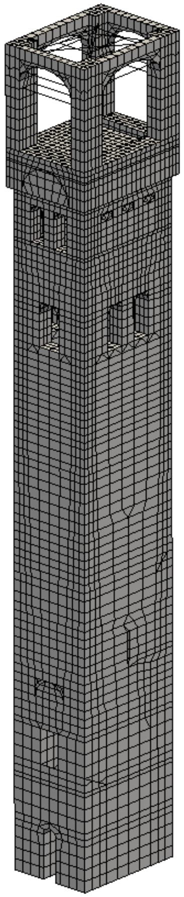
Sensors setup

3. The finite element model of the tower

NOSA–ITACA code is used, together with model updating techniques, in order to fit the experimental results in the linear elastic and the nonlinear (masonry–like) case.

<u>Finite element model charateristics:</u>

- 11383 brick elements;
- 34149 degrees of freedom;
- steel tie rods and wooden elements of the roof discretized by beam elements;
- Wood: Young's modulus E = 10000 MPa; density ρ = 800 kg/m3;
- structure clamped at the base and additional boundary conditions.



4. Model updating

Hypothesis: bell tower made of a homogeneous isotropic masonry-like material with Poisson's ratio $\nu = 0.2$, Young's modulus E and mass density ρ.

Model updating conducted by varying E and ρ in the following intervals:

$$2500 \text{ MPa} \leq E \leq 5500 \text{ MPa}$$

$$1700 \text{ kg/m}^3 \leq \rho \leq 2100 \text{ kg/m}^3$$

Minimization of the functions:

$$e^l(E, \rho) = \sum_{i=1}^{4} (f^l_i(E, \rho) - f_i^{exp})^2 \quad \text{linear case}$$

$$e(E, \rho) = \sum_{i=1}^{4} (f_i(E, \rho) - f_i^{exp})^2 \quad \text{nonlinear case}$$

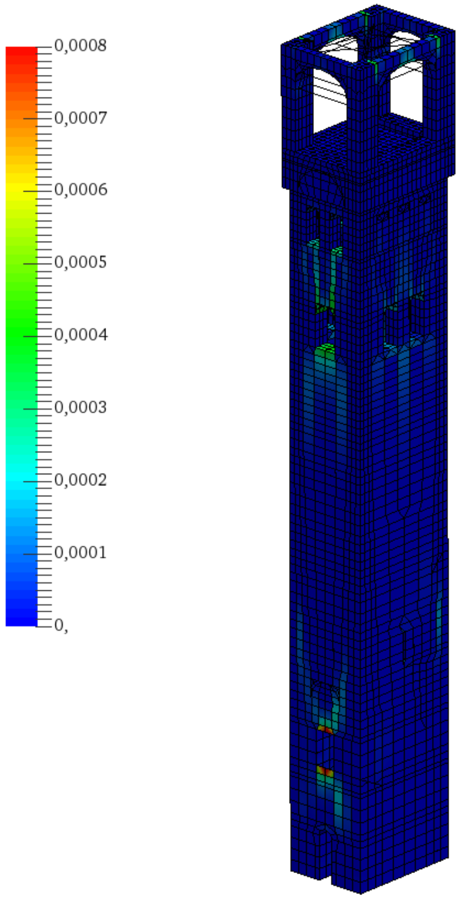
4. Model updating

	ϕ_1	ϕ_2	ϕ_3	ϕ_4
ϕ^l_1	**0.998**	0.039	0.019	0.020
ϕ^l_2	0.038	**0.997**	0.008	0.011
ϕ^l_3	0.003	0.008	**0.810**	0.580
ϕ^l_4	0.024	0.000	0.580	**0.800**

Table of MAC-M (ϕ^l_i, ϕ_j)

	f_i^{exp} [Hz]	f^l_i [Hz]	$\mid f_i^{exp}-f^l_i \mid / f_i^{exp}$ [%]	f_i [Hz]	$\mid f_i^{exp}-f_i \mid / f_i^{exp}$ [%]
Mode shape 1	1.05	0.98	7.0	1.08	3.0
Mode shape 2	1.30	1.24	5.0	1.28	2.0
Mode shape 3	4.20	4.32	3.0	4.24	1.0
Mode shape 4	4.50	4.38	3.0	4.52	0.4

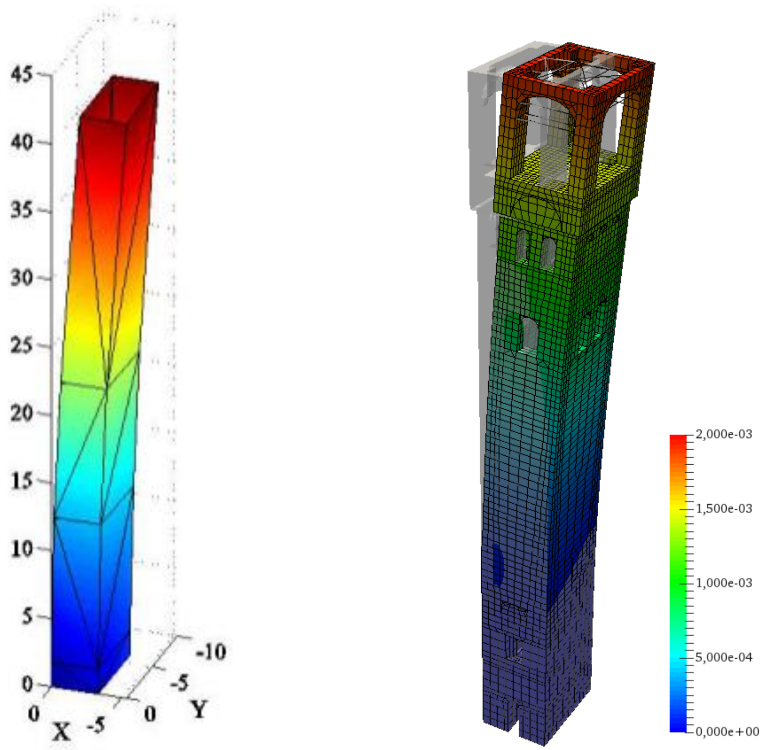
Frequencies: f_i^{exp} experimental, f^l_i linear case, f_i nonlinear case



Maximum principal fracture strain
E = 4500 MPa; ρ = 2100 kg/m^3

4. Model updating

Comparison between **experimental** results and **numerical** results (nonlinear masonry-like)

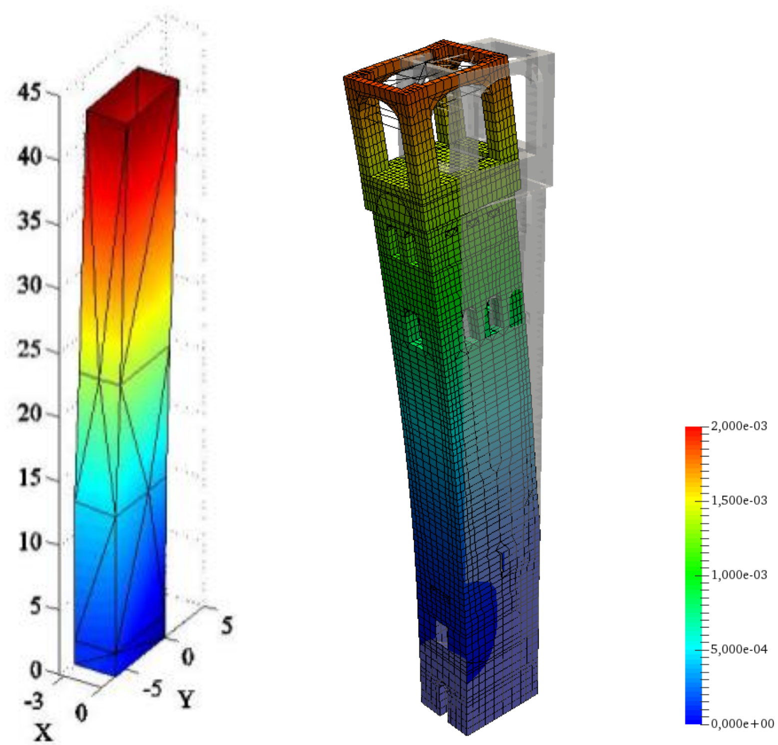


Mode 1: bending mode along X

f_1^{exp} = 1.05 Hz

f_1 = 1.08 Hz

MAC = 0.97



Mode 2: bending mode along Y

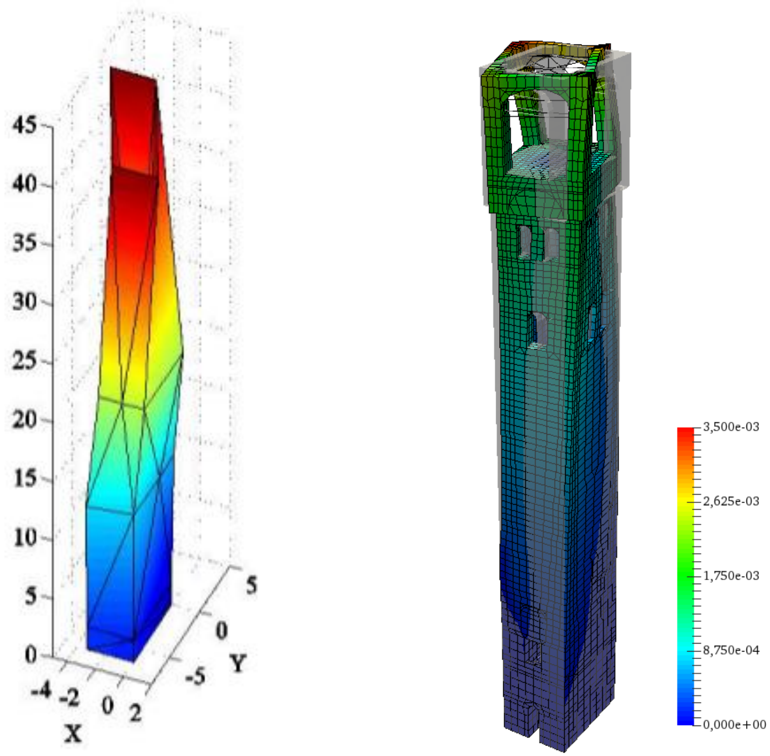
f_2^{exp} = 1.30 Hz

f_2 = 1.28 Hz

MAC = 0.93

4. Model updating

Comparison between **experimental** results and **numerical** results (nonlinear masonry-like)

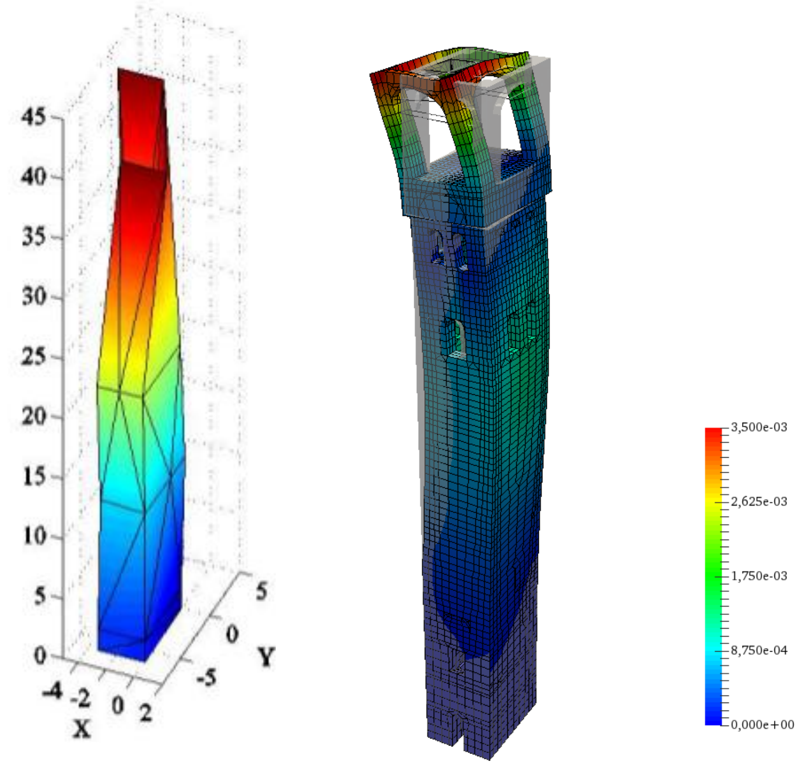


Mode 3: torsional mode

f_1^{exp} = 4.20 Hz

f_1 = 4.24 Hz

MAC = 0.81



Mode 4: bending and torsional mode

f_2^{exp} = 4.50 Hz

f_2 = 4.52 Hz

MAC = 0.52

5. Conclusion

- A new numerical procedure, implemented in the finite element code NOSA–ITACA, for the modal analysis of masonry structures is proposed.

- The procedure **allows** the user **to** automatically **take into account the influence of the stress distribution on the system's stiffness matrix**, thereby evaluating the effects of the presence of cracked material on the structure's dynamic properties.

- The method proposed has been applied to the "Clock Tower" in Lucca.

- The model updating in the linear elastic case has been compared to that in the nonlinear case, applied to the tower subjected to its own weight while taking into account the crack distribution induced by the load.

Thank you
for your kind attention

Acknowledgements

This research has been supported by the Region of Tuscany (PAR-FAS 2007-2013) and by MIUR, the Italian Ministry of Education, Universities and Research (FAR) within the Call FAR-FAS 2014 (**MOSCARDO Project:** “ICT technologies for structural monitoring of age old constructions based on wireless sensor networks and drones”, 2016-2018). This support is gratefully acknowledged.

D. Pellegrini[1], M. Girardi[1], C. Padovani[1] and R.M. Azzara[2]

[1] Institute of Information Science and Technologies, Italian National Research Council, Pisa, Italy
[2] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Osservatorio Sismologico di Arezzo, Italy