Title:

FE model updating of the Matilde donjon in Livorno

CC 16. Structural Health Monitoring and Model Updating for Heritage Structures

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Ambient vibrations, Seismic monitoring, Structural dynamic response, Operational Modal Analysis, Masonry Buildings, FE Analysis, Model Updating, Frequency Matching.

Introduction (300 words)

The combined use of ambient vibration monitoring, dynamic identification techniques, finite element analysis and model updating can provide important information about the dynamic characteristics of historical buildings and improve the knowledge of such structures in terms of mechanical characteristics of their constituent materials and/or boundary conditions. To this end, the use of highly sensitive experimental equipment, able to detect low vibration levels, and efficient computational tools, capable of handling detailed and complex finite element (FE) models, are crucial. In October 2017 an ambient vibration monitoring experiment was carried out on the Matilde donjon, a fortified keep belonging to the "Old Fortress", nearby the ancient Medici Port of Livorno, Italy (Figure 1).

The ambient vibrations of the tower were monitored for a few hours via five SARA SS20 seismometric stations, positioned according to different layouts. This monitoring campaign allowed identifying some of the donjon's natural frequencies and mode shapes using OMA techniques in both the frequency and the time domain and implemented by ISTI-CNR. Then, a detailed numerical model of the tower has been constructed via the NOSA-ITACA code and calibrated in order to fit the experimental frequencies using a numerical procedure for model updating specifically implemented by the authors. The algorithm is based on the construction of local parametric reduced-order models embedded in a trust region scheme for solving the constrained minimum problem; it exploits the structure of the stiffness and mass matrices and the fact that only a few of the smallest eigenvalues have to be calculated in order to solve the problem. This new procedure reduces both the overall computation time of the numerical process and user effort, and proved to be an efficient tool specific for FE model updating [1,2].

Figure 1. The "Old Fortress" and the Matilde donjon

Methods (300 words)

The donjon of the “Old Fortress” is a 26 m high cylindrical tower, dating back to the 13th century. The cross section has a mean outer radius of 6 m and the walls have constant thickness of 2.5 m along the height. There is no information available on the mechanical properties of the constituent materials; by visual inspection, the tower appears to be made of mixed brick-stone masonry with the internal layer constituted by clay bricks and mortar joints, and the outer, more irregular, by stone blocks and bricks. The tower hosts inside four vaulted rooms (Figure 2); at the base there is a large cistern for collecting rainwater, about 6 m high. Inside the tower’s wall a helicoidal staircase, starting from so-called “Capitani” room, (level 0, see Figure 2) allows reaching the upper floor and the roof terrace, crowned by cantilevered merlons. The tower is well stuck to the Old Fortress external walls for a height of about 9 m from the level of the lower galleries (Figure 3).

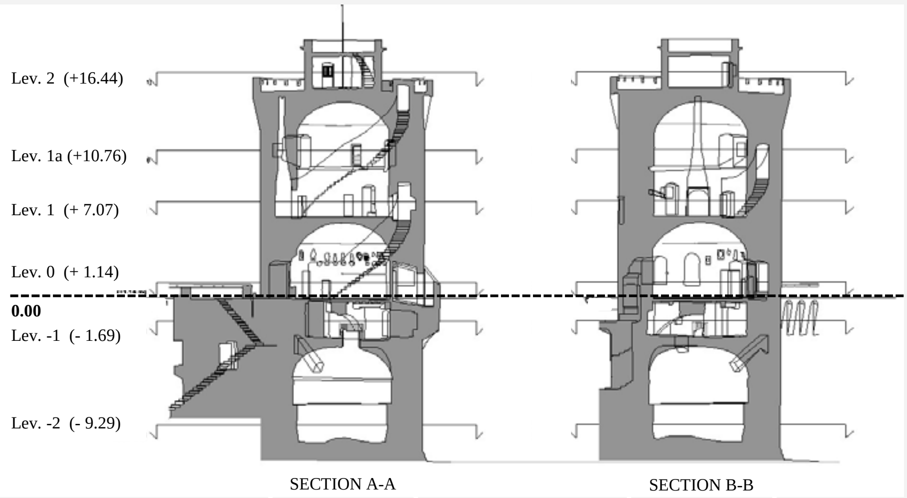

Figure 2. Vertical section of the Matilde donjon

Figure 3 shows the layout of the sensors installed on the donjon on 25 October 2017. During the five tests (from T1 to T5), each lasting about thirty minutes, two sensors were kept in a fixed position, one at the base (level -2) and the other on the roof terrace (level 2), while the remaining sensors were moved in different positions along the tower’s height and the surrounding area, in order to obtain information on the mode shapes and the connection degree between the Old Fortress’ structures and the tower itself.

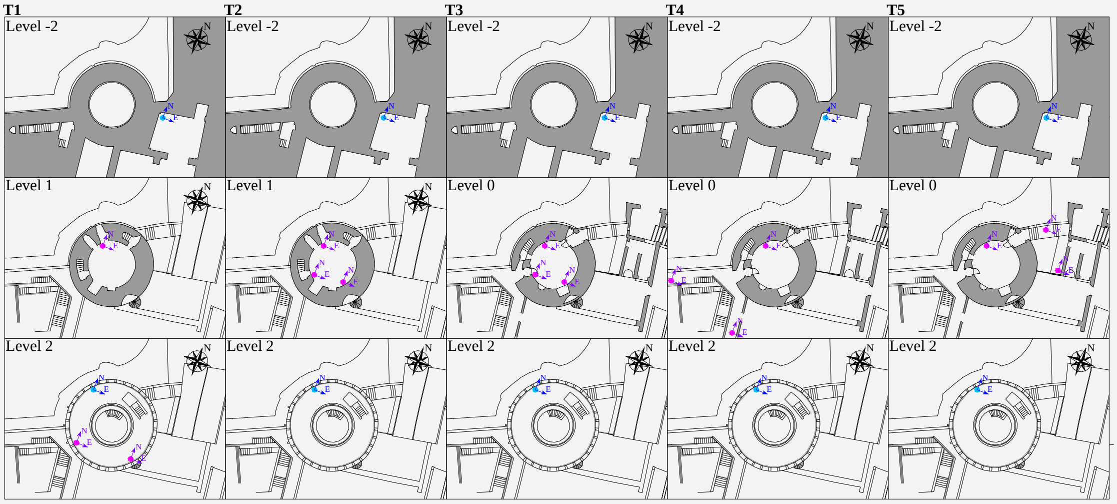

Figure 3. Sensors layout during the experimental campaign

All data have been processed using two Matlab tools implemented by ISTI-CNR, based on the Enhanced Frequency Domain Decomposition Method (EFDD) and the Eigensystem Realization Algorithm (ERA) [3]. The results obtained via the two algorithms are in good agreement. Then, a FE model of the tower and the surrounding area has been created via the NOSA-ITACA code (www.nosaitaca.it). The structure has been discretized into 64380 isoparametric 8-node brick elements (element 8 of NOSA-ITACA library) for a total number of 193140 degrees of freedom (Figure 4).

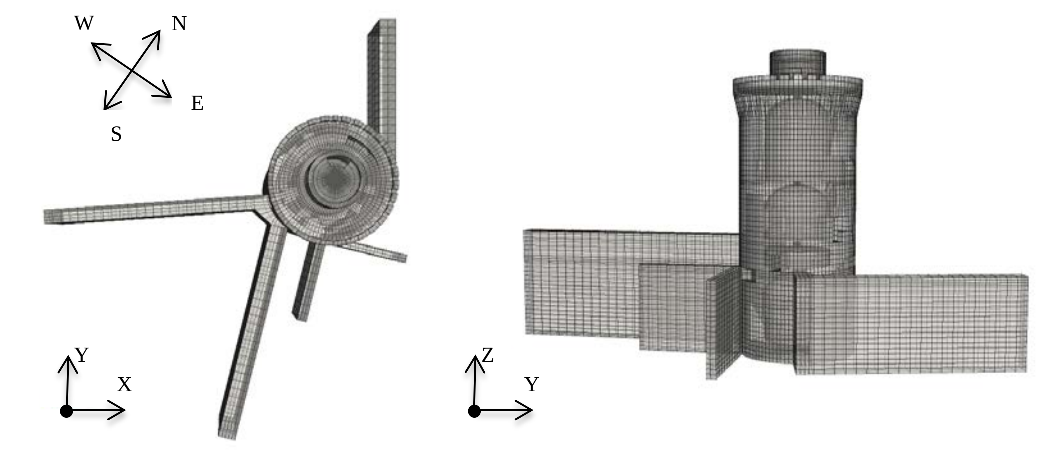

Figure 4. Mesh of the structure created by NOSA-ITACA code

Finally, the FE model updating algorithm described in [1,2] has been applied to the discretized structure, in order to obtain a preliminary estimation of the constituent materials' mechanical properties .

Results (300 words)

The EFDD and ERA algorithms allowed estimating the first natural frequencies, damping and mode shapes of the structure; the mean values (on the five tests) of the first four frequencies identified via both methods are: 2.69 Hz, 3.37 Hz, 8.10 Hz and 11.95 Hz, corresponding to bending along W-E direction, bending along N-S direction, torsion and a torsion mixed with bending along N/E-S/O direction. The model updating algorithm implemented in NOSA-ITACA has been used, to estimate the values of the Young's moduli of the inner ($E_{t,i}$) and the outer ($E_{t,e}$) layers of the tower's walls, and the Young's modulus E_m of the masonry constituting the Fortress' walls. These parameters have been allowed to vary inside the intervals:

$$1500\text{MPa} \le E_{t,i} \le 5000\text{MPa}$$
$$1500\text{MPa} \le E_{t,e} \le 5000\text{MPa}$$
$$1000\text{MPa} \le E_{m} \le 6000\text{MPa}$$

The Poisson's ratio of masonry is fixed to 0.2, the mass density of the tower's walls is fixed to 1800 kg/m^3 and 2000 kg/m^3 for the inner and outer layer, respectively; the mass density of the side walls is assumed equal to 2000 kg/m^3. The total computation time for the model updating procedure is 650.84 s and the optimization process converges in 7 iterations. The parameters found are:

$$E_{t,i} = 3007\text{MPa} \quad E_{t,e} = 1843\text{MPa} \quad E_{m} = 6000\text{MPa}$$

Table 1 shows the tower's frequencies found numerically after optimization, their relative errors Δf with respect to the experimental values and the MAC values calculated between experimental and numerical mode shapes. Finally, in Figure 5 the first mode shape calculated via the NOSA-ITACA code is plotted.

f_{exp} [Hz]	f_{num} [Hz]	Δf [%]	MAC
2.69	2.76	-2.60	0.96
3.37	3.27	2.99	0.96
8.13	7.60	6.51	0.81
11.95	11.10	7.11	0.70

Table 1- Experimental (f_{exp}) and numerical (f_{num}) frequencies, relative errors (Δf) and MAC values.

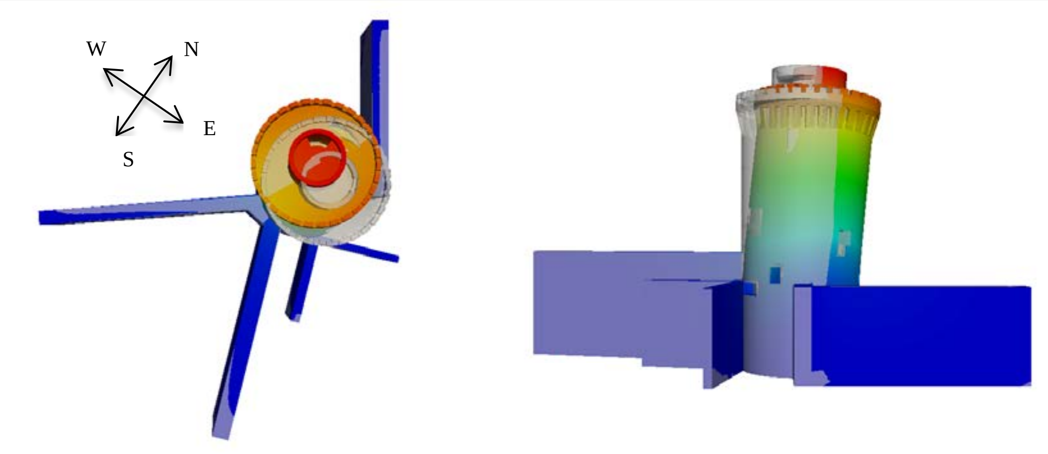

Figure 5. The first numerical mode shape of the tower.

Conclusions and Contributions (300 words)

The paper describes a preliminary experimental campaign conducted on The Matilde donjon in Livorno (Italy) aimed to characterize its dynamic behaviour, and the corresponding numerical analysis conducted on a FE model created via the NOSA-ITACA code. From the experimental point of view, it seems clear that further investigations are needed in order to better understand the dynamic behaviour of the tower with respect to the high frequencies and corresponding mode shapes. From the numerical point of view, a detailed FE model of the tower constructed via the NOSA-ITACA code has been calibrated in order to fit the experimental frequencies using a numerical procedure for model updating specifically implemented by the authors in the code. The parameters obtained by optimization process are able to fit well the low frequencies while the highest ones present a maximum relative errors of 7% with respect to the experimental values. Further investigations involving the boundary conditions and a sensitivity analysis are therefore required.

References

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Abstract summary (400 words)

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The ambient vibrations of the tower were monitored for a few hours via five seismometric stations, positioned according to different layouts. This monitoring campaign allowed identifying some of the donjon’s natural frequencies and mode shapes using OMA techniques in both the frequency and the time domain and implemented by ISTI-CNR. Then, a detailed numerical model of the tower has been constructed via the NOSA-ITACA code and calibrated in order to fit the experimental frequencies using a numerical procedure for model updating specifically implemented by the authors. The algorithm is based on the construction of local parametric reduced-order models embedded in a trust region scheme for solving the constrained minimum problem; it exploits the structure of the stiffness and mass matrices and the fact that only a few of the smallest eigenvalues have to be calculated in order to solve the problem. This new procedure reduces both the overall computation time of the numerical process and user effort, and proved to be an efficient tool specific for FE model updating.