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Nonlinear static analyses to improve the seismic damage assessment of monitored masonry palaces: application to the Consoli Palace of Gubbio, Italy

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Abstract

The conservation of the built architectural heritage in seismic-prone regions is a topical task in modern civil engineering. The ongoing diffusion of structural health monitoring systems calls for innovative and efficient methodologies for damage identification and condition assessment from field data. For this purpose, the paper proposes a novel model-based and data-informed approach relating the variation of the modal properties of the structure to increasing levels of seismic damage, looking into the outcomes of pushover analysis from a frequency-domain perspective. The direct problem is addressed through nonlinear static analyses, in which the structure is progressively damaged by applying simplified distributions of earthquake-induced horizontal forces, followed by a modal analysis at each degraded damage state. Addressing the inverse problem, starting from experimentally identified variations of the spectral properties and exploiting the simulation results, efficiently provides valuable insights into potential damage levels suffered by the structure. The forward methodology is exemplified by the application to a continuously monitored monumental masonry palace, the Consoli Palace of Gubbio, Italy, which was recently hit by a low-to-medium intensity earthquake and exhibited a slight reduction of its natural frequencies.

Keywords: equivalent frame model; finite element model; nonlinear static analyses; damage assessment; modal identification; structural health monitoring.

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1. Introduction

Structural monitoring systems are being widely implemented for the real-time sensing, identification, and prediction of the health conditions of heritage structures. With the advent of smaller, cheaper, and more sensitive sensors, together with the development of next-generation non-contact technologies, a huge effort is being spent to manage and fuse the huge amount of heterogeneous data provided by this emergent diagnostic tool (Ierimonti et al. 2023). Nonetheless, there is still a significant gap between data provided by Structural Health Monitoring (SHM) systems and the information which must be extracted and interpreted for engineering purposes (Kamariotis et al. 2022), although this constitutes a fundamental step to reliably support the inspection, management, maintenance, and conservation of structural assets.

In such a context, pure data-driven approaches—which saw a big leap in progress from the recent developments in artificial intelligence (Mishra, M., 2021)—are being challenged by hybrid data-informed but model-based methodologies (Venanzi et al. 2020, Sivori et al. 2022, Zhang et al. 2023), in which physics-based computational models are employed to better interface with experimental data. This tendency seems particularly relevant for the health monitoring of old and heterogeneous heritage structures such as monumental masonry palaces, which encompass a large architectural and cultural value exposed to the seismic risk and, for their peculiar characteristics, pose interesting challenges in the monitoring of their structural health conditions.

The paper proposes a hybrid SHM methodology fusing a digital model of the structure with the experimental measurements coming from its monitoring system, aimed at supporting the health assessment of monumental masonry palaces. Among the possible modelling strategies (D'Altri et al. 2021, Cattari et al. 2022), the proposal exploits the low computational burden of the Equivalent-Frame (EF) representation of the structure to, first, perform efficient simulations of the nonlinear response to the earthquake and, second, to directly relate increasing levels of seismic damage to the corresponding variation of the modal properties of the structure. This same knowledge is extremely valuable in attacking the inverse problem, starting from experimentally identified variations of the spectral properties to deduce the level of damage potentially suffered by the structure and predict the evolution of its performance. On the one hand, approaching this task from the experimental point of view solely would be challenging, given the lack of monitoring and observational data regarding damaged structures and the limitations of pure data-driven approaches in the prognosis phases. On the other hand, the employment of high-fidelity formulations—such as Finite Element (FE) models—is unlikely to be paired with real-time applications due to the high computational capabilities required, if not relying on model-order reduction techniques such as surrogate representations (Ierimonti et al. 2021). The proposal stands in the middle, improving data interpretation through a synthetic EF model—which could be regarded itself as a physics-based surrogate—and accounting for the limitations related to the simplifying assumptions that make this choice viable from a computational point of view.

Section 2 summarizes the forward methodology which aims, first, at simulating seismic damage scenarios of increasing severity through nonlinear static analyses and, second, at identifying the corresponding variations in the modal properties of the structure through modal analyses. In particular, the degradation of the global stiffness is estimated starting from the diffusion of structural damage in masonry elements, whose stiffness reduction is quantified from the relationship linking the actual drift to the resistant shear.

Section 3 exemplifies the procedure for a continuously monitored monumental masonry palace, the Consoli Palace of Gubbio, Italy, which was recently hit by a low-to-medium intensity earthquake and exhibited a slight reduction of its natural frequencies (García-Macías et al. 2022).

Finally, Section 4 looks forward to future real-time employment of the EF model as a physics-based surrogate to support the SHM-informed damage evaluation and decisional processes in the post-seismic emergency phase, outlining other potential fields of application such as the assessment of ageing and degradation phenomena.

2. A simplified methodology to build an Equivalent Frame-based surrogate model from NonLinear Static Analyses

This paragraph outlines the methodological approach proposed to simulate increasing levels of seismic damage in masonry palaces and identify the corresponding variation of their modal properties, exploiting the execution of

NonLinear Static Analyses (NLSA) on a dynamically calibrated EF model of the structure. The procedure, illustrated in the flow-chart of Fig. 1, follows these logical steps:

a) elaborate the EF model of the structure: calibrate the elastic mechanical properties based on the experimental modal properties $\boldsymbol{\omega}^*$, $\boldsymbol{\Phi}^*$ (natural frequencies, mode shapes) representative of the pre-seismic undamaged state
b) simulate damage scenarios of increasing severity through NLSA: reduce the stiffness K of each structural element based on the maximum achieved element drift $\theta_{\max}$
c) solve the forward problem: given a set of reduced element stiffnesses $\boldsymbol{K}_{\mathrm{d}}$ representative of a certain damage scenario, find the corresponding set of spectral properties $\boldsymbol{\omega}_{\mathrm{d}}$, $\boldsymbol{\Phi}_{\mathrm{d}}$

$$\boldsymbol{K}_{\mathrm{d}} \rightarrow \boldsymbol{\omega}_{\mathrm{d}}, \boldsymbol{\Phi}_{\mathrm{d}}$$

d) address the inverse problem: given a set of post-seismic experimental spectral properties $\boldsymbol{\omega}^*_{\mathrm{d}}$, $\boldsymbol{\Phi}^*_{\mathrm{d}}$ representative of an actual damage scenario, find—if it exists—a corresponding set of reduced element stiffnesses $\boldsymbol{K}_{\mathrm{d}}$

$$\boldsymbol{\omega}^*_{\mathrm{d}}, \boldsymbol{\Phi}^*_{\mathrm{d}} \rightarrow \boldsymbol{K}_{\mathrm{d}}$$

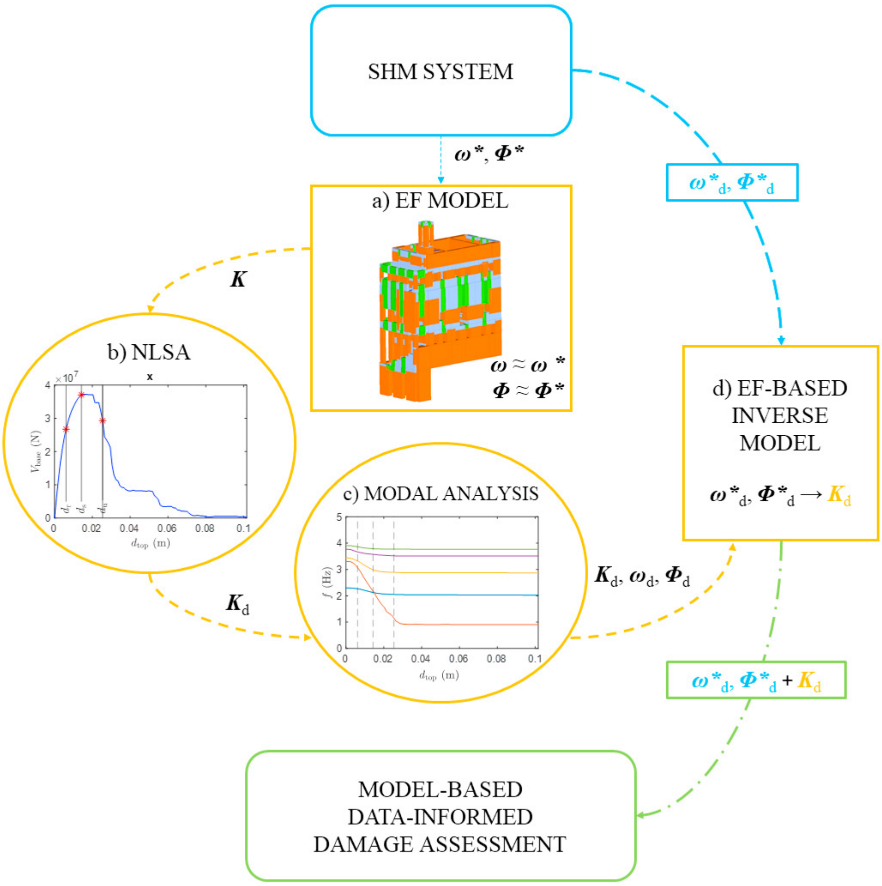

Fig. 1. Flowchart of the proposed methodology.

The first step, namely point a), involves the development of a detailed EF model based on the prior engineering knowledge of the existing structure. In the EF formulation, deformability and nonlinearity are concentrated only in specific portions of the masonry walls, i.e., *piers* and *spandrels*, in which seismic damage tends to concentrate according to experimental observations. For what concerns masonry palaces, structures which can strongly deviate from the classical constructive rules recognizable in ordinary masonry buildings, this phase strongly relies on a proper engineering judgement—related to the EF mesh definition, the choice of boundary conditions and element connections, the modelling of floor diaphragms, and more. A discussion on these aspects related to the EF modelling of masonry palaces is reported in Cattari et al. 2021a. Nonetheless, epistemic and aleatory uncertainties can be further addressed based on the results of SHM measurements (Ponte et al. 2021, Cattari et al. 2021b, Degli Abbati et al. 2022). In the elastic regime, the mechanical parameters of the model can be calibrated for the set of k-natural circular frequencies $\boldsymbol{\omega} = [\,\omega_1, \omega_2, \ldots, \omega_k]$ and mode shapes $\boldsymbol{\Phi} = [\,\boldsymbol{\Phi}_1, \boldsymbol{\Phi}_2, \ldots, \boldsymbol{\Phi}_k]$ to fit the experimentally identified sets $\boldsymbol{\omega}^*$, $\boldsymbol{\Phi}^*$ representative of the structure in its undamaged—baseline—state.

Once the model has been properly calibrated, in the second step named point b), the structure is subjected to a simplified distribution of increasing horizontal forces representative of the seismic action. This simulation, known as NonLinear Static Analysis (NLSA) or *pushover* analysis, allows investigating the nonlinear static response of the structure for increasing intensity of the seismic input with a low computational burden—if compared to more accurate but expensive NonLinear Dynamic Analysis (NLDA). In this paper, the first option is being investigated, the second having been explored by some of the Authors in previous research works to define a seismic damage chart of the structure for its SHM (see Sivori et al. 2022). Indeed, a wider and more comprehensive population of increasing-severity damage scenarios can be simulated, for example, considering aleatory uncertainties in the definition of the mechanical parameters (modelled through probability distributions), as well as the variability in the seismic input (modelled through different force distributions).

To the evolution of the structural response, which is represented in terms of responding base shear V_{base} with respect to the achieved top displacement d_{top} by the pushover curve of the structure, corresponds an increasing grade of structural damage. In the EF formulation, such damage is represented by the severity and diffusion of damage among structural elements—piers and spandrels. Damaging of elements, i.e. their damage level (DL), is commonly defined (Dolatshahi, Beyer 2019) as the exceeding of conventional thresholds in terms of element drift θ, to which correspond, initially, to reductions of the initial stiffness K and, eventually, drops of the resistant shear (Fig. 2). Based on the maximum achieved element drift $\theta_{\max}$, the evaluation of the reduced element stiffness K_{d} can be pursued considering the secant to the resistant shear or, more precisely, the least-squares fit of the current hysteretic response—after a complete cycle of loading and unloading, accounting for shear and flexural damage modalities (Fig. 2).

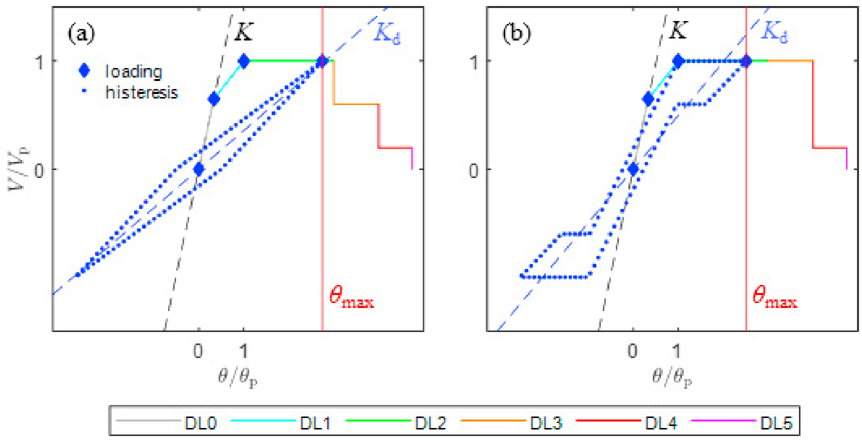

Fig. 2. Pier shear-drift relationship (normalized to the peak resistant shear V_{p} and corresponding drift θ_{p}) and hysteretic cycle at $\theta_{\max}$ for (a) shear and (b) flexural damage modalities. Initial stiffness K and least-squares estimate of the reduced stiffness K_{d}.

Once the equivalent stiffness reduction for each element and step of the analysis—damage scenario—is known, it is possible to identify the corresponding spectral quantities $\boldsymbol{\omega}_{\text{d}}$, $\boldsymbol{\Phi}_{\text{d}}$ through the solution of the related eigenvalue problem, i.e. a simple modal analysis. Thus, the solution of the forward problem allows, point c), to evaluate the effects of seismic damage on the natural frequencies and mode shapes of the structure, the two proxy quantities more frequently employed in the vibration-based condition assessment of monitored structures.

Previous steps can be performed during peacetime. A further step towards the integration between the computational model and experimental data, here only mentioned and to be investigated deeply in the future, regards the operative employment of such valuable results for the quasi-real time SHM in a seismic damage assessment framework. The task, point d), requires addressing an inverse problem, i.e. starting from variations in the experimental spectral properties $\boldsymbol{\omega}^*$, $\boldsymbol{\Phi}^*$ identified on the structure after an earthquake and, through the information provided by simulations, deducing information about damage severity, diffusion and localization—a distribution of reduced stiffnesses $\boldsymbol{K}_{\mathrm{d}}$. This phase should be approached with great caution, given the fact that nor the uniqueness nor the existence of such an inverse solution is guaranteed. A possibility is to seek the solution to an optimization problem through an appropriate model-updating technique (Ierimonti et al. 2021), a strategy which plausibly—in the Author's opinion—could be applied to the synthetic EF model directly, even in quasi-real-time applications requiring fast and efficient computations. The matter is further discussed in the future developments of the research (Section 4).

3. Application to a continuously monitored monumental masonry palace: the Consoli Palace of Gubbio, Italy

3.1. Synthetic description of the palace and AVT configuration

The Consoli Palace is a 60 meters high medieval building, located in Gubbio, Umbria, central Italy (Fig. 3b). The Palace is built in calcareous stone masonry and it has a complex internal architectural configuration with vaulted ceilings, differently oriented.

With the main objective of better understanding the dynamic interaction between the palace and the bell tower and improving the calibration of computational models (Section 3.2), an AVT with a denser sensor array compared to the one used for long-term SHM purposes, notably including the bell tower, was carried out on the Palace on May 7th, 2021, whose configuration is reported in Fig. 3a. In detail, a total number of 18 (A1-A18) PCB393B12 unidirectional accelerometers wired to a NI CompactDAQ-9132 data acquisition system have been installed on Arengo hall, Nobili floor, rooftop and bell tower. For the sake of synthesis, results of dynamic identification are reported in Section 3.2, Table 1, in a direct comparison with the one simulated by the initial and calibrated EF models.

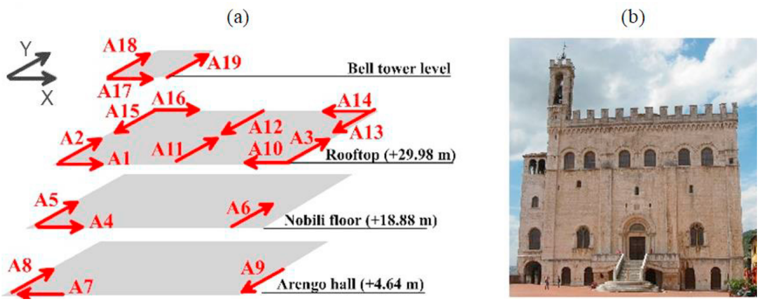

Fig. 3. (a) AVT configuration of (b) the Consoli Palace of Gubbio, Italy.

3.2. EF model updating and simulation results

The EF model of the structure, developed in previous research (Cattari et al. 2021) and analysed in the following with the research version of the TREMURI program (Lagomarsino et al. 2013), has been newly calibrated based on the results of AVT on the Consoli Palace (Section 3.1) which includes, among the other additional sensors with respect to the SHM system already installed, three horizontal measurement channels placed on the top of the bell tower. The primary role played by this structural element in the dynamics of the low-frequency modes of the structure has been already discussed in previous works (Kita et al. 2021, Cattari et al. 2021) and it is again confirmed by the results of the calibration, synthetically presented in the following paragraph.

Table 1. Results of the EF model elastic calibration.

Target	Initial - iteration 0, $\chi^2 = 12.265514$	Updated - iteration 37, $\chi^2 = 0.405137$
	$E_{p,x} = E_{p,y} = E_{bt,x} = E_{bt,y} = 4.752e+09$ Pa	$E_{p,x} = 5.582e+09$ Pa, $E_{p,y} = 7.331e+09$ Pa

							$E_{bt,x}$ = 5.157e+09 Pa, $E_{bt,y}$ = 6.003e+09 Pa			
Mode	Type†	f^* (Hz)	f (Hz)	Δf (%)	MAC	MAC (no b.t.)	f (Hz)	Δf (%)	MAC	MAC (no b.t.)
1	G-F_y	2.316	1.506	-34.95	0.94	0.99	2.301	-0.63	0.98	0.99
2	L(b.t.)-F_x	2.997	2.371	-20.89	0.09	0.14	3.302	10.17	0.97	0.60
3	L(b.t.)-F_y	3.542	2.454	-30.72	0.41	0.35	3.436	-3.00	0.98	0.87
4	G-F_x	3.746	3.005	-19.77	0.80	0.30	3.764	0.48	0.96	0.95
5	G-T_z	4.221	3.112	-26.28	0.42	0.65	3.904	-7.51	0.92	0.88

†G global mode, L local mode, F flexural mode, T torsional mode ("b.t." stands for "bell tower")

The calibration of the elastic mechanical properties of the model is pursued through a sensitivity-based iterative procedure (Mottershead et al. 2007), weighted and regularized, implemented through the Levenberg-Marquardt algorithm. Such algorithms iteratively minimize the sum of the squares of the errors between the model output and experimental data—in this case, the set of first five natural frequencies $\boldsymbol{f}$ and modal displacements $\boldsymbol{\Phi}$. The sensible updated parameters are the Young moduli of the masonry of the palace in the two directions, namely $E_{p,x}$ and $E_{p,y}$, and those of the bell tower, namely $E_{bt,x}$ and $E_{bt,y}$. On the one hand, separating the moduli between the two directions aims at overcoming some limitations in the present EF formulation, which is not accounting for the out-of-plane stiffness of masonry elements—a common and reliable assumption dealing with the modelling of ordinary masonry buildings which, as discussed in Cattari et al. 2021, loses its robustness due to the significant thicknesses of the palace masonry walls. On the other hand, accounting for different moduli for the masonry of the palace and for that of the bell tower aims at better capturing the dynamic behaviour and interactions between these two macro-elements. Other parameters, such as masonry mass density, are fixed according to previous results (see Cattari et al. 2021).

Convergence in parameters—a relative variation less than one part per thousand—is obtained after 37 iterations, each accounting for 5 function evaluations at least (four to estimate the Jacobian matrix and one for the update). The solution is achieved in around 30 minutes, exploiting parallel computing in a modern quad-core CPU. Table 1 summarizes the starting and updated values of the calibrated parameters, the initial and final relative frequency difference $\Delta f = (f - f^*) / f^*$ between simulated f and experimentally identified f^* natural frequencies, mode shapes correlation (MAC values). The results are satisfying, with (i) relative frequency differences lower than 5% for the first, third and fourth mode, very close and lower than 10% for the second and fifth mode respectively and (ii) MAC values higher than 0.9, resulting in a significant lowering of the sum of squared errors (fitness function χ^2, Table 1).

Interestingly, observing the mode shape correlation without considering the identified modal displacement of the bell tower (no b.t.) remarks how this element is governing the dynamics of the palace in the low-frequency band, even for modes which appear to be global (see MAC values for mode 4, initial model, Table 1). This is probably related to the in- or out-of-phase movement between the palace and the bell tower, which is not always captured correctly by the numerical model (and to the MAC dependency on the number of nodal displacements considered in the comparison). A significant increase in the Young modulus of the palace masonry along the y-direction $E_{p,y}$ with respect to the other moduli had already been observed in previous calibrations (Cattari et al. 2021), confirming this effect to be independent of the calibration strategy (global, local) and plausibly related to modelling assumptions, in particular (i) the unmodeled out-of-plane stiffness and (ii) the wall masses lumped at the storey level.

The calibrated EF model is employed to perform NLSA in both the main directions of the palace, considering a mass-proportional distribution of horizontal forces. At each step of the analysis, according to the proposal of Section 2, the stiffness of each structural element is decreased based on the maximum achieved element drift and, finally, a modal analysis is performed (less than 5 minutes for the whole process). The results, in terms of pushover curve and corresponding variations in natural frequencies and MAC values with respect to the initial undamaged state, are illustrated in Fig. 4. Table 2 reports explicitly such variations for a few significant points of the pushover curve, the end of the linear phase (d_r), the attainment of the maximum resistant shear (d_s) and its post-peak decay of 30% (d_u).

It can be observed (bold in Table 2) how different modes respond with different modalities and intensities to each damage scenario: pushing along the x-direction seems to affect primarily both the frequencies and mode shapes of a local mode, the flexural mode of the tower along the same direction (mode 2). Conversely, the analysis along the y-direction affects primarily the frequency of the global flexural mode of the structure in the same direction (mode 1), leaving the mode shape almost unchanged. These results show the possibility to estimate, through a calibrated EF model and efficient NLSA, the evolution of the modal behaviour of masonry palaces for increasing levels of seismic damage, aiming at their employment together with the SHM system for conditions assessment (Section 4).

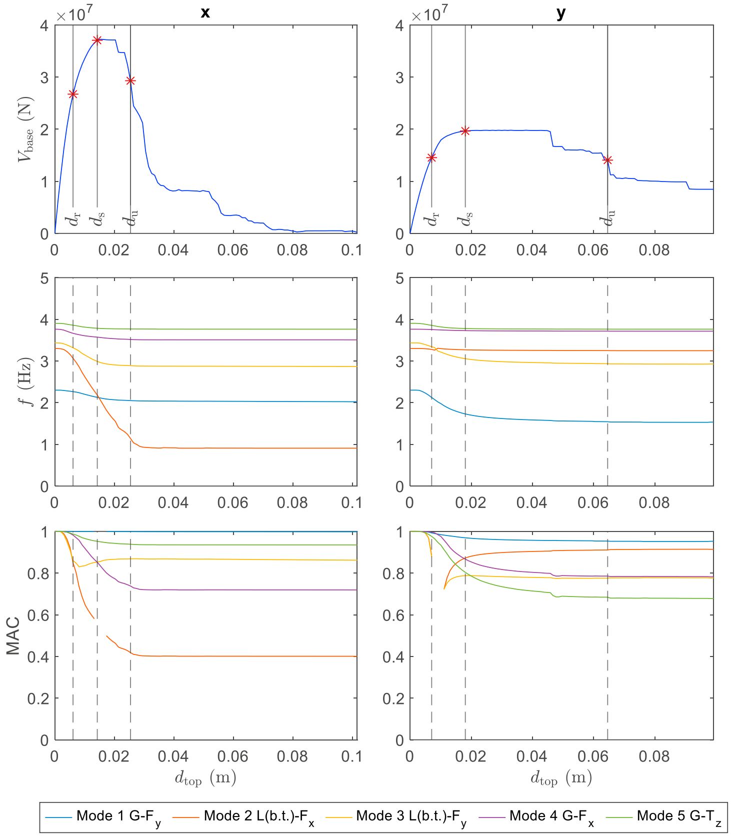

Fig. 4. NLSA results: (top) pushover curves along the two main directions of the palace, corresponding (middle) reduction of natural frequencies and (bottom) variations in the mode shape due to the damaging of structural elements.

Table 2. Reduction of natural frequencies and variations in mode shapes (MAC value) with respect to the undamaged state for significant damage steps, as generated by NLSA.

	x						y					
	d_r		d_s		d_u		d_r		d_s		d_u	
Mode	Δf (%)	MAC	Δf (%)	MAC	Δf (%)	MAC	Δf (%)	MAC	Δf (%)	MAC	Δf (%)	MAC
1	-1.6	1.00	-7.5	//	-10.9	1.00	**-7.7**	**0.99**	**-24.8**	**0.97**	**-32.9**	**0.95**
2	**-7.1**	**0.85**	**-33.9**	//	**-65.4**	**0.42**	-0.7	0.89	-1.0	0.87	-1.6	0.91
3	-3.5	0.86	-12.9	0.85	-15.9	0.87	-2.8	0.88	-11.1	0.79	-14.6	0.78
4	-2.6	0.98	-5.1	0.85	-6.6	0.74	-0.2	1.00	-0.9	0.87	-1.2	0.79
5	-1.2	0.99	-3.0	0.95	-3.4	0.94	-1.3	0.98	-3.2	0.80	-3.6	0.68

4. Conclusions

The paper has outlined a methodology to support the seismic monitoring of monumental masonry palaces, exploiting the EF formulation and its nonlinear capabilities. The application to a real case study shows the possibility, with low computational power and short simulation time, to estimate the variations of the modal properties of the structure for increasing levels of seismic damage. Future steps of the research are aimed at the integration with real vibration-based SHM systems, seeking the implementation of a hybrid model-based and data-informed damage evaluation framework to be automatically employed in the post-earthquake phase. The use of a synthetic EF representation of the structure as a physics-based surrogate model, thanks to a proper balance between simulation accuracy and time, could satisfy the requirement of quasi-real-time (order of minutes) seismic SHM, fulfilling both diagnosis—damage detection, quantification and localization—and prognosis—structural operativity and usability, residual capacity to seismic loading—tasks.

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References

Ierimonti, L., Venanzi, I., Cavalagli, N., García-Macías, E., Ubertini, F., 2023. Bayesian-Based Fusion of Monitoring Data and Visual Inspections in Monumental Structures. In: European Workshop on Structural Health Monitoring (pp. 1066-1075). Springer, Cham.

Kamariotis, A., Chatzi, E., Straub, D., 2022. Value of information from vibration-based structural health monitoring extracted via Bayesian model updating. Mechanical Systems and Signal Processing, 166, 108465.

Mishra, M., 2021. Machine learning techniques for structural health monitoring of heritage buildings: A state-of-the-art review and case studies. Journal of Cultural Heritage, 47, 227-245.

Venanzi, I., Kita, A., Cavalagli, N., Ierimonti, L., Ubertini, F., 2020. Earthquake-induced damage localization in an historic masonry tower through long-term dynamic monitoring and FE model calibration. Bulletin of Earthquake Engineering, 18(5), 2247-2274.

Sivori, D., Cattari, S., Lepidi, M., 2022. A methodological framework to relate the earthquake-induced frequency reduction to structural damage in masonry buildings. Bulletin of Earthquake Engineering, 1-36.

Zhang, H., Reuland, Y., Chatzi, E., Shan, J., 2023. Near-Real Time Evaluation Method of Seismic Damage Based on Structural Health Monitoring Data. In European Workshop on Structural Health Monitoring (pp. 114-122). Springer, Cham.

D'Altri, A. M., Sarhosis, V., Milani, G., Rots, J., Cattari, S., Lagomarsino, S., Sacco, E., Tralli, A., Castellazzi, G., de Miranda, S., 2020. Modeling strategies for the computational analysis of unreinforced masonry structures: review and classification. Archives of computational methods in engineering, 27(4), 1153-1185.

Cattari, S., D'Altri, A. M., Camilletti, D., Lagomarsino, S., 2022. Equivalent frame idealization of walls with irregular openings in masonry buildings. Engineering Structures, 256, 114055.

Ierimonti, L., Cavalagli, N., Venanzi, I., García-Macías, E., Ubertini, F., 2021. A transfer Bayesian learning methodology for structural health monitoring of monumental structures. Engineering Structures, 247, 113089.

García-Macías, E., Ubertini, F., 2022. Least Angle Regression for early-stage identification of earthquake-induced damage in a monumental masonry palace: Palazzo dei Consoli. Engineering Structures, 259, 114119.

Cattari, S., Sivori, D., Alfano, S., Ierimonti, L., Cavalagli, N., Venanzi, I., Ubertini, F., 2021a. Calibration of numerical models to support SHM: the Consoli Palace of Gubbio, Italy. Proceedings of the 8th Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2021).

Ponte, M., Bento, R., Vaz, S. D., 2021. A multi-disciplinary approach to the seismic assessment of the National Palace of Sintra. International Journal of Architectural Heritage, 15(5), 757-778.

Cattari, S., Degli Abbati, S., Alfano, S., Brunelli, A., Lorenzoni, F., da Porto, F., 2021b. Dynamic calibration and seismic validation of numerical models of URM buildings through permanent monitoring data. Earthquake Engineering and Structural Dynamics, 50(10), 2690-2711.

Degli Abbati, S., Morandi, P., Cattari, S., Spacone, E., 2022. On the reliability of the equivalent frame models: the case study of the permanently monitored Pizzoli's town hall. Bulletin of Earthquake Engineering, 20(4), 2187-2217.

Dolatshahi, K. M., Beyer, K., 2022. Stiffness and strength estimation of damaged unreinforced masonry walls using crack pattern. Journal of Earthquake Engineering, 26(2), 837-856.

Lagomarsino, S., Penna, A., Galasco, A., Cattari, S., 2013. TREMURI program: an equivalent frame model for the nonlinear seismic analysis of masonry buildings. Engineering structures, 56, 1787-1799.

Kita, A., Cavalagli, N., Ubertini, F., 2019. Temperature effects on static and dynamic behavior of Consoli Palace in Gubbio, Italy. Mechanical Systems and Signal Processing, 120, 180-202.

Mottershead, J. E., Link, M., Friswell, M. I., 2011. The sensitivity method in finite element model updating: A tutorial. Mechanical systems and signal processing, 25(7), 2275-2296.