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Towards the Seismic Monitoring of a Monumental Structure in Mixed Masonry-RC

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Abstract

The monumental historical heritage is recognized and appreciated worldwide. It is the result of the succession of different cultures that have inevitably influenced and characterized history; therefore, it represents an inestimable value to be preserved for future generations in order to transmit culture and art.

In addition, there is a growing engineering interest in the protection of cultural heritage since it is strongly vulnerable. In the present work, the authors present the first attempt of geometric and mechanical modeling (Finite Element Model) and the subsequent sensitivity analysis of the Upper Basilica of the Sanctuary of Oropa (Chiesa Nuova), characterized by a mixed structure in masonry and reinforced concrete.

The analysis conducted is placed at the beginning of a path of knowledge which, in subsequent steps, allows the understanding of the static and dynamic behavior of the analyzed structure. The goal of this work is to discriminate and validate which of the elastic parameters characterizing the individual components of the structure have a significant effect on the dynamic response of the structure, to facilitate the subsequent analysis aimed at defining the dynamic monitoring sensing system to be installed on the structure, and to support vulnerability analyses.

Keywords: Structural Health Monitoring; Sensitivity Analysis; Finite Element Models; Architectural Heritage; Monitoring Sensing System.

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1. Introduction

Nomenclature

FE	Finite Elements
DoFs	Degree of Freedom(s)
MAC	Modal Assurance Criterion
OSP	Optimal Sensor Placement
j	Free variable denoting a mode of the FE model
k	Free variable denoting a model parameter
K	Total number of FE model parameters
i	Free variable denoting the value of a model parameter
I	Total number of parameter values
$p_{k,i}$	Parameter value
$f_{j,k,i}$	Natural frequency
$\sigma_{j,k}^2$	Variance of the *j-th* natural frequency with respect to a variation of the *k-th* parameter
$r_{j,k}$	Fraction of variance for parameter k and mode j
E	Young's modulus
ν	Poisson ratio
ρ	Density

Historical masonry structures are intrinsically vulnerable to seismic actions (Asteris et al. 2014; Ferraris et al. 2020) due to the low tensile strength of the constituent materials and due to the presence of countless critical elements (e.g., pushing elements, presence of cavities in the load-bearing structures, etc.). Furthermore, most of the time, the high uncertainty and lack of knowledge of geometry, construction details, and materials increase the already difficult task of assessing structural vulnerability. In this context, to evaluate the safety of historical structures against seismic actions, and therefore to adopt an effective prevention policy, it is essential to achieve an adequate knowledge of dynamic behavior, especially in the case where the structural concept is not conventional, as in the mixed reinforced concrete-masonry buildings. The path of knowledge can be considered complete when a mechanical model of the analyzed structure faithfully traces the actual response of the system (Lenticchia et al. 2017). The analyzes and steps that characterize the knowledge of the dynamic behavior are represented by: (i) *sensitivity analysis* (Boscato et al. 2013, 2015), which allows to understand which of the parameters that characterize a mechanical model are significant and which are not significant in relation to the dynamic response of the structure; (ii) *OSP* (Lenticchia et al. 2018; Jaya et al. 2020; Civera et al. 2021), i.e. having defined the significant parameters in relation to the dynamic response of the system, the optimal position in which to locate the sensors to the structure is sought with different configurations of these parameters, in order to better grasp the actual structural response; (iii) *dynamic identification* (Andersen et al. 1999; Peeters and De Roeck 2001; Ceravolo et al. 2017), this occurs through operational or experimental modal analysis techniques; (iv) *model updating* (Qin et al. 2018; Ceravolo et al. 2020), which on the basis of the information obtained from dynamic identification, consists in updating the significant mechanical parameters of a numerical model, in order to make the predicted structural response consistent to the modal response of the actual structure.

In this work, the analyses conducted are placed at the beginning of the previously described path knowledge for the dynamic behavior. The objective of this paper is to discriminate which of the elastic parameters characterizing the individual macro components of the structure of the Sanctuary of Oropa (mixed structure in reinforced concrete-masonry) have a significant effect on the dynamic response in terms of modal frequencies. The paper is structured as follows: in Section 2, the method of the analyzes carried out is reported; in Section 3, the case study and the analyzes carried out are explained in detail; in Section 4, the results of the analyzes are discussed; finally, in Section 5, the conclusions of the study are drawn. The graphical abstract of the paper is depicted in Fig. 1, where the main steps needed for calibrating numerical models are highlighted.

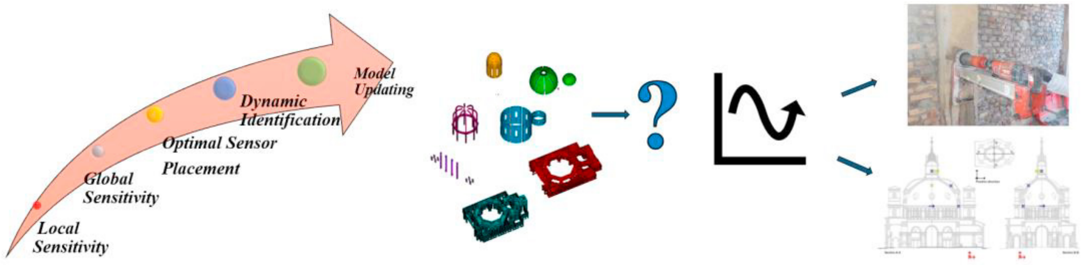


Fig. 1. Graphical abstract.

2. Methods

Given a generic value *i* of parameter *k*, $p_{k,i}$, and a natural frequency $f_{j,k,i}$ for the mode *j* the parameter *k* and the parameter value *i*, the variance of the *j-th* natural frequency with respect to a variation of the *k-th* parameter is evaluated as follow:

$$\sigma_{j,k}^2 = \sum_{i=1}^{I} \frac{\left(f_{j,k,i} - \widehat{\mathbf{f_{j,k}}}\right)^2}{I-1} \tag{1}$$

where I indicate the total number of values of the parameter k, while $\mathbf{f_{j,k}}$ is the vector containing the values of the natural frequency for mode *j* due to a variation of the parameter *k*, while the remaining parameters remain constant to the nominal value. Then, the symbol ˆ denotes the average value of $\mathbf{f_{j,k}}$.

For each mode *j*, the fraction of variance $r_{j,k}$ of parameter *k* is computed as follow:

$$r_{j,k} = \frac{\sigma_{j,k}^2}{\sum_{k=1}^{K} \sigma_{j,k}^2} \tag{2}$$

where *K* is the total number of parameters used in the modelling. In this context $r_{j,k}$ is used as indicator for the sensitivity analysis, to with the methodology discussed refers.

3. Application

In the paper, the fraction of variance $r_{j,k}$ has been calculated for K=21 parameters, each of which has been evaluated in I=30 values. Then, the analysis focused on the first three modes of the structure (i.e., j=1, 2, 3). Before performing the sensitivity analysis (i.e., calculating $r_{j,k}$), a static analysis due to gravitational load was performed to better understand which structural component is naturally mainly stressed by the weight of the structure. Then the extraction of the modal parameters has been performed to allow the sensitivity analysis.

3.1. Case study

The Sanctuary of Oropa is located near Biella in Piedmont (Italy). The Sanctuary was designed by Amedeo Galletti in 1774, but the construction started only in 1885. The structure of the Sanctuary presents a mixed configuration of masonry and reinforced concrete. In fact, the main body of the building, realized starting from 1885, was built in masonry, while the structure bearing the prepubescence of the dome structure (i.e., the columns, the drum, and the dome itself) was built in reinforced concrete. The dome was designed by architect Pietro Paolo Bonora as well as the engineer Amilcare Cucco, who designed a dome of 33 m in diameter and 80 m in height (from the ground floor), supported by eight great columns. This large portion of the Sanctuary was built starting by substituting the existing columns in masonry with the reinforced concrete ones between 1938-1941. So, the structure of the Sanctuary can be divided into several macro components:

- **Basement**: it extends from the ground floor at an altitude of z = 0 [m], up to an altitude of z = 22 [m] an altitude at which the entablature develops from the eight reinforced concrete columns.

- **Columns**: they extend to a height of 19.4 [m] and have a radius of 1 [m]. The structural component also includes the sixteen columns with the related horizontal elements (in syenite), which are located below the two-barrel vaults from which the two side wings develop.
- **Floors**: they develop on 4 levels. From a structural point of view, they allow to distribute the seismic action on the different resistant elements that characterize the structure.
- **Drums**: historically, the construction of the drum is due to the need to make the dome visible and to be able to build churches with a Latin cross. The upward extrusion of the dome, thanks to the construction of the drum has, in fact, led to the definition of a structural system known as the dome-drum system, which is very vulnerable to seismic action.
- **Buttresses**: it consists of the eight reinforced concrete columns (radius 1 [m] and height 22 [m]) which support the Major Dome (radius 33 [m]). Continuing to the columns and above the entablature it is possible to observe the eight reinforced concrete ribs of 1.15 x 1.76 [m], which from the structural point of view, represent a stiffening of the dome-drum system in relation to the horizontal actions.
- **Domes**: the component is composed of the two domes of the New Church. The main dome is of particular interest. The latter with a radius of 33 [m] and made of reinforced concrete (it differs from a structural point of view to the construction techniques of masonry domes), it is one of the largest reinforced concrete domes in the world. The minor dome, also made of reinforced concrete, has a radius of 7.5 [m].
- **Lantern**: represents the last macro-element that defines the entire structural system of the New Church. From a structural point of view, this macro-element is very important as its slenderness represents an element of vulnerability towards seismic actions.

A picture of the *Basilica Superiore* in Oropa is reported in Fig. 2, together with a plan of the structure.

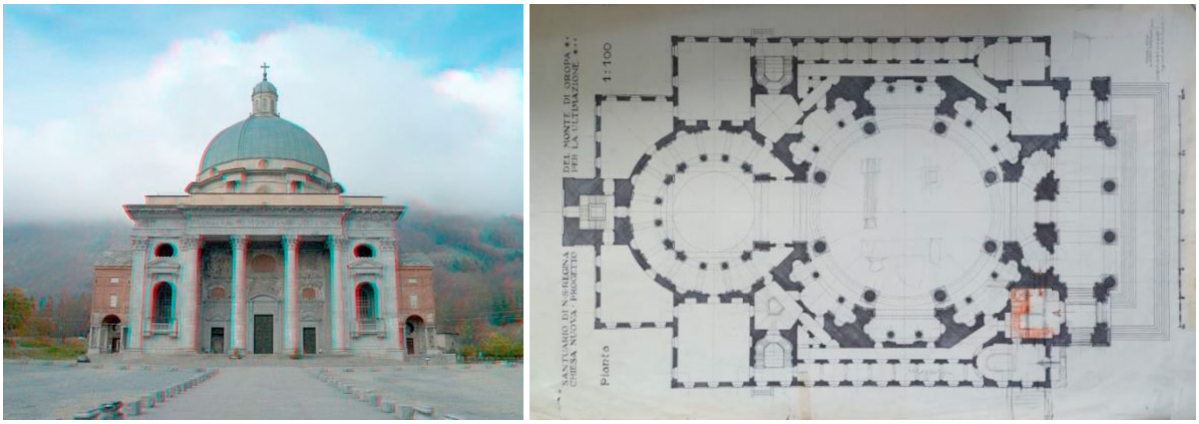


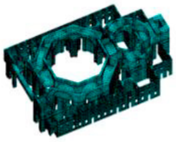
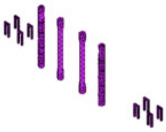
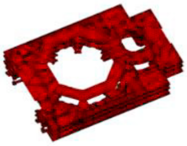
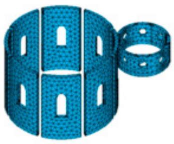
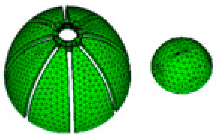
Fig. 2. (a) picture of the *Basilica Superiore* in Oropa; (b) plan view of the structure.

3.2. Geometric and mechanical modelling

The geometric model has been divided into 7 solid components with uniform mechanical characteristics. Then the geometry was implemented in a FE model. This has been developed with solid elements with 8 nodes (3 DoFs at each node) with an average step size of the mesh equal to 1.25 [m], and a total number of nodes equal to 159618. A linear elastic constitutive law has been used for the study. The nominal elastic parameters of the structure's components are reported in Table 1, while the geometrical and mechanical FE models of the structure are depicted in Fig. 3.

Table 1. Assumed elastic properties of the *Basilica Superiore* in Oropa.

Id #	Component	Name of the component	Young's modulus [Pa]	Poisson ratio [-]	Density [kg/m^3]

1		Masonry Basement	$4 \cdot 10^9$	0.25	1800
2		Sienite Columns	$60 \cdot 10^9$	0.25	2900
3		Brick-concrete Floors	$20 \cdot 10^9$	0.25	2200
4		Masonry Drums	$4 \cdot 10^9$	0.25	1800
5		Reinforced Concrete Buttresses	$30 \cdot 10^9$	0.25	2500
6		Reinforced Concrete Domes	$30 \cdot 10^9$	0.25	2500
7		Masonry Lantern	$4 \cdot 10^9$	0.25	1800

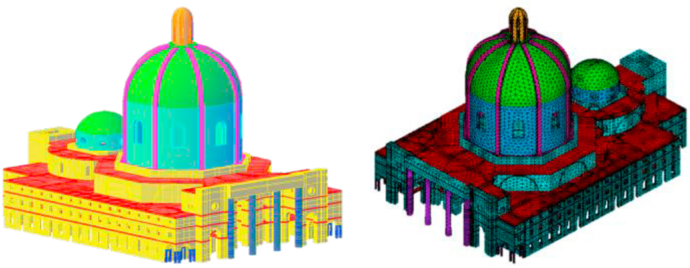


Fig. 3. (a) geometrical model; (b) mechanical Finite Elements (FE) model.

3.3. Analyses

The first analysis performed was a static analysis where just the gravitational loads were applied. This was useful to recognize the most critical components in terms of stress and strain distributions due to vertical loads. The analysis highlighted that the most stressed components in terms of von Mises stress are the buttresses of the drum, while the highest von Mises strains are detected in the drum. Fig. 4 reports the deformed configuration and the von Mises stress and strain of the structure subjected to gravity loads.

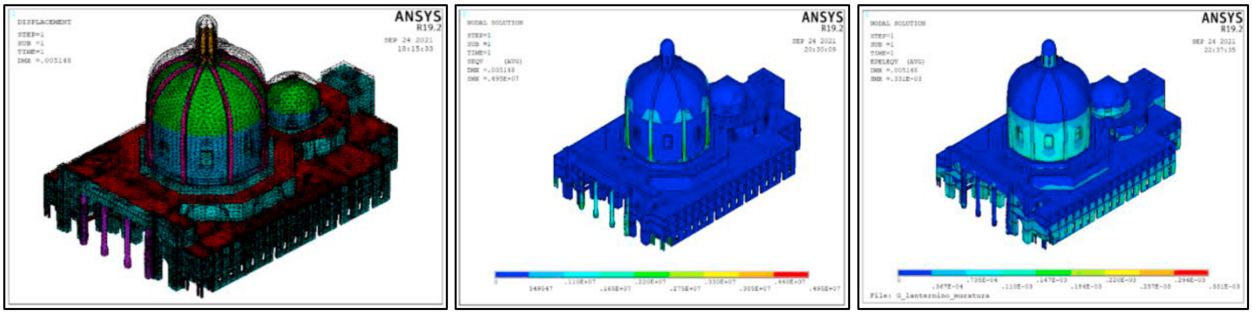


Fig. 4. (a) deformed configuration due to gravity loads; (b) von Mises stress field due to gravity loads; (c) von Mises strain field due to gravity loads.

With the second analysis, the eigenvalues and eigenvectors of the structure were estimated to predict the natural frequencies and the mode shapes. The first three modes resulted in two bending modes in the horizontal directions and a torsional mode in the vertical. These are the global modes of the structure in terms of modal mass, and not only in terms of eigenvector amplitude (high mass with relatively low amplitude is still important in this definition of globality). Table 2 reports the 3 main natural frequencies of the *Basilica Superiore*, while Fig. 5 depicts the first 3 mode shapes, respectively.

Table 2. Main natural frequencies of the structure.

Id #	Description	Natural frequency [Hz]
1	1st bending mode in Y	2.66
2	1st bending mode in X	2.76
3	1st torsional mode in Z	5.02

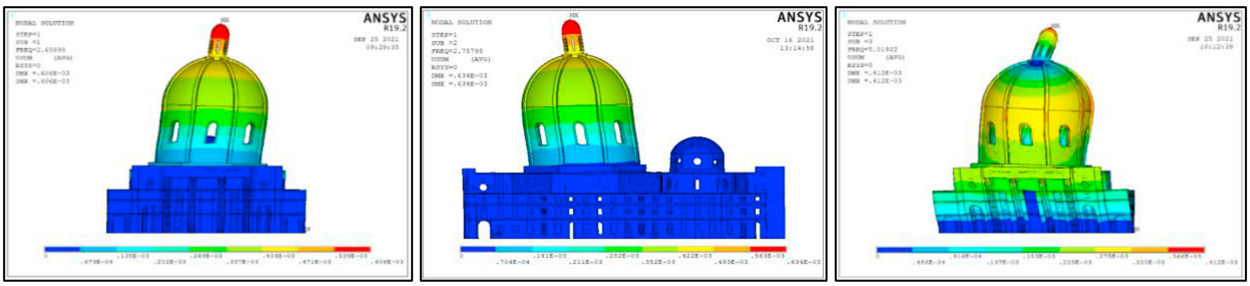


Fig. 5. (a) Mode 1 (1st bending mode in Y) at 2.66 [Hz]; (b) Mode 2 (1st bending mode in X) at 2.76 [Hz]; (c) Mode 3 (1st torsional mode about Z) at 5.02 [Hz].

With the third analysis, a local sensitivity was performed. The domain of variation of the parameters was chosen in accordance with literature values, ensuring at the same time a similar range of variation (normalized variation) of the values (30 values of each parameter were investigated). In order to track the modes at changing parameter values, the MAC criterion was followed. In Fig. 6, the mode shapes of the torsional mode (mode 3) have been evaluated with a value of Young's modulus of the drum equal to $0.2 \cdot 10^9$ [Pa] (Fig. 6b) and $6.2 \cdot 10^9$ [Pa] (Fig. 6c), respectively.

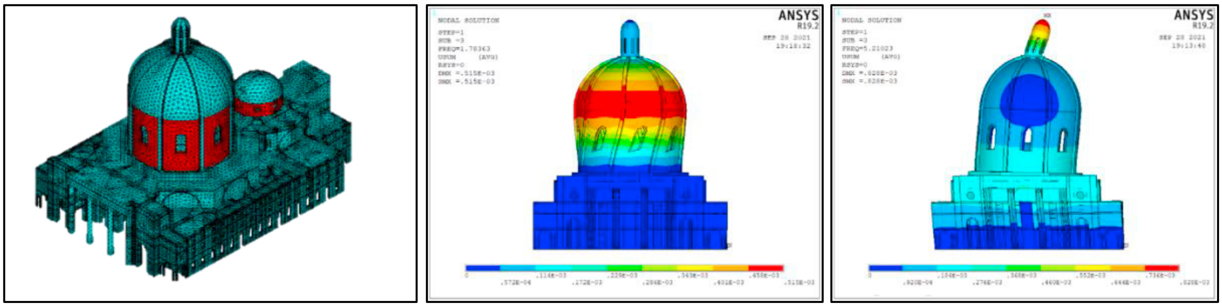


Fig. 6. (a) drum component highlighted in red; (b) Mode 3 (1st torsional mode about Z) with Young's modulus of drum equal $0.2 \cdot 10^9$ [Pa]; (c) Mode 3 (1st torsional mode about Z) with Young's modulus of drum equal $6.2 \cdot 10^9$ [Pa].

4. Discussion and results

The sensitivity analysis highlighted the contribution of the elastic parameters of the structure to the total variance of the predicted natural frequencies. In these terms, the Young's moduli resulted in being the most sensitive parameters for the first three modes, followed by densities and Poisson rations. More in detail, considering the first three modes, the Young's modulus of the drum and basement contribute, on average, to 65% of the total variance. Then the density of the dome affects 7% of the total variance. Among the other parameters also the Young's modulus of lantern and buttresses add perceptible contributions in terms of fraction of variance (being the first torsional mode strongly influenced by the stiffness of the lantern, a not obvious result). In order to reach a good resolution in the sensitivity, 30 values of each parameter were considered in the analysis, this meaning that the initial total number of combinations to be tested for OSP was close to infinity. After the sensitivity analysis, just 5 parameters were selected as fundamental, allowing the reduction of the total number of combinations for OSP to $6.3864 \cdot 10^{21}$. Fig. 6 summarizes the results of the local sensitivity analysis in terms of a fraction of total variance for the first 8 modes.

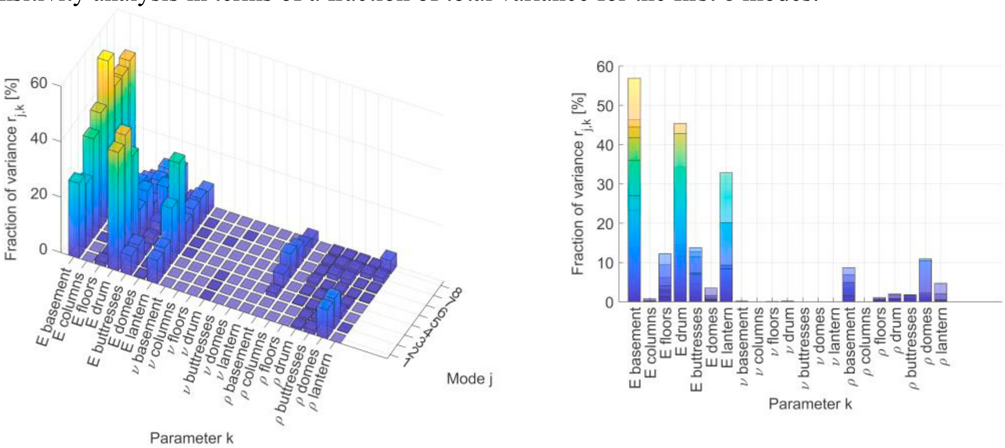


Fig. 7. (a) results of local sensitivity analysis in terms of fraction of total variance, $r_{j,k}$; (b) projection of the results on the parameter axis. In the figure, E, v and ρ denote the Young's modulus, Poisson ratio and density parameters, respectively.

4. Conclusions

With the local sensitivity analysis performed the combinations to be analyzed for OSP have been reduced from infinite combinations to $6.3864 \cdot 10^{21}$.

- Only 5 parameters of the 21 analyzed are significant in terms of modal response.
- The results of the sensitivity analysis highlight the need to deepen the knowledge of the mechanical characteristics of the 5 most sensitive structural components, i.e., drum, basement, dome, lantern, and buttresses.

References

Andersen P, Brincker R, Peeters B, et al (1999) Comparison of system identification methods using ambient bridge test data. In: Proceedings of the 17th International Modal Analysis Conference (IMAC), Kissimmee, Florida, USA, February 8-11, 1999. pp 1035–1041

Asteris PG, Chronopoulos MP, Chrysostomou CZ, et al (2014) Seismic vulnerability assessment of historical masonry structural systems. Eng Struct 62:118–134

Boscato G, Ceravolo R, Pecorelli ML, et al (2013) Sensitivity analysis of damaged monumental structures: the example of S. Maria del Suffragio in L'Aquila. In: XXI AIMETA Congress

Boscato G, Russo S, Ceravolo R, Fragonara LZ (2015) Global sensitivity-based model updating for heritage structures. Comput Civ Infrastruct Eng 30:620–635

Ceravolo R, De Lucia G, Miraglia G, Pecorelli ML (2020) Thermoelastic finite element model updating with application to monumental buildings. Comput Civ Infrastruct Eng 35:628–642

Ceravolo R, Matta E, Quattrone A, Zanotti Fragonara L (2017) Amplitude dependence of equivalent modal parameters in monitored buildings during earthquake swarms. Earthq Eng Struct Dyn 46:2399–2417. https://doi.org/10.1002/eqe.2910

Civera M, Pecorelli ML, Ceravolo R, et al (2021) A multi-objective genetic algorithm strategy for robust optimal sensor placement. Comput Civ Infrastruct Eng mice.12646. https://doi.org/10.1111/mice.12646

Ferraris M, Civera M, Ceravolo R, Surace C, & Betti R (2020). Using enhanced cepstral analysis for structural health monitoring. In Proceedings of the 13th International Conference on Damage Assessment of Structures (pp. 150-165). Springer, Singapore.

Jaya MM, Ceravolo R, Fragonara LZ, Matta E (2020) An optimal sensor placement strategy for reliable expansion of mode shapes under measurement noise and modelling error. J Sound Vib 487:115511

Lenticchia E, Ceravolo R, Antonaci P (2018) Sensor Placement Strategies for the Seismic Monitoring of Complex Vaulted Structures of the Modern Architectural Heritage. Shock Vib 2018:. https://doi.org/10.1155/2018/3739690

Lenticchia E, Ceravolo R, Chiorino C (2017) Damage scenario-driven strategies for the seismic monitoring of XX century spatial structures with application to Pier Luigi Nervi's Turin Exhibition Centre. Eng Struct 137:256–267

Peeters B, De Roeck G (2001) Stochastic system identification for operational modal analysis: a review. J Dyn Sys, Meas, Control 123:659–667

Qin S, Zhang Y, Zhou Y-L, Kang J (2018) Dynamic model updating for bridge structures using the kriging model and PSO algorithm ensemble with higher vibration modes. Sensors 18:1879