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First hypothesis for Optimized Monitoring Strategy through Ambient Vibrations in historic buildings

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ABSTRACT

Dynamic identification strategies and, in particular, Operational Modal Analysis (OMA) approaches demonstrated to be a significant source of information about the condition of an investigated building, as well as, repeated data acquisitions and processing methods, developed in the field of Structural Health Monitoring (SHM), have been successfully used to track the evolution of this condition over time. Nonetheless, planning a cost-effective ambient vibration monitoring campaign is still an open challenge as several uncertainties must be considered to ensure a beneficial trade-off between number of sensors or set-ups and quality of the information collected. This is particularly important when dealing with historical masonry buildings. The present work discusses the preliminary results of a project, currently under development, whose aim is the definition of optimised protocols for data acquisition and processing for built cultural heritage dynamic identification and monitoring, with specific focus on the Venetian palace typology.

1. Introduction

Structural Health Monitoring (SHM) has a strategic importance for the management of built Cultural Heritage (CH) [1], which is constantly threatened by natural and man-made hazards. Indeed, long term monitoring of the dynamic behaviour of CH assets demonstrated to be a potentially invaluable informative tool to support their preventive conservation. However, the fragility of historic structures together with their significant mass and stiffness prevent the effective use of forced vibrations. These issues suggest a peremptory application of OMA approaches. On the other hand, the insufficient available vibration extent not always allows to excite high response frequencies through these approaches and, sometimes, they fail to overcome typical limitations. that arise in SHM of historic buildings,

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such as the absence of a global response, the influence of local modes in the collapse of the structure and the huge uncertainty related to physical and mechanical parameters, which may vary within the same structure and may be accentuated by the state of preservation and damage. Enormous strides forward have been taken with the development of software and hardware components, while room for improvement still exists regarding the optimization of measurement protocols (e.g. spatial distribution of sensors, acquisition parameters setting, etc.). Here, it is presented a project, currently under development, whose aim is to address the aforementioned issues, by defining a comprehensive protocol for dynamic identification and monitoring of CH, with specific focus on the Venetian palace. This CH typology comprises a significant set of buildings with peculiar characteristics, described in Section 2. The research methodology, presented in Section 3, will be applied to several case studies. The cases study are presented and the Preliminary results of the project are discussed in Section 4. Finally, in Section 5, conclusions are drawn and future scopes are outlined.

2. The Venetian Fabrique

The environment in which Venice was built 1600 years ago, especially the interaction with its lagoon, the systematic shortage of space and the presence of a soft superficial soil layer, has made it an extremely peculiar example of engineering skills. Wood and masonry are the main materials of the civil buildings and they work together following the stresses and changing their behaviour to settling the whole fabrique due the admissible displacements. The venetian basic layout consists of a vertical frame with full-height piers connected to the horizontal slab by connections like as hinges. The typical Venetian palace, also called *casa da stazio* (Fig.1a), is divided into three longitudinal partitions: a central, called *portego*, crossing the whole building from one side to the other and two side areas divided into small rooms. At the ground floor, the *portego* was used as a warehouse/storage with the porch on the water to allow the docking of the boats. Upstairs, it was dedicated to party and dances, while the side rooms assumed a private destination; the last floor was the attic. In some cases, a mezzanine, called *mesà*, is placed between the ground floor and the first floor, on the side areas. The venetian horizontal diaphragms (Fig1.c), named *terrazzo*, consists of the composition of a massive block of concrete lying on a traditional timber scheme (e.g. fir, larch, pine) of boards and beams with a typical length of 5-7m, placed every 20-30 cm. In a *terrazzo* slab, the chip is the aggregate element (i.e. inert materials) while the binder is traditionally made of mortar (either hydraulic or non-hydraulic lime mortar). The width of the whole structural slab is about 20-25 cm. This peculiar combination of the wooden planks and the beams both increases the stiffness in horizontal direction and decreases the deflection of the slab (Fig.1b). In the Venetian palace, the façade is an essential component. It consists of a massive block of decorated stone that rises from the water to give slimness and elegance to the building and to reflect the prestige of the owner. Several long and narrow windows and arcades are present on the façade and provide light to the internal ambient.

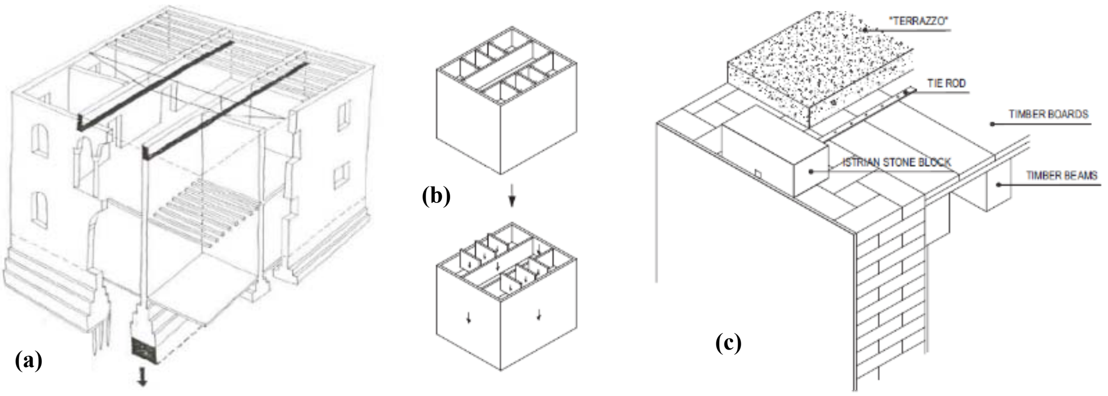

Fig. 1: Description of the structural layout of the Venenetian Fabrique: a) example of *casa da stazio* from the foundation to the floors ; b) Relationships between the longitudinal and transverse walls of Venetian building; c) typical scheme of horizontal diaphragm and connection between the vertical one.

3. The Research Method

The dynamic assessment of CH is subject to uncertainties related to the physical and mechanical properties of the structural elements and their connections [2]. OMA approaches succeed in providing answers in this regard [3], but making the best use of all available resources, in terms of cost, time and knowledge is still an open challenge for the future. An Optimized Monitoring Strategy applicable to Heritage is presented in this paper (Fig.3). This has been outlined within a project, currently under development, aimed at the definition of a suitable monitoring scheme to investigate historic masonry buildings. Two independent approaches are exposed. Both produce a dynamic identification, namely modal parameters such as natural frequencies and mode shapes of the building. These results are processed through an Optimal Sensor Placement (OSP) method to obtain the vital sensors for dynamic identification and monitoring purposes [4].

The first approach aims at reaching a very high level of knowledge of the structure and its dynamic behaviour through a large and extended campaign of ambient vibration measurements with a specific instrumentation, namely three-component velocimeters, known as tromographs (TROMINO®). The instrumentation consists of a portable, light and compact unit (~10×14×7 cm and 1 Kg) which can be easily positioned directly on the floor without any fixing system. Couple of devices are used together and linked by the built-in radio, making a synchronized set-up consisting of a Master, fixed always in the same position, and a Rover which is moved in the different locations among the structure. Acquisitions are processed through the Standard Spectral Ratio (SSR) technique, preferred for his expeditive character, to eliminate the effect of the underground site. The ratio between homologous Hi/H0 components is used to identify different mode shapes [5]. Grilla, as the tromograph software related to the Tromino, allows to determine the site effect [6] and use the well-known fast Fourier transform (FFT) to obtain related spectra [7]. This rapid feature extraction method can be used to support a more detailed identification by means of robust estimators as the Extended Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Identification (SSI) [8]. In this scenario, a numerical model of the structure is not strictly required and the optimisation of the monitoring network can be carried out by optimising the distribution of the sensors selecting the minimum number of essential locations from the large set considered in the preliminary extended campaign. The second approach is based only on primary field investigation to gain a minimum level of knowledge about parameters such as history, geometry, typology of the structure, construction techniques, damage and deterioration. Generally, investigations are carried out by visual inspection, in-situ and laboratory test [9]. In the presented approach, only a direct and immediate visual inspection is used to understand the conditions of the buildings and the uncertainties are addressed numerically by means of a finite element model. The effects of the uncertainties in geometrical and mechanical parameters on the dynamic response

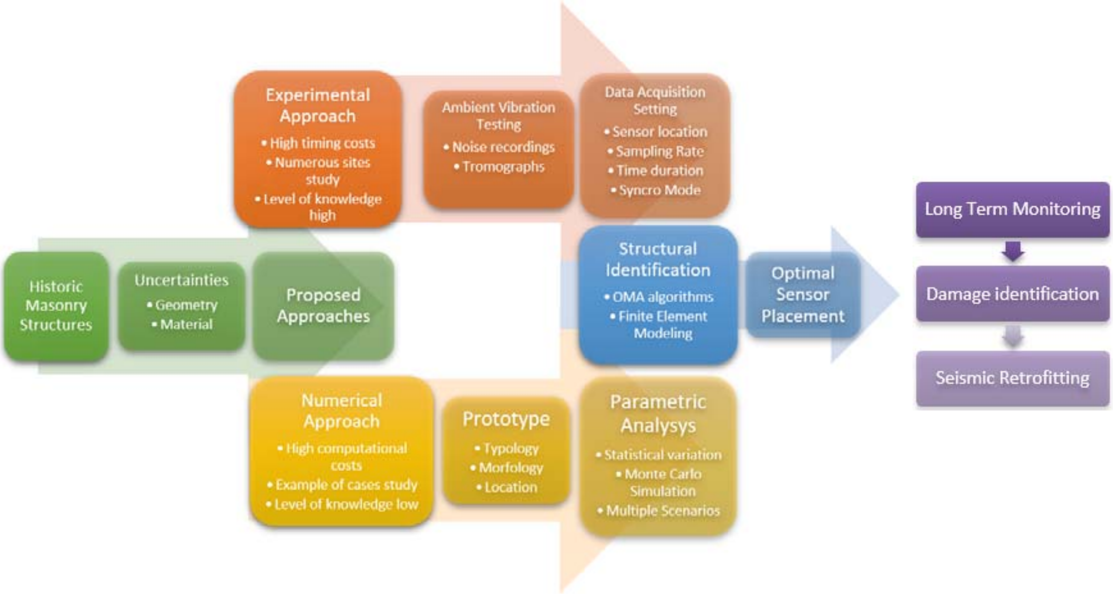

Fig. 2: Flow chart of the Optimized Monitoring Strategy

are investigated by considering their expected statistical distribution, sampling a wide number of scenarios following a Monte Carlo simulation. In this case, the optimal sensor placement procedure is applied to the different simulated scenarios, in order to define a sensor network topology that ensure a correct dynamic identification, irrespective of the values assumed by the uncertain parameters, within their expected statistic distributions.

4. Description of case studies and preliminary results

As mentioned in the previous dedicated sections, the Venetian environment has unique peculiarities in the world that creates problematic issues (e.g. rising moisture, walls out of plane). Venetian architects, master craftsmen, masons and builders were capable of designing and constructing buildings that could withstand the severe actions of the lagoon. The evolution of the structural response that buildings undergo according to these specific laws renders Venice as an interactive multi-disciplinary open-air laboratory. Several disciplines are concerned with the study of these effects, and many researchers of the University of IUAV are active in this regard, studying ad example the relationship with phenomena such as climate change and water high tide [10]. In particular, among those of them involved in structural engineering field [11] [12], an active research group has focused on the experimental monitoring of some historic masonry buildings belonging to the IUAV's real estate and located in Venice: the former convent of Terese and the noble palaces in Canal Grande Ca' Tron and Ca'Masieri. In addition, Ca'Loredan is also presented although not belonging to the group of buildings investigated, as it will be used for the numerical approach previously presented. The project here presented relies on a set of significant case studies for development, validation and testing purposes. All the investigated buildings (Fig.3) have a high artistic value and has been subjected to interventions and changes of use over time. The understanding of the new structural layouts given by the interventions will allow to understand how to plan the optimal monitor scheme and subsequently to correlate them with the experimental results [13].

The convent of Saint Teresa with its Church attached was built in the second half of XVII century, designed by Andrea Cominelli. The building complex develops around a single large cloister, characterized by arcades and loggias. The two wings of the monastery enclose the façade of the church, which is actually closed to the public. The former convent currently houses the Faculty of Design and Arts of the IUAV University of Venice, which has taken charge of the renovations to change the intended use. The restoration works were carried out in different phases from 1977 to 2004. The state of degradation was evident and the distribution of the spaces was improper to the new purpose as campus with classrooms and workrooms. The intervention mainly concerned the ancient plasters, the stone materials and the wooden floors.

Ca 'Tron is a historic building overlooking the Grand Canal with a small Italian-style garden. The origins of the noble palace probably date back to the Gothic period. The building, whose plan is "a U", consists of the ground floor, a mezzanine and two noble floors. The façade is asymmetrical with the left part smaller: the portal and the central openings of the noble floors are, therefore, moved to the left of the axis. It was purchased by IUAV in 1972 and restored to a project by architect Luigi Bellemo. Actually, the palace houses the Faculty of Urbanistic and Planning. Inside, the palace has been deeply modified: static consolidation, reorganisation of the layout and recovery of spaces (such as the ground floor) required for the new functions assigned to the building were carried out.

The evolution of Ca'Masieri is in many ways emblematic due the story of Angelo Masieri, an architect of great promise, who died tragically in 1952 in the United States, where he was working with Frank Lloyd Wright. The commitment of the great American master to design a house in Volta de Canal for Masieri and his young wife turned into the "Masieri Memorial" a foundation/forestry for scholars and students of architecture. In 1968, after several rejections to the American projects, a new commission was entrusted to Carlo Scarpa, who only in 1973 received approval for an innovative project: the façade was detached from the ceilings by large "cuts" and the height of the floors was reduced to create an additional living space. The inauguration of Ca'Masieri took place in January 1983 and actually hosts the IUAV Project Archive and architecture exhibitions.

Lastly, Ca'Loredan is a building whose oldest core is in Venetian-Byzantine style, being among the buildings on the Grand Canal that most preserve traces of it despite renovations. It passed to the municipality of Venice in 1867 and became the seat of the city hall along with Ca' Farsetti: new renovations heavily altered its original plan.

In each acquisition campaign it was possible to investigate specific issues related to the signal processing and sensor placement.

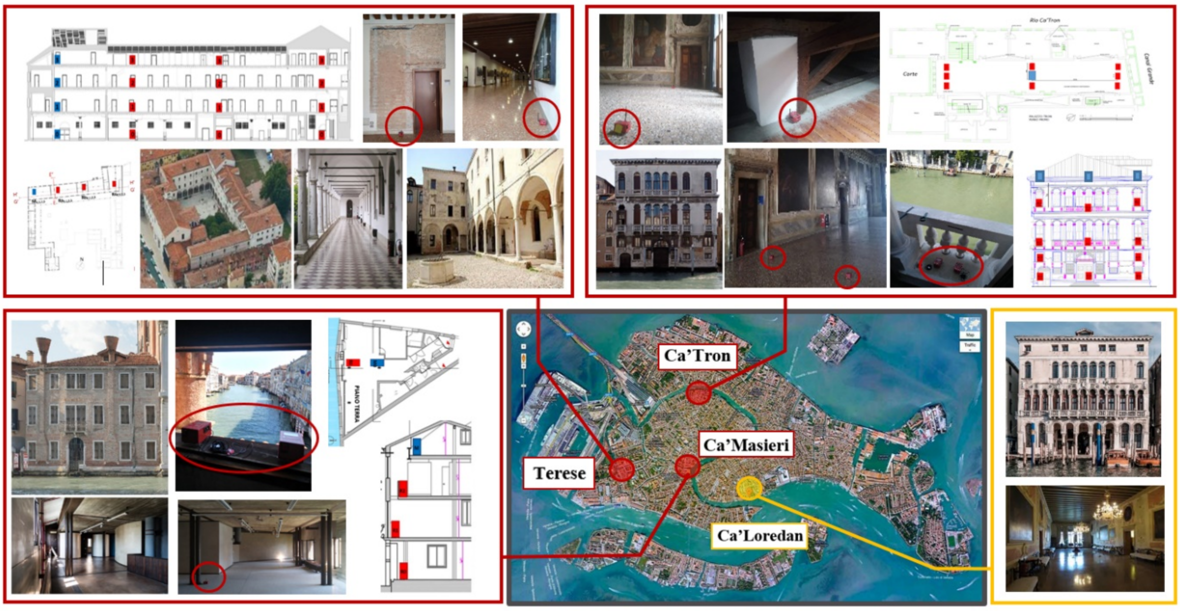

Fig. 3: Locations of the case studies in Venice with monitoring scheme and sensor locations: Terese, Ca’Tron and Ca’ Masieri (red) follow the experimental approach, while Ca’Loredan (yellow) is related with the numerical approach.

A preliminary analysis of the effect of the approach used for feature extraction has been carried out on the north wing of the Terese case study. The huge central hall, with the function of a *portego*, stretches over 80 meters in length with almost no interruption given by structural elements, especially at the second level. Three set-ups (M-R_A,M-R_B,M-R_C) were used, in each floor, with the sensors aligned along the horizontal plane and synchronized through the built-in radio. Each sensor is located with the North-South instrumental component parallel to the longer dimension of the wing. In set-up A, the roving sensor was placed about 23 meters far from the master, while in set-up B and C, the distance was doubled and tripled, respectively. Therefore, a total of 16 couple of measurements were recorded, with 12-minutes of duration and a sampling rate of 128 Hz. The modal parameters of the system were obtained by means of the SSR and the EFDD technique, processing the acquired velocity data. The combined use of the two approaches, at this stage, demonstrated to be extremely beneficial as the natural frequencies, identified by peak-picking on the SSR curves, supported the processing and feature extraction through the EFDD (Fig.4). It must be emphasized that the two approaches process measurements differently. The SSR technique works considering the set-up vertically and obtaining 4 alignments (A, B, C, D). Synchronization between the traces is not considered by organizing the measurements in this way, and the phase of the signal is compromised. This hypothesis does not allow the correct estimation of the mode shapes. However assuming the stationarity of the signal under environmental noise it is still possible to correctly identify the modes of the structure [14] using an external reference measurement located in the proximity of the building to eliminate site effects [15]. Only the results regarding the vertical C are shown. In the N-S component of the amplitude spectra in velocity (Fig.4a) two peaks are clearly identified corresponding to the two first longitudinal modes f1=2.39 Hz and f3 =4.67 Hz, while in the E-W component of the amplitude spectra (Fig.4b) it is defined the first transversal mode f2 = 3.59 Hz. The macroelement vibrates at higher frequency along the E-W axis because this is parallel to the axis of minor inertia [16] and the peaks are distinct because the measurements are not affected by interactions with other portions of the buildings connected to the wing [17]. In the EFDD technique the recordings are processed considering the set-up horizontally as initially described. This allows to take advantage of the synchronization between the instruments. It is emphasized that in addition to a correspondence with the expeditive fundamental frequencies, the modal deformations also consistently follow the direction of the components indicated by the SSR analysis (Fig.4c).

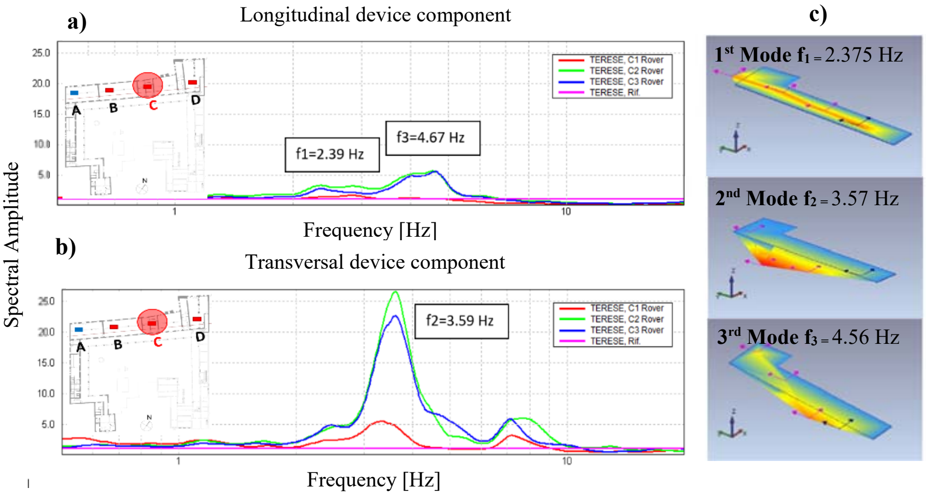

Fig. 4: Dynamic identification: SSR amplitude spectra in velocity of N-S component a) and of E-W component b); mode shapes of the first three modes of vibration according to EFDD technique c).

The extensive preliminary experimental campaign carried out at Ca'Tron allowed to analyse the influence of the sensor location and acquisition parameter setting on the dynamic identification of the three *terrazzo* floors. The sensors are mutually located in every possible structural node. Three acquisition settings were compared, namely 256 Hz sampling rate during 6 minutes of acquisition, 256 Hz for 12 minutes and 512 Hz for 12 minutes. Spectra of horizontal and vertical component of set-up M2R2 at first noble floor are shown in Fig.5. In the graphs represented, two dotted lines divide the spectra in three sections at 1 Hz and 10 Hz. The recordings of Master (in red) and of Rover (in green) from 0 Hz to 1 Hz in each component for the first acquisition setting attempt are not well defined. In the central sector from 1 Hz to 10 Hz the spectra recorded with the second setting are almost perfectly overlapping except along the vertical component. Lastly with the third attempt in each component there is a good matching between the spectra of the two sensors. An evident variation in the signal quality emerged. The SESAME recommendations [18**]** suggest to use a time duration of 12-15 minutes for a standard and efficient test [19]. Although it is indicated that the duration time is a key parameter for a successful test, the frequency of acquisition also affects the results, especially regarding the vertical component of the measurements.

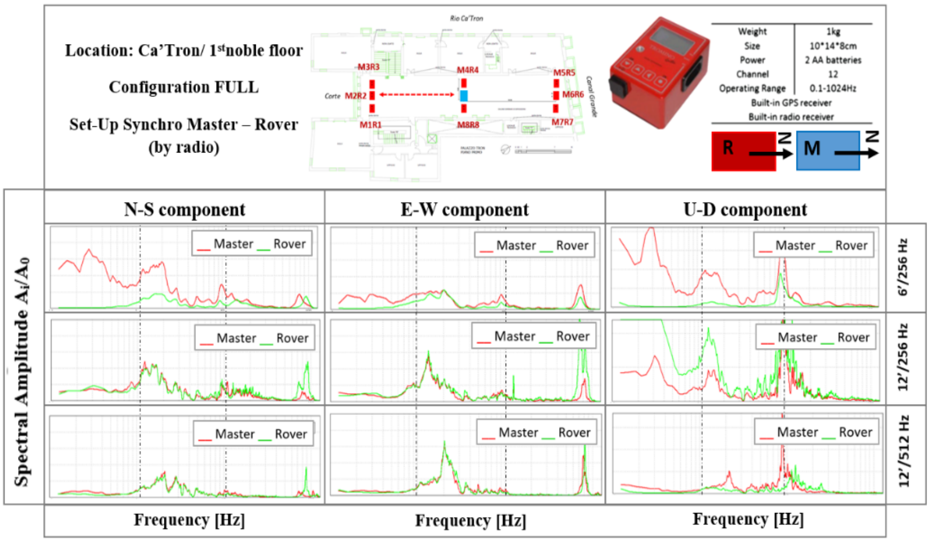

Fig.5: Spectra of Amplitude in N-S, E-W, U-D for combo in the 1st Noble floor in point M2R2

In the third survey, the massive interventions made in steel and reinforced concrete in Ca'Masieri modify the dynamic response of the original building. For this reason, and also due the unusual layout of the building, a total of three vertical set-ups locating the sensors at each level were performed with a sampling rate of 128 Hz and a time length of 12 minutes. The Master is positioned on the top of the building and is synchronized with the Rover at the lower lever. The gps-based synchronization mode was employed, taking advantage of the presence of windows in order to place the antenna outside the building. In Fig.6, the spectra of amplitude obtained through SSR technique for each vertical are shown. The similarity in the spectra at different locations may be due to a global response of the buildings, without local modes in the investigated range. However, the significant stiffness of the building, after the interventions as well as the presence of larger buildings attached to the side of the noble palace likely explain the absence of clear peaks and the low amplitude in the range of interest. Therefore, different considerations regarding the topology of the monitoring scheme and acquisition setting need to be explored further for the future purpose of characterizing the building in more detail.

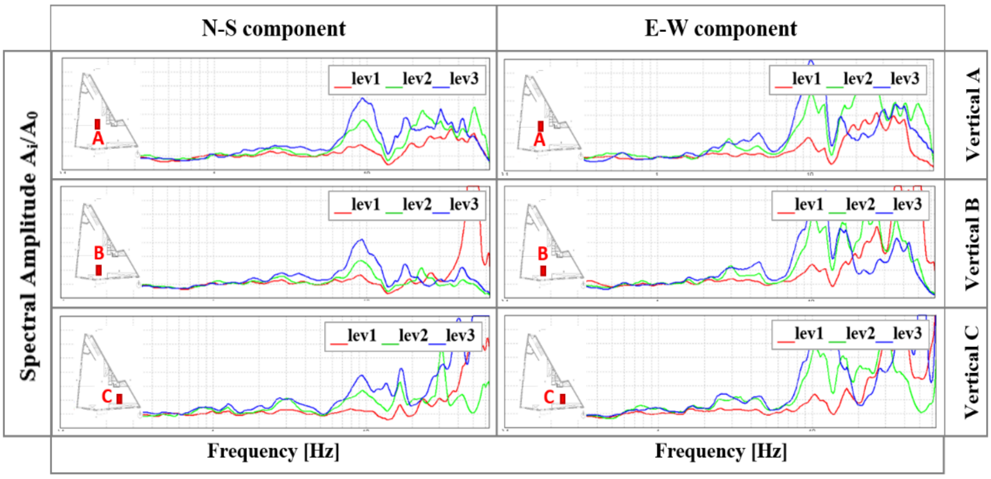

Fig.6 **:** SSR analysis of Ca'Masieri and related spectra of N-S and E-W component of vertical A,B,C

5. Conclusions and future scopes

A strategy to optimise the structural health monitoring of historical masonry buildings, with specific focus on the Venetian palace typology is proposed. Two alternative, although potentially complementary, approaches to address the uncertainties that arise in the definition of the monitoring campaign are envisaged. The first, experimental-based, aims at a very high level of knowledge of the building through a detailed preliminary identification with a large number of measurement points, subsequently reduced to reach an optimal minimum number of points. The second, numerical-based, aims at simulating and predicting the effect of the sources of uncertainties on a finite element model of the investigated building, upon the achievement of a minimum level of knowledge, to identify the optimal number and location of the sensors that ensure a clear identification of a set of target modes. To support the development and validation of the strategy, a set of relevant case studies have been selected and a preliminary testing campaign has been carried out. Hitherto, the following conclusions, relevant to the future scopes of the work, can be drawn:

- The combination of two different estimators for dynamic identification, one expeditious and the other more rigorous, succeeded in producing satisfactory results, providing complementary information which supported the definition of the modal parameters;
- The acquisition parameter setting (e.g. sampling rate and duration of the record) significantly affect the quality of the information collected, thus, the dynamic identification of the structural macroelements;
- Variations to the boundary conditions and the connections between macroelements may change significantly the dynamic behaviour, therefore deeper considerations are needed to plan a suitable topology of the monitoring scheme.

- The authors believe that from the vast amount of information derived from both approaches, a third, very fascinating advanced approach called Automatic Operational Modal Analysis (AOMA) [20] may result in the future. This approach is applied in a Machine Learning (ML) framework, albeit still based on AV testing.

Acknowledgements

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