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Full-scale Ambient Vibration survey of an Irregular Reinforced Concrete Building

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Abstract

Ambient vibration test as well as the subsequent data analysis aims at obtaining structural modal parameters (i.e., natural frequencies, damping ratios and mode shapes) from measured dynamic response, where the structure is under its operational condition. It is often treated as the first stage for damage detection, model updating, and more generally, structural health monitoring. As the development of modal identification techniques and economy in operation, ambient vibration test has attracted considerable attention in the dynamic characterisation of civil infrastructures. This paper presents a full-scale ambient vibration survey on an irregular multi-storey reinforced concrete building, whose mass and stiffness along the height are not uniformly distributed as normal buildings. This underlines the importance of exploring the dynamic behaviour of the structure in the operational condition. A number of twelve degrees of freedom (DOFs) were measured employing four force balance accelerometers with a total number of four setups. This multi-setup strategy allows of using a limited number of sensors to measure a relatively large number of DOFs in an economy manner. A novel Bayesian frequency domain modal identification method is adapted for data analysis and the overall mode shapes are assembled using a global least square method. As a result, six modes are identified within a frequency range of 0 to 5 Hz, including four translational and two torsional modes.

1. Introduction

Nowadays, materials, construction rules and inspection technologies are all focused on high structural performances and safety for newly constructed and existing buildings. The most demanding scenarios are seismic areas, where structures must be designed and controlled in time with particular care. Therefore, it is an increasing demand of developing novel and robust monitoring methods, so that technicians are able to check the structural health status during construction stages of new buildings, or after unexpected events acting on existing structures, such as earthquakes or storms. Innovative constructions put designers and engineers in front of geometries, irregularities, and weights ever harder to be verified respect to the safety factors. Relative projects, models and simulations are always more complicate and require reliable inspections, which ensure the complete correspondence with the real structural response of the construction. This paper presents a full-scale ambient vibration test performed on a multi-storey irregular reinforced concrete building. This structure represents one of the most important Italian cases of postmodern architecture that follows the movement called “deconstructivism”. One of the typical aspects of this construction style is the irregularity of lines and shapes, which bring to an uncommon dynamic behaviour of the entire building. This is an unsuitable condition in seismic areas, nevertheless, it is possible to concept such constructions by guaranteeing the right safety factors in the design process and during the construction, but much more important, by verifying those parameter during the whole service life.

In this way, an objective inspection method that furnishes the correct dynamic responses of a portion or the whole structure could be necessary. Interesting information acquired during or after the construction of an important building could be: confirmation of the stiffness supposed in foundation; the effective independence of two adjacent parts divided by a technical joint [1]; check of mass and stiffness expected on the elevated levels. All these controls could be integrated in an efficient model update process that characterise with a proper finite element model (FEM) the structure analysed [2]. Furthermore, modern and advanced structures must be monitored, guaranteeing their integrity and efficiency even after an unpredictable event. Another modern requirement is the necessity of maintenance plans and reports that consider all the ordinary and exceptional loads on the structure and provide eventual preservation interventions. Now more than ever, engineers’ and technicians’ community is looking for valid and efficient inspection and monitoring methods that guarantee quick and cheap controls on the civil structures [3, 4].

In this scenario, operational modal analysis (OMA) represents a valid solution, by furnishing to the operator an experimental modal identification through, at least, the determination of natural frequencies, mode shapes and damping ratios [5, 6]. All the OMA methods present an important cost saving in the monitoring process, since the input energy, necessary for the dynamic excitation of the structure, is represented by the ambient noise vibrations. This means that it is possible to obtain the modal parameters of a structure economically and during its usual service conditions. The assumption at the base of all these methods is that vibrations in input are statistically random, and the recordings are long enough in time to acquire all the intrinsic responses and dynamic properties of the building [7]. An accurate dissertation of the ambient noise vibrations is nontrivial and covers many scientific aspects of statistic and geology, assembled in sophisticated analytical models [8]. Ambient noise acting on the civil constructions could be substantially classified in three categories. They are microseisms (in a frequency range below 0.5 Hz), caused by massive natural events such as ocean movements or huge atmospheric perturbations; microtremors (above 1 Hz), due to anthropic activities or local environment effects; vibrations in the middle frequency range (between 0.5 ÷ 1 Hz), where the human and natural interferences act together [9]. Such a fine excitations must be detected by proper devices. These could be accelerometers or seismometers located in the main nodes of the structure, able to collect in synchrony the dynamic responses of the relative DOFs into specific recording digital units. Such a diagnostic system could be intended as mobile (post-applied on the portion of interest and moved after the acquisition), or resident (with fixed units properly located in the buildings, in continuous recording mode). Advantages of the first typology is the cost saving and the versatility of application with relative quick records. The second system, instead, offers the opportunity to have a continuous track of the dynamic excitation on the building with the fundamental function given by real time alerts in case of an exceptional event, such as an earthquake [10, 11]. A resident dynamic acquisition system could be essential to control vibrations in strategic buildings such as high technology research centres or hospitals where sensible instruments and delicate devices are installed.

The modal identification approach used in this study is the Bayesian method [12, 13, 14] that furnishes with a statistical approach the modal parameters (natural frequencies, damping ratios and mode shapes). Main concept is that the plausibility of results is seen as a statistical interference problem in the frequency domain [15]. This approach could be adapted with multiple scanning setups that allow covering in huge structures many relevant DOFs, not at the same time [16, 17]. In this way, it is possible to reconstruct the main mode shapes for the whole building [18, 19] with a substantial costs saving respect to a synchronised permanent system [20]. This is one of the most important advantages presented by OMA and it ensures a great versatility and reliability even on huge structures.

2. Modal Identification Technique

The dynamic modal parameters estimation on a generic structure, excited by the ambient noise vibrations, usually is focused on the mode shapes and relative reference frequencies. The stochastic nature of the excitation source makes the identification process not trivial, since numerical (spurious) modes and physical (effective) modes must be separated. Last studies present different approaches and algorithms, in both time and frequency domains. For example, the Stochastic Subspace Identification (SSI) method [2] could be integrated with the stability diagram [5] as tool for a correct modal discrimination. The Frequency Domain Decomposition (FDD) analysis [1], instead, considers the power spectral density matrix (PSD) decomposed by its singular values (SVD). These, once plotted with respect to the frequency band, represent an efficient way for the identification when the modes are well separated. In those cases where the natural frequencies are close each other, valid analysis implementations are the modal coherence between the channels acquired or the modal assurance criterion (MAC) [5].

2.1 Operational modal analysis basic principles

In the specific, the operational modal analysis (OMA) works around the concept that many signals, generated from the same Gaussian excitation source, are collected and compared among them. This comparison is analytically approached through the autocorrelation and cross-correlation functions for a series of signals in the time domain, respectively assembled into the diagonal and out of diagonal coefficients of the correlation matrix $\mathbf{R}(\tau)$:

$$\mathbf{R}(\tau) = \mathrm{E}\left[\mathbf{y}(t)\mathbf{y}^{T}(t+\tau)\right] \tag{1}$$

where E represents the statistic expected value of the factors in brackets, $\mathbf{y}(t)$ is the response vector that collects all the signals acquired, while (τ) is a discrete increment of time from the reference one (t). This matrix formulation relies to the correlation equation for a singular signal $x(t)$, averaged in time:

$$R_x(\tau) = \frac{1}{T}\int_0^T x(t)\,x(t+\tau)\,dt \tag{2}$$

where T represents the total length of the time window acquired.

By considering two or more dynamic responses, generated from the same white noise excitation, their cross-correlation in time could be interpreted as the free oscillations of the structure, characterised by the own modal parameters. All these correlation formulas in time find their equivalences in the frequency domain through the spectral densities. In fact, by applying the Fourier transform to the autocorrelation function [eq. (2)], it has the auto spectral density $G_x(\omega)$ that represents the energy distribution of the signal, respect to the own frequencies excited:

$$G_x(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R_x(\tau)\, e^{-i\omega\tau}\, d\tau \tag{3}$$

where ω is the angular frequency, defined as: $(\omega = 2\pi f)$ with f that is the frequency considered. Since $G_x(\omega)$ refers to the energy of the signal, often it is called power spectral density (PSD) and could be easily associated to two or more signals as cross power spectral density $G_{xy}(\omega)$.

In the context of stochastic noise excitation, hence zero mean signals, a statistic analysis of $G_{xy}(\omega)$ associates the area under the cross power spectral density function as the covariance of the two signals $x(t)$ and $y(t)$. The relative properties [5], referred to a matrix formulation, allow considering the power spectral density matrix $\mathbf{G}(\omega)$ as Hermitian, so always equal to the transpose of its complex conjugate. This important characteristic, referred to signals acquired in a relative long time, allows seeing the convolution integral of equation (2) in a simpler way related to the frequency domain, where the cross PSD could be easily calculated as:

$$G_{xy}(\omega) = X^*(\omega)\, Y(\omega) \tag{4}$$

where $X(\omega)$ and $Y(\omega)$ are the Fourier transforms of the respective signals $x(t)$ and $y(t)$, while the symbol "*" indicates the complex conjugate.

Furthermore, the previous assumptions on the excitation source permit to consider the complex vibration response of the entire structure as decoupled in singular degrees of freedom (SDOFs), where each one is representative to the relative dynamic mode and influences a narrow band around the own natural frequency. This modal decomposition is analytically related to the singular value decomposition (SVD) of the power spectral density matrix PSD, which furnishes a useful representation where all the singular values (one for each channel recorded) are plotted as function of frequency. In this way, starting from the peak picking of the highest values and continuing with more sophisticate techniques, it is possible to identify the principal modal parameters of the structure. The main idea is to consider the structural responses collected in time, $\boldsymbol{y}(t)$, as function of the relative mode shapes $\mathbf{a}_i$ and modal coordinates $q_i(t)$:

$$\mathbf{y}(t) = \mathbf{a}_1 q_1(t) + \mathbf{a}_2 q_2(t) + \mathbf{a}_3 q_3(t) + \ldots = \mathbf{A}\mathbf{q}(t) \tag{5}$$

where **A** is the mode shape matrix that collects all the mode shapes as column vectors $\mathbf{a}_\mathrm{i}$, while **q**(t) is the modal coordinates vector. By introducing this parametric notation in the correlation matrix of equation (1), it has:

$$\mathbf{R}(\tau) = \mathrm{E}\left[\mathbf{y}(t)\mathbf{y}^T(t+\tau)\right] = \mathbf{A}\,\mathrm{E}\left[\mathbf{q}(t)\mathbf{q}^T(t+\tau)\right]\mathbf{A}^T = \mathbf{A}\mathbf{R}_q(\tau)\mathbf{A}^T \tag{6}$$

where $\mathbf{R}_q(\tau)$ represents the same correlation matrix, but in modal coordinates. By applying the Fourier transform, similarly to [eq. (3)], it has the PSD matrix $\mathbf{G}_q(\omega)$ in modal coordinates:

$$\mathbf{G}(\omega) = \mathbf{A}\mathbf{G}_q(\omega)\mathbf{A}^T \tag{7}$$

For modal coordinates uncorrelated each other, it is possible to consider both matrices $\mathbf{R}_q(\tau)$ and $\mathbf{G}_q(\omega)$ as diagonal (with zero values out of diagonal). Furthermore, the mode shape matrix **A** includes complex values coming from the Hermitian $\mathbf{G}(\omega)$, which is better respect to the transpose form. Hence, the positive, Hermitian and diagonal PSD matrix $\mathbf{G}_q(\omega)$ can be decomposed instead of the way expressed in equation (7), through the singular value decomposition SVD with the following form:

$$\mathbf{G}(\omega) = \mathbf{U}\mathbf{S}\mathbf{U}^H = \mathbf{U}\left[s_n^2\right]\mathbf{U}^H \tag{8}$$

where **S** represents the diagonal matrix of the singular values s_n^2, while **U** is the matrix that collects the resulted singular vectors. Finally, the **S** and **U** matrices can be respectively interpreted as the auto spectral densities and the mode shapes Φ [5].

At this point, the singular values plotted as function of frequency help to separate the electrical noise coming from the instrumentations respect to the real response coming from the structure.

A common way to discriminate the proper modes respect to the numerical ones is represented by the construction of the modal assurance criterion matrix (MAC). This is a correlation parameter that allows comparing two or more mode shape vectors $\boldsymbol{\varphi}_\mathbf{i}$ between them:

$$MAC = \frac{\left|\varphi_\mathbf{i}^H \varphi_\mathbf{j}\right|^2}{\left(\varphi_\mathbf{i}^H \varphi_\mathbf{i}\right)\left(\varphi_\mathbf{j}^H \varphi_\mathbf{j}\right)} \tag{9}$$

with (i, j = 1… n° modal shape vectors compared).

By considering the inner product rules between two complex vectors, this parameter can be geometrically interpreted as the $cos^2(\theta)$ of the angle between them. In the case they represent the same mode shape, the MAC value is close to one; if they are linear independent, so orthogonal each other, this parameter will be near to zero. In this way, a three-dimensional plot of the MAC matrix could be useful to compare same mode shapes obtained with different algorithms, or to have an idea of how much are different the modes found on the structure analysed with the same technique. In particular, this use of the MAC matrix makes sense when the modes are well separated and almost all the DOFs of the structure are represented and collected in the ambient vibration records. In case the natural frequencies are close each other, the relative mode shape vectors are very sensitive to small perturbations and only their same subspace has any physical meaning; consequently the MAC become useless. Furthermore, considering for example that not all the DOFs are represented in the same structure, it could be that two translating modes Tx1 and Tx2 acting on the same direction, return MAC higher than zero because their orthogonal evidence is described by the DOFs lost.

This is not the experimental case studied in this paper, where the few DOFs of the prototype structure are well represented and recorded.

2.2 The fast Bayesian FFT approach

Since the modal identification process becomes non-trivial for closely spaced modes, a proper identification algorithm is used in order to have a comparison of results for the same experimental data. The Bayesian method is a valid technique operating in the frequency domain mostly improved in the last years by (Siu-Kui Au et al.) [14, 16]. The Bayesian procedure is based on a statistic approach of the modal problem, where the stochastic nature of the excitation source, opportunely modelled, allows seeing the modal parameters in terms of their probability and plausibility. In this way, the main aim of the method is to find the posterior probability density function (PDF) related to the modal parameters, where further than the corresponding estimation, it gives their uncertainty:

$$p(\boldsymbol{\theta}|D,M) = p(D|M)^{-1}\,p(D|\boldsymbol{\theta},M)\,p(\boldsymbol{\theta}|M) \tag{10}$$

where $\boldsymbol{\theta}$, D, M represent respectively the set of modal parameters, the measured data, and the model assumptions used to relate the first two terms. The likelihood function $p(D|\boldsymbol{\theta},M)$ inverts the usual order for the identification problem, introducing the question of data D respect to the knowledge of the modal parameters $\boldsymbol{\theta}$ [16]. Once approximately solved the likelihood function (since the problem is nonlinear), and improved the algorithm computational strategy, it is possible to find the most probable value (MPV) and relative uncertainty for all the modal parameters of interest.

In Bayesian modal identification, modal parameter $\boldsymbol{\theta}$ consists of the natural frequency (f), damping ratio (ζ), modal force PSD (S), prediction error (S_e) and mode shape ($\boldsymbol{\varphi}$), i.e., $\boldsymbol{\theta} = \{f, \zeta, S, S_e, \boldsymbol{\varphi}\}$. Define $\{\mathbf{y}_j \in R^n\}_{j=0}^{N-1}$ as the time history of ambient acceleration data with n measured DOFs. The (scaled) FFT of $\{\mathbf{y}_j\}$ is defined as

$$\mathcal{F}_k = \sqrt{2\Delta t / N} \sum_{j=0}^{N-1} \hat{\mathbf{y}}_j \exp\left[-2\pi \mathbf{i} kj / N\right] \qquad (k = 0, ..., N) \tag{11}$$

where $\mathbf{i}^2 = -1$ and Δt is the sampling interval. Let $\{\mathcal{F}_k\}$ denote the collection of FFT data over a selected frequency band around the mode of interest. For small Δt and large N, it can be shown that are asymptotically independent and jointly 'circularly complex Gaussian' with zero mean and covariance matrix equal to the PSD matrix of data [21]. Correspondingly, the NLLF is given by

$$L(\boldsymbol{\theta}) = nN_f \ln \pi + \sum_k \ln |\mathbf{E}_k(\boldsymbol{\theta})| + \sum_k \mathcal{F}_k^* \mathbf{E}_k(\boldsymbol{\theta})^{-1} \mathcal{F}_k \tag{12}$$

where the sum is over the selected frequency band with N_f FFT points; $\mathbf{E}_k(\boldsymbol{\theta}) = E[\mathcal{F}_k \mathcal{F}_k^* | \boldsymbol{\theta}]$ is the theoretical PSD matrix of data for given $\boldsymbol{\theta}$. Considering the selected frequency band is dominated by a single mode, $\mathbf{E}_k$ is given by

$$\mathbf{E}_k = SD_k \boldsymbol{\varphi}\boldsymbol{\varphi}^T + S_e \mathbf{I}_n \tag{13}$$

where $\mathbf{I}_n$ is the $n \times n$ identity matrix; the mode shape is assumed to have unit Euclidean norm, i.e., $\|\boldsymbol{\varphi}\|^2 = \boldsymbol{\varphi}^T \boldsymbol{\varphi} = 1$; D_k is the dynamic amplification factor

$$D_k = [(1-\beta_k^2)^2 + (2\zeta\beta_k)^2]^{-1} \qquad (\beta_k = f / \mathrm{f}_k) \tag{14}$$

2.3 **Multiple setups merging**

Possibility to cover many DOFs in different setups implicates a great cost saving by involving only few dynamic sensors contemporarily. This means that, in the post-processing phase, the analysis of data concerns necessity to merge the mode shapes coming from different setups. Natural frequencies, instead, are deducted on the data set coming from each single setup [17]. Reconstruction of overall mode shapes is a useful dynamic parameter that gives an idea of how the entire structure is affected by a dynamic event. The assimilation of each single shape requires an objective scaling factor between the different setups, because the input excitation source is not constant in amplitude but random in time. Consequently, each single mode shape, referred to the DOFs monitored in a single setup, presents amplitudes that are not necessarily comparable with the other setups. The scaling operation requires a set of DOFs in common between the various setups. In such a way, it is possible to have the response of the structure at the same place, for the same main directions, during the time of acquisition of the different inspection setups. Once chosen the most representative acquisition system for the building (reference setup *rs*), this one will be compared with all the other setups for the same mode shape. Common DOFs between them will give the scaling factor to uniform the overall merged shape.

It is possible to consider a generic mode shape $\boldsymbol{U}_i$, of a generic setup k, as an array composed by:

- a series of responses coming from the reference DOFs ('), recorded by the same sensors placed in common positions respect to all the other setups;
- all the remaining DOFs that require to be scaled ('').

$$\left(\mathbf{U}_k\right)_i = \begin{Bmatrix} u'_k \\ u''_k \end{Bmatrix}_i \tag{15}$$

In order to obtain consistent overall shapes, there will be a scaling factor α for each direction (x, y, z), for each k setup compared to rs and for each i mode shape analysed. For example, by considering the first direction x, it has:

$$\left(\overset{x}{\alpha}_{rs,k}\right)_i = \left\{\frac{\overset{x}{u'}_{rs}}{\overset{x}{u'}_k}\right\}_i \tag{16}$$

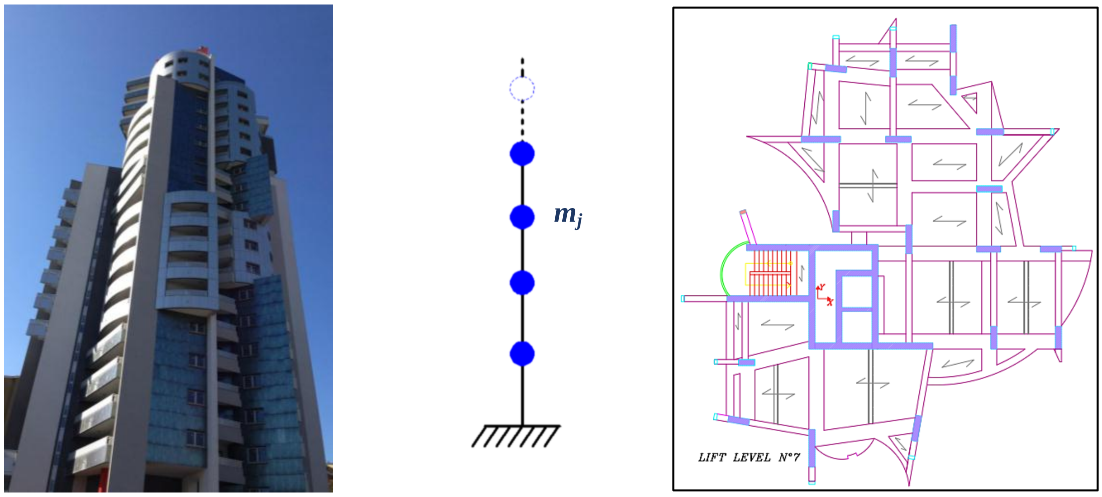
Once obtained all the required scaling factors, it is possible to assemble each overall modal shape where only the DOFs coming from the setup *rs* remain not scaled [5]:

$$
(\mathbf{U})_i = \begin{Bmatrix} u'^{(x,y,z)}_{rs} \\ u''^{(x,y,z)}_{rs} \\ \alpha^{(x,y,z)}_{rs,2} \cdot u''^{(x,y,z)}_{2} \\ \vdots \\ \vdots \\ \alpha^{(x,y,z)}_{rs,k} \cdot u''^{(x,y,z)}_{k} \end{Bmatrix}_i \tag{17}
$$

It is possible to notice that the common reference sensors require to be placed in a significant position respect to almost all the principal modal shapes. In fact, if a reference sensor is located in a nodal point respect to the considered modal shape, the relative scaling factor will be underestimated, with consequences on the overall result. Of course, this condition is not trivial to be respected for all the main modes, especially on huge structures. Consequently, in these cases, it is suitable having more than one reference sensor to use for the scaling procedure.

3. Building Analysis

The operational modal analysis (OMA) executed by mean of the Bayesian approach in the frequency domain [15] was applied on a tall twenty-two storeys reinforced concrete building located in Cosenza, in the south of Italy. The position of the construction was relevant since it stood in an active seismic area, classified as first category for the seismic risk in Italy. This recent construction, concluded in the year 2011, was designed by following the Italian technical rules for constructions *(D.M. 16-01-1996).* One of the principal peculiarities of the building was that it followed the deconstructivism style so the tower was not regular along its height, but presented shapes similar each other in blocks, and there were at least five consecutive blocks in elevation [Figure 1a]. This meant that there were continuous changes of stiffness and mass along the height, which brought to particular care during the design and construction phases. The overall dynamic behaviour of the building could be compared to a vertical rod, fixed ended at the base, with concentrated masses in correspondence of the different floors [Figure 1b]. This last condition is plausible since the foundation of the building consisted in a rigid reinforced concrete raft, 3m thick, placed on piles 22m deep. This massive foundation conditioned the dynamic behaviour of the first floors, much more rigid than the elevation ones. By starting from the base, raised up a rigid nucleus, including stairs and lift compartments, with the presence of reinforced concrete pillars and shear walls placed as satellites all around each storey [Figure 1c].



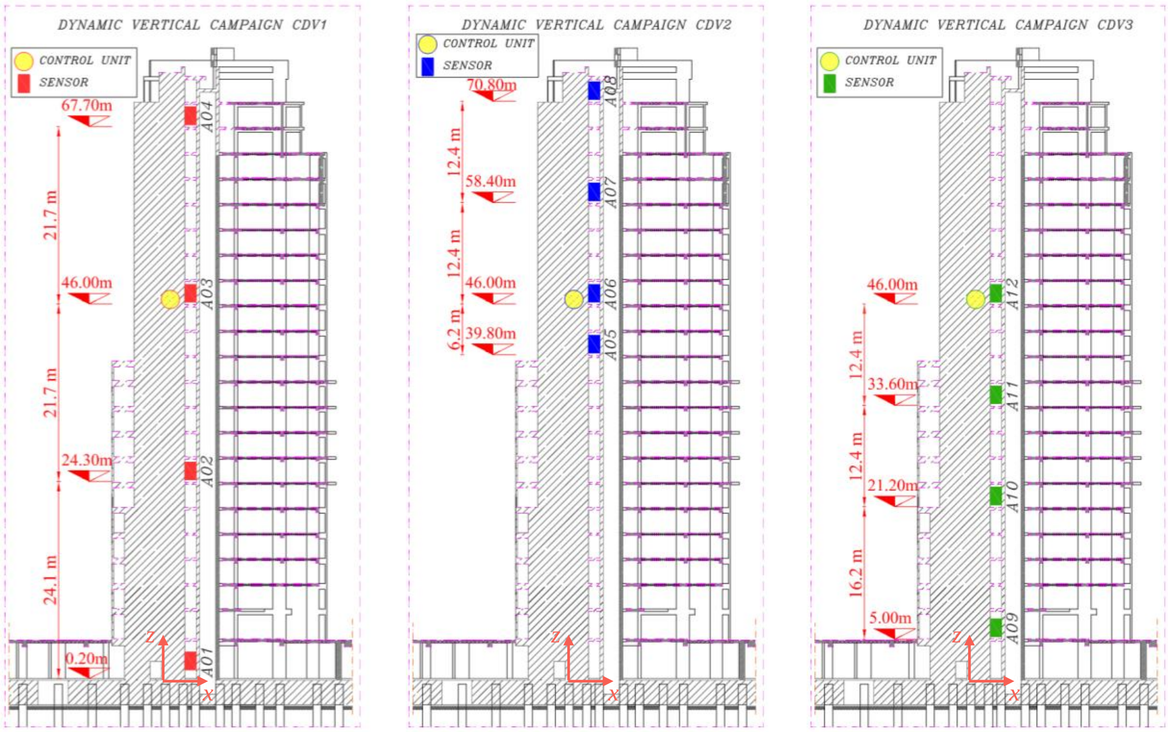
(a) (b) (c)

Figure 1. (a) Multi-storey building analysed; (b) Vertical rod model, fixed ended at the base; (c) Pillars disposition on the representative storey n°7.

Another important feature of this building was that during the construction stages it was installed a resident system of optic fibres for the static monitoring of the whole structure. This system guaranteed a continuous control of the main structural parts of the tower, useful for the maintenance plan during its service life. The addition of operational modal analysis furnished a complete experimental structural description of the building for both dynamic and static behaviours.

4. Instruments and Preliminary Tests

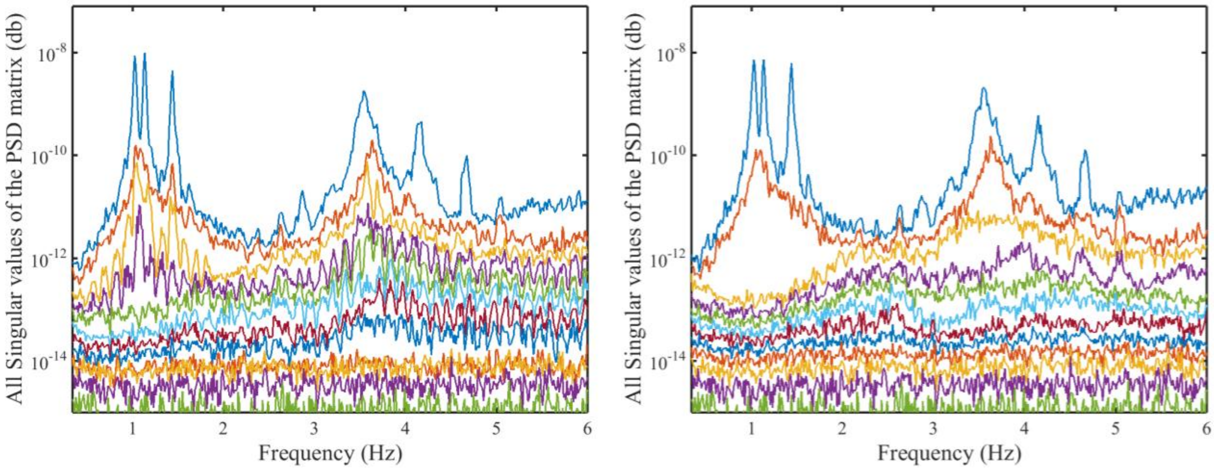
A complete reconstruction of the dynamic behaviour requires the monitoring of many DOFs and this could be obtained with expensive recording units and many transducers along the whole building. Operational modal analysis, instead, allows merging different setups where only few DOFs are collected contemporarily and post processed for the entire dynamic reconstruction. In the analysed building, it was fundamental to design a-priori the different dynamic campaigns in order to collect only the principal DOFs for an adequate assembling and modal reconstruction. In [Figure 2] cross sections of the structure represent the three dynamic vertical campaigns adopted. Each one had four sensors, contemporary active and only one transducer has been left at the same place as reference. These configurations, once assembled, allowed to cover the main DOFs of the tall building analysed in order to obtain a satisfactory mode shape reconstruction.



(a) (b) (c)

Figure 2. (a) Vertical campaign along the entire height CDV1; (b) Upper levels vertical campaign CDV2; (c) Lower levels vertical campaign CDV3.

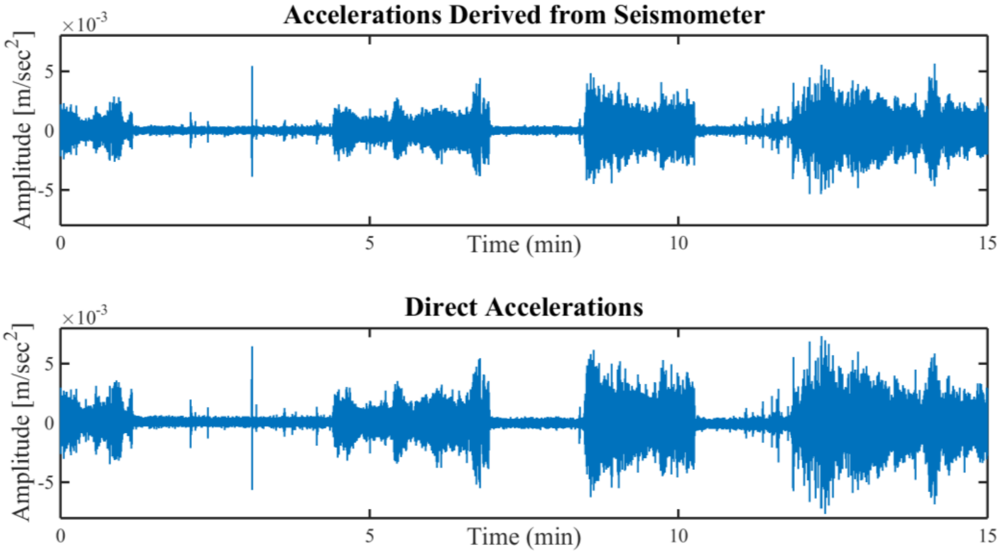
Dynamic ambient noise vibrations were recorded in temporal steps of 15 minutes, a time considered long enough to include the stationarity of the stochastic noise in input. Signals were collected and sampled by a central digital unit, remote controlled, with a resolution of 24 bit, able to record up to 12 channels at the same time. Dynamic three axial transducers were used in order to monitor the main DOFs of the structure. An important feature relative to the digital recording unit was the capacity to collect all the signals exactly at the same time, without any digital clock delay. In this way, it was possible to analyse any setup collected, in the relative singular value spectrum, by having a first idea of how many close modes insisted in the same frequency band. If all the tracks of the same setup were not synchronised each other, there were evident consequences apart from the time series, also in the frequency domain. In this case, in fact, the corresponding singular value spectrum showed many channels raised together chaotically in the same bands [Figure 3a]. In a synchronised setup, instead, the first singular value represented a reference, where the highest peaks indicated the main modes frequencies. If in a specific frequency band, two or more than a singular value raised up, this meant that there were two or more modes close each other [Figure 3b].



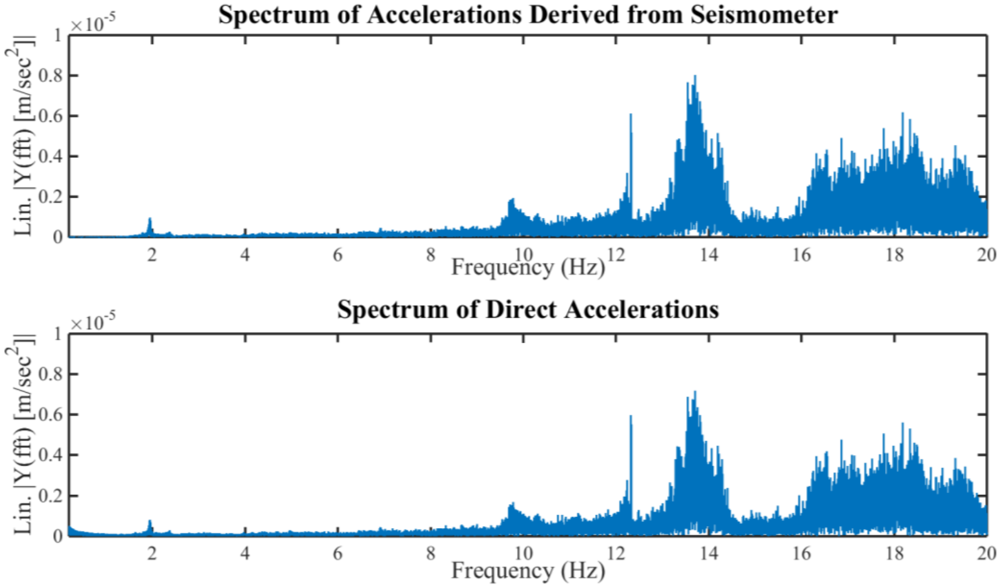
(a) (b)

Figure 3. (a) Singular Value spectrum for channels not synchronised; (b) Singular Value spectrum for synchronised tracks.

Preliminary tests involved the opportunity to use a set of four three-axial seismometers, with geophone transducer inside, able to return direct velocities tracks in time, with a maximum resolution of 1000Hz and a dynamic range > 130dB. In alternative, a set of four three-axial force balanced accelerometers that guarantee at least a sampling frequency of 200Hz and a dynamic range > 165dB was available too. Velocities measurements were adapted to the modal identification algorithm through the finite differences derivation method, obtaining relative accelerations in time. In this way, a higher resolution in the original data allowed to avoid any information loss during the computation. It was compared the response of the two type of devices from an identical ambient noise input. Following [Figure 4] compares a derived accelerations track, coming from one seismometer, respect to the pure accelerations proper of the second kind of sensors, in both time and frequency domains. It was evident that there were not relevant variations between the two tracks, so the setup chosen was those with the four accelerometers that guaranteed a cost saving and a satisfactory frequency resolution [7] set as 0.012Hz.



(a)



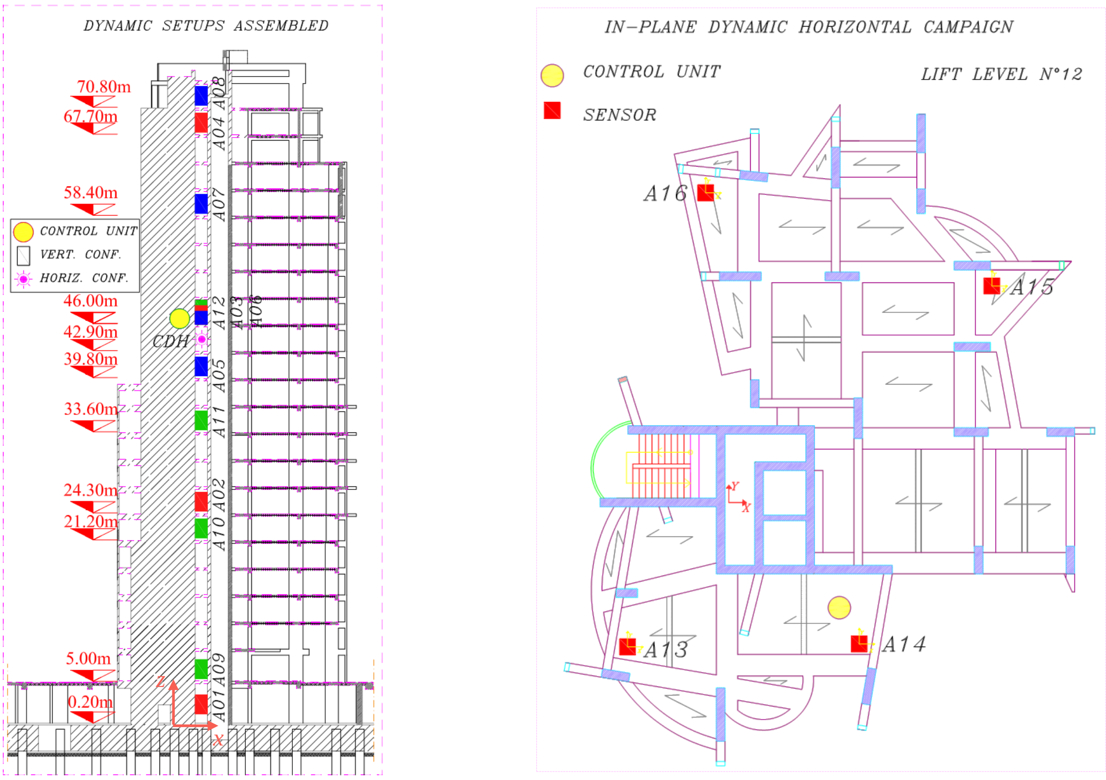
(b)

Figure 4. (a) Accelerations in time, comparison between derived and direct signals; (b) Spectral comparison between derived and direct accelerations.

5. Experimental Results

The complete dynamic characterisation of the tall building was designed by means of three vertical setups where each one of the three axial sensors, representative for the relative floor, has been located in the middle of the stairs compartment as origin of the planar reference frame [Figure 1c]. This choice allowed to easily vertically align all the transducers, in order to capture the single participation of each storey to the global mode shape. Furthermore, all the setups had a common sensor used as reference, fixed at level 13, which allowed scaling all the single mode shapes in the overall one. An overview of all the vertical setups assembled is given in the following [Figure 5a].

A further setup was designed in order to better discern eventual vertical and torsional modes. This one, in fact, considered a planar disposition of the four available accelerometers in order to cover all the perimeter of a reference floor [Figure 5b].



(a) (b)

Figure 5. (a) All dynamic setups assembled; (b) Horizontal campaign on Level n°12.

The Bayesian approach was applied to each setup individually, obtaining almost identical natural frequencies for each dynamic campaign. In the following [Figure 6] it is represented the singular value spectrum of the first setup, which covered the entire height of the building, thus it could be elected as the most representative of the whole structure.

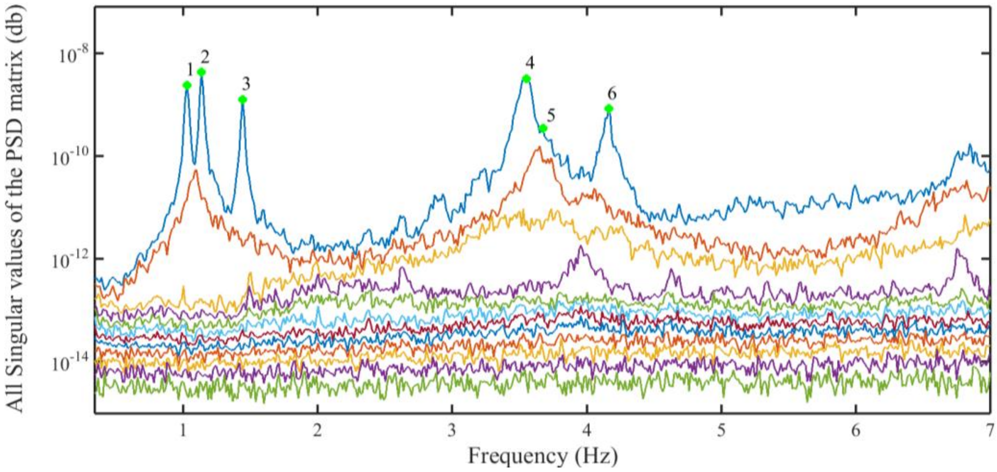


Figure 6. Singular Value spectrum for the first vertical dynamic setup.

The reference sensor, fixed at the same place for all the vertical setups, allowed to perform a scaling and orientation of the single mode shapes in accordance with [eq. (17)], giving a representation of the overall dynamic behaviour of the building. In the vertical setups, only one accelerometer represented the relative floor so it was difficult to discern any torsional component from the flexural ones for each single mode. This is why in the following [Figure 11], the torsional third and sixth modes, shows only the flexural part of the mode shapes. Moreover, the overall mode shapes MAC representation, coming from [eq. (9)], showed a clear dependence between the first (flexural predominant on direction Y) mode and the third (torsional) mode, as well as the fifth (flexural predominant on Y of the 2° order) mode and the sixth one (torsional of the 2° order) [Figure 8]. A further advice respect to the mode shapes classification came from the planar inspection configuration *(CDH)* [Figure 5b], which gave a clear indication on the torsional effects on the third and sixth modes [Figure 9].

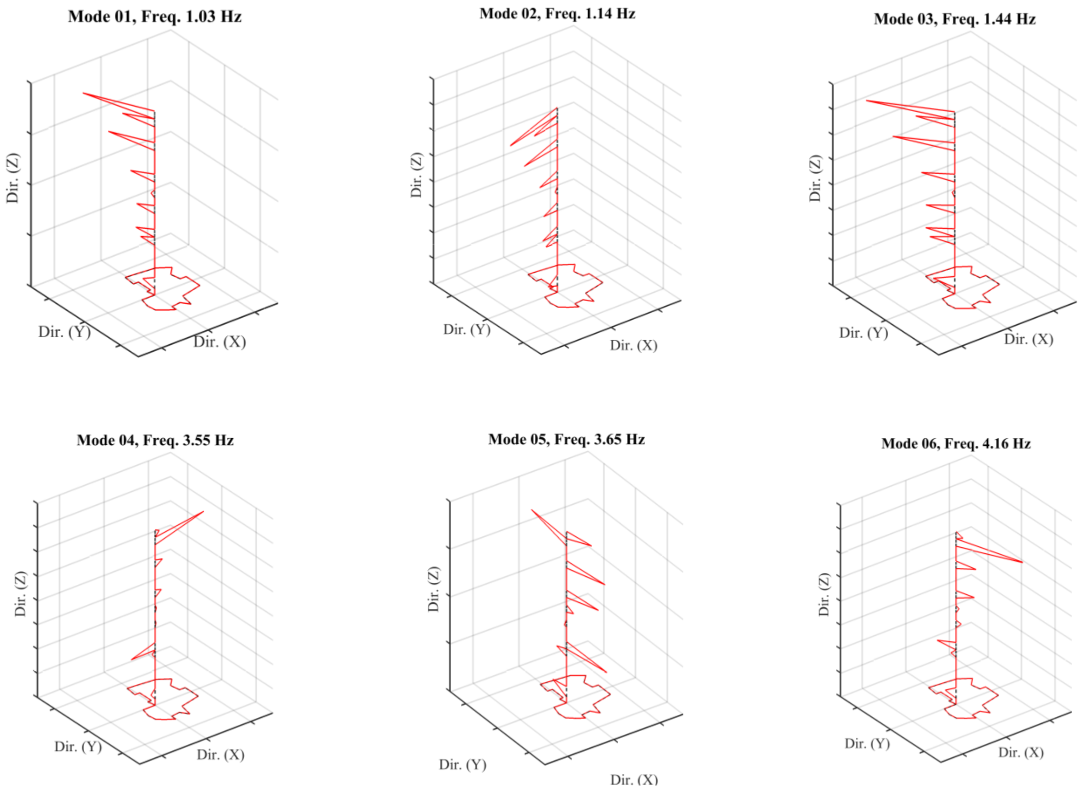


Figure 7. Vertical modes assembled in an overall setup for the first six experimental mode shapes.

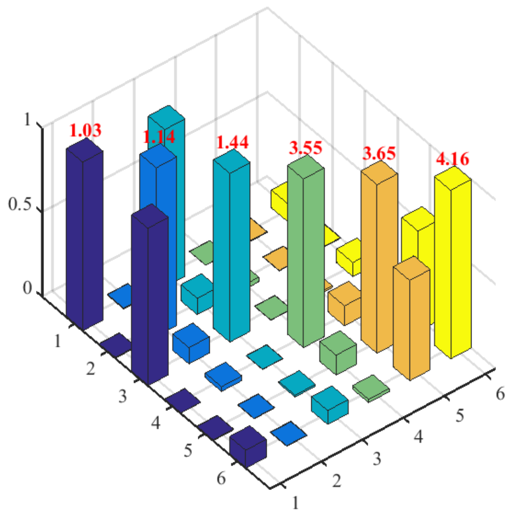


Figure 8. MAC of the assembled vertical modes.

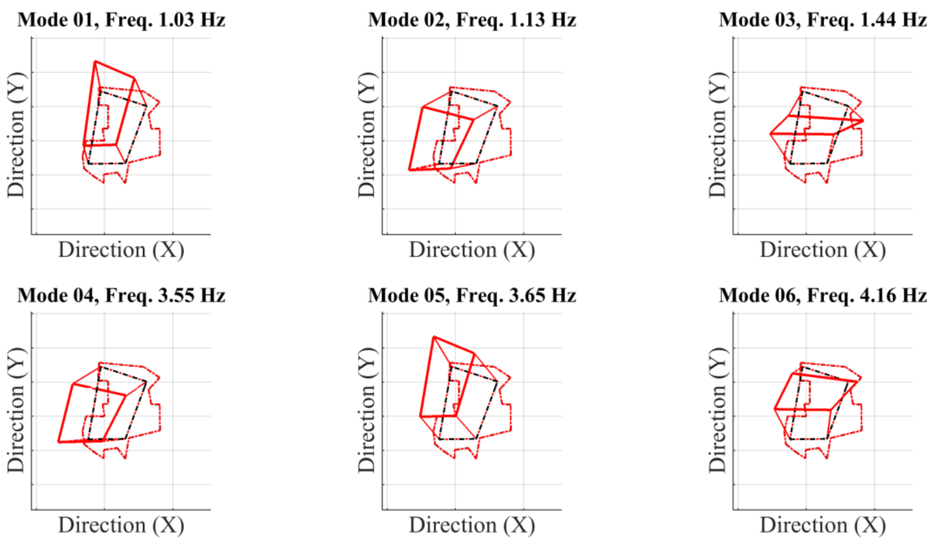


Figure 9. In-plane mode shapes from CDH at the lift level n°12 (top view).

The experimental dynamic reconstruction allowed having a reference for the finite element simulation. The relative FEM reconstruction, in fact, consisted in a complex numeric model, which contemplated all the structural elements of the building such as shear walls, pillars, beams, decks, stairs, lift compartments and the foundation with its interaction with the ground [Figure 10].

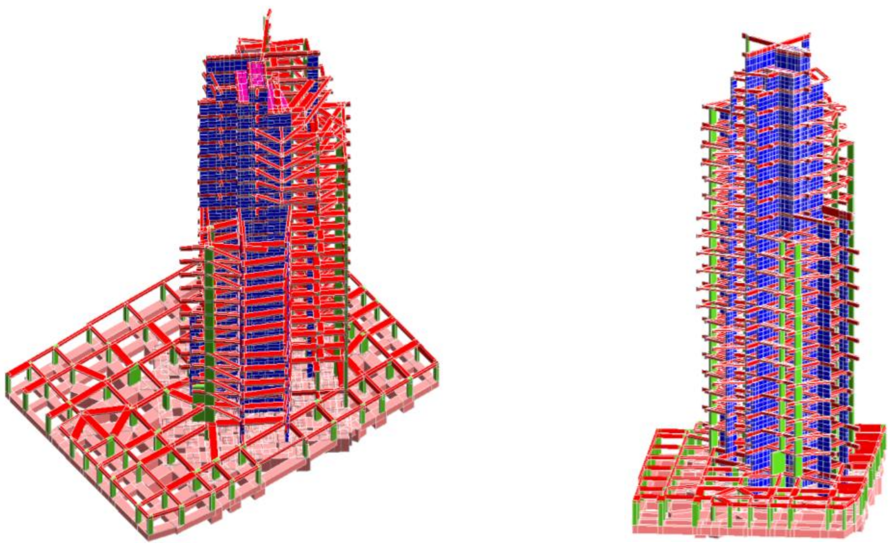


Figure 10. Finite elements model.

The first comparison between the experimental and numerical analyses could be between the relative mode shapes. Of course, in the numeric simulation all the DOFs were well described so all the mode shapes resulted more accurate. An important result was that the experimental dynamic reconstruction and the numeric model showed for the first six modes the same directions and the same flexural or torsional nature of the shapes [Figure 11]. In this way, it was confirmed the reliability and the value of the experimental reconstruction.

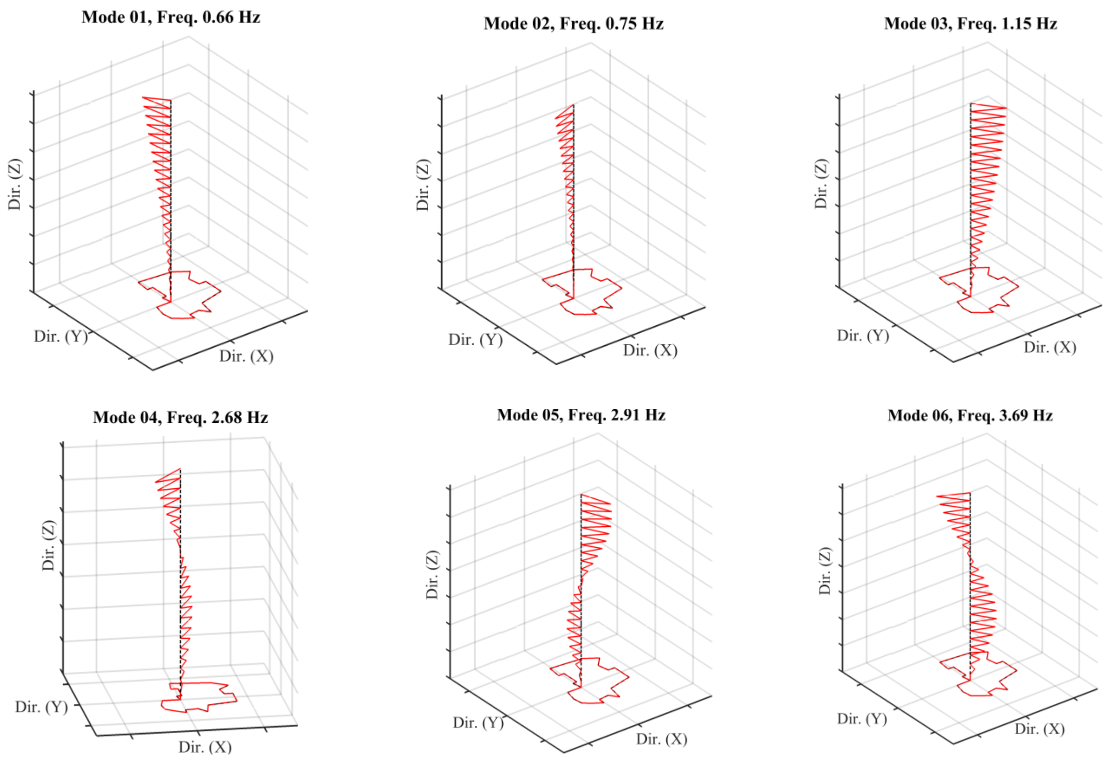


Figure 11. Vertical mode shapes simulated with the FEM model.

Even these mode shapes presented mixed components for the third and sixth modes that were prevalently torsional. As showed before, the flexural modes did not insist only on the x or y directions but they had mixed components due to the asymmetry of the entire building.

The frequency comparison is showed in the following [Table 1]. It is important to notice that despite the accuracy and complexity of the numeric model, frequencies found were lower than the experimental ones around 28% for the first modes. This discrepancy underlined the importance to have a reference experimental analysis, able to furnish objective values of the dynamic parameters. In this case of study, differences with the FE model underline a more real rigid behaviour of the entire structure. This could be justified with:

- the more rigid interface between ground and the complex foundation of the building;
- the increasing of stiffness produced by the strictly non-structural elements of the building, such as the thick perimeter walls.

Experimental Dynamic			**Legend:** ∨ Reduction 1^{st} vs. 2^{nd} term ∧ Increasing 1^{st} vs. 2^{nd} term		**FEM Dynamic Simulation**		
Mode	**Dir.**	***f*[Hz]**	**Variation %**		**Mode**	**Dir.**	***f* [Hz]**
1	Prev. Y	1,03	∧	28,0%	1	Prev. Y	0,74
2	Prev. X	1,13	∧	25,9%	2	Prev. X	0,84
3	X, Y + Trx	1,44	∧	14,7%	3	X, Y + Trx	1,23
4	Prev. X2°	3,55	∧	16,6%	4	Prev. X2°	2,96
5	Prev. Y2°	3,65	∧	13,6%	5	Prev. Y2°	3,16
6	X, Y+Trx2	4,16	∧	3,7%	6	X, Y+Trx2	4,00

Table 1. Comparison between Bayesian and FEM analysis for the intact prototype (*Pi*).

6. Conclusions

This dissertation proposes an experimental campaign focused on the structural dynamic reconstruction, in multiple setups, of a tall real reinforced concrete building. The inspection method used is the operational modal analysis through a Bayesian identification approach in the frequency domain. Results show the importance to have an objective experimental dynamic reference to compare with the structural numeric simulations proper of new or existing buildings. Reliability and benefit of the method is enhanced by the possibility to have quick and simple inspection setups, properly designed on the structure, without any interruption of usual service conditions. Possibility to analyse and assemble different setups, referred to specific DOFs of the structure, is one the principal advantages of OMA that directly affects the cost saving of the entire method.

Proposed approach could be successfully applied on any structure in order to monitor in time the health status of the main supporting parts, or to compare dynamic parameters before and after an unexpected event such as natural calamities: earthquakes, storms; or artificial events: explosions or structural interventions. In this way, local or overall dynamic properties like mass and stiffness of the structure could be inversely reconstructed from the random ambient noise vibrations.

In this paper, the building analysed presented a not regular shape along its height, therefore, experimental results confirm versatility of the method in complicate structures, in accordance with the numerical simulation.

Future applications will be focused on the automation of the procedures and the ulterior cost saving of instruments, by giving to the OMA applications a relevant position in the panorama of non-destructive inspections.

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