16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 506

Registration Code: S-V1462999584

ON THE APPLICATION OF OUTPUT-ONLY MODAL IDENTIFICATION TO BASE EXCITED FRAME STRUCTURES

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Abstract

The work focuses on the application of modal identification techniques to plan-asymmetric building structures that are subjected to base excitation. The challenging problem related to the identification of high-order modes and, especially, torsional modes is taken into account for different lengths of time and directions of the applied base excitation. The evaluation of the identification accuracy was performed through a simulation approach: analytical models of plan-asymmetric RC frames, which are characterized by different structural eccentricities, were subjected to white noise base excitation. This kind of input is rather idealized for real buildings, which are generally excited by earthquake or traffic loads, but it is commonly adopted in experimental programs related to vibration-based damage detection using scaled or full-size buildings tested on shaking tables. The output-only modal identification was applied using the response time-histories only and the modal parameters, in terms of natural circular frequencies, modal damping ratios and mode shapes, were determined. These identified parameters were then compared with the true values related to the initially assumed analytical models. Firstly, the analyses were performed for one structural configuration, for a fixed direction of the applied base excitation, but considering various durations of such input. The results showed that the accuracy related to mode shapes identification was lower for the first torsional mode with respect to the second longitudinal mode, which is a higher-order mode. In addition, the identified torsional mode shape exhibited major modal complexity than the longitudinal mode, as a result of simulated noise and identification errors. Secondly, the analyses were conducted considering different structural configurations, a fixed duration of the base excitation, but different directions of the applied input. The outcomes showed that the accuracy in mode shape estimations, evaluated by calculating the Modal Assurance Criterion (MAC) between identified and analytical mode shapes, was strongly dependent on the direction of the applied input, especially for high-order modes. It was also observed that these MAC values are directly correlated with the modal participation factors of the structure, evaluated for the different directions of the base excitation. Referring to the torsional mode shapes, the results showed that the number of input directions, for which these modes can be identified, are higher for the structures with major structural eccentricities.

Keywords: output-only modal identification, plan-asymmetric buildings, base excited structures

1. Introduction

System identification techniques [1] can be profitably applied to civil structures that are instrumented with Structural Health Monitoring systems. Ambient vibration or earthquake response data can be measured and used for the application of these techniques. The main purposes are related to the calibration of structural models or to the detection and the localization of damages in structures [2,3].

Recent studies of vibration-based damage detection have been conducted on full-scale earthquake-damaged buildings using shaking table testing, such as the studies conducted by Moaveni et al. [4] and by Astroza et al. [5]. Full-scale reinforced concrete buildings were progressively damaged by earthquake ground motions and at various level of damage, ambient vibration and white noise base excitation tests were performed. Starting from these data, the modal parameters were extracted using different algorithms related to both output-only and input-output identification. Referring to white noise base excitation tests, both input-output and output-only modal identification techniques can be applied but, as pointed out in [4], the latter perform better than the former. This statement is supported by the fact that more consistent result in term of mode shape estimation have been obtained when applying different identification algorithms in the output-only case with respect to the input-output one [4].

The experimental studies on white noise base excited structures reported in [4,5] showed that the identification of the mode shapes related to high-order modes and, especially, to torsional modes, is the most challenging. Indeed, as pointed out in [4,5], this is due to the fact that the first modes have a predominant contribution to the structural response, while high-order modes have a lower contribution and a higher signal-to-noise ratio with respect to the first modes [5]. In addition, a higher modal complexity was observed on the identified mode shapes related to high-order modes and, especially, for coupled longitudinal and torsional modes [4,5].

The objective of the paper is to study the modal identification applied to plan-asymmetric building structures that are subjected to base excitation, in order to investigate and confirm the experimental observations reported in [4,5]. The main problem addressed is related to the identification of high-order modes and, especially, torsional modes by considering different durations and different directions of the applied base excitation.

The identification was applied using the approach based on numerical simulation and assuming analytical models of the structures in order to generate the structural response due to the applied base excitation. In this way, the accuracy of the modal identification was derived by comparing the identified modal parameters with the true values obtained by the analytical models. Moreover, the modal participation factors were calculated starting from the analytical models of the structures and they were compared with the outcomes of modal identification.

The analyses were carried out on plan-asymmetric reinforced concrete (RC) frame structures that were excited by white noise base excitation, according to the type of excitation adopted in [4,5]. Due to the type of excitation, an output only modal identification method, which is the Eigensystem Realization Algorithm (ERA) [6,7] combined with the Natural Excitation technique (NExT) [8,9], was applied. The analyses were repeated by considering different directions of the applied white noise base excitation, carrying on the previous and preliminary work by Landi et al. [10]. Differently from this work, various and multiple configurations of the plan-asymmetric frames, which are characterized by different values of the structural eccentricities, were taken into account. In addition, different durations of the white noise signal assumed as a base excitation, instead of a fixed length of time as adopted in [10], were considered.

2. Output-only modal identification

Output-only modal identification can be applied to civil structures that are subjected to ambient vibration testing or are implemented with long-term monitoring systems. These structures can be tested under operational conditions, taking advantage of natural excitations such as wind or traffic loads. Starting from the vibration response only and applying the techniques and the algorithms of Operational Modal Analysis (OMA) [2], the modal properties of the structures can be obtained. The main assumption in OMA is that the unknown and stationary inputs, which excite the structures, are considered as zero mean Gaussian white noise signals. In addition, the best condition in OMA is having multiple, random and uncorrelated inputs at different spatial locations, and long enough recorded time histories are required in order to perform the calculations [2].

Output-only modal identification can also be applied to structures subjected to base excitation when the input can be considered as a white noise signal. In this kind of test a single input is applied to the structure and thus one of the assumptions for the application of the output-only modal identification in OMA [2], is not fulfilled. Indeed referring to the identification of building structures, the estimation of torsional mode shapes, for example, is more challenging in case of base excitation in comparison to ambient vibration testing, as pointed out in [4].

The identification method used for the numerical analyses presented in the paper is the Eigensystem Realization Algorithm (ERA) [6,7] combined with the Natural Excitation technique (NExT) [8,9]. ERA is a time-domain identification method that has been originally developed to compute discrete state-space realizations of structural systems, assumed as linear and time-invariant, starting from experimental measurements of their free decays. In case of output-only response data a pre-identification technique, such as NExT, is required for the application of the ERA method. This technique estimates the correlation functions for the different output signals of the system with respect to a reference channel. This is a common approach in output-only modal identification since correlation functions can be assumed as free decays of the structure [2].

3. Accuracy estimation in modal identification using a simulation approach

When applying system identification techniques through a simulation approach the identified model can be compared with the model that has been initially assumed for the generation of the data. The parameters related to this last model represent the target solution for the identification and the discrepancies with respect to the identified parameters can be computed.

Referring to the modal identification of structures, the focus is posed on the estimation of the modal parameters in terms of natural circular frequencies, modal damping ratios and mode shapes. In this section the criterions used for estimating the modal identification accuracy in the following numerical analyses, are presented. At first, two indices that have been used for the evaluation of the accuracy in mode shape estimation are considered. Secondly, the criterions related to natural circular frequencies and modal damping ratios are taken into account.

The Modal Phase Collinearity (MPC) [7] evaluates the linear dependence between the real and the imaginary parts of complex-valued mode shapes. This index is commonly used in model validation when modal identification is applied to real data. However, in a simulation approach of modal identification performed on proportionally damped structures, this parameter can be also used for the quantification of the identification accuracy. The Modal Phase Collinearity is defined as

$$MPC_i = \frac{\left(S_{xx} - S_{yy}\right)^2 + 4S_{xy}^2}{\left(S_{xx} + S_{yy}\right)^2} \tag{1}$$

where $S_{xx}=Re\ \boldsymbol{\psi}_i^T\ Re\ \boldsymbol{\psi}_i$, $S_{yy}=Im\ \boldsymbol{\psi}_i^T\ Im\ \boldsymbol{\psi}_i$, $S_{xy}=Re\ \boldsymbol{\psi}_i^T\ Im\ \boldsymbol{\psi}_i$ and $\boldsymbol{\psi}_i$ is the vector containing the components of the i-th complex-valued identified mode shapes. MPC values belong to the range $0 \leq MPC \leq 1$ and if the MPC is one or very close to it, the real and the imaginary parts of the mode shapes are proportional, as expected for proportionally damped structures. Otherwise, in case of low values of the MPC the resulting modal complexity is only generated by identification errors if the structure has been assumed as proportionally damped in the simulation.

In addition, the Modal Assurance Criterion [11] can be adopted in order to compare the mode shapes obtained through the modal identification and the corresponding eigenvectors that derive from an analytical model. The Modal Assurance Criterion, or cross MAC, is defined as

$$crossMAC_{ik} = \frac{\left(\phi_{ID,i}^{T}\phi_{AN,k}\right)^{2}}{\left(\phi_{ID,i}^{T}\phi_{ID,i}\right)\left(\phi_{AN,k}^{T}\phi_{AN,k}\right)} \tag{2}$$

where $\boldsymbol{\phi}_{ID,i}$ is the real-valued identified mode shape of the i-th mode and $\boldsymbol{\phi}_{AN,k}$ is the real-valued analytical mode shape of the correlated mode computed from the analytical model. The parameter is evaluated for each i, k = 1 … m, where m is the number of the modes. Each component of the cross MAC matrix is in the range $0 \leq$ cross $MAC_{ik} \leq 1$ and in case of a good correlation between the identified and the analytical mode shapes such values are close to one (e.g., higher than 0.9).

Referring to natural circular frequencies and modal damping ratios, which are scalar quantities, two indices defined in the range from zero to one are adopted in order to evaluate the identification accuracy. The index $r_{\omega,i}$ related to natural circular frequencies is defined as

$$r_{\omega,i} = \left|\frac{\omega_{ID,i}}{\omega_{AN,i}}\right| \tag{3}$$

where $\omega_{ID,i}$ is the identified natural circular frequency of the i-th mode and $\omega_{AN,i}$ is the natural circular frequency of the correlated mode computed from the analytical model. A correction to the index $r_{\omega,i}$ is applied

$$r_{\omega,i}^{*} = \begin{cases} r_{\omega,i} & if\ r_{\omega,i} \leq 1 \\ \dfrac{1}{r_{\omega,i}} & if\ r_{\omega,i} > 1 \end{cases} \tag{4}$$

in order to obtain values in the range $0 < r^{*}_{\omega,i} \leq 1$. The lower the values of the index $r^{*}_{\omega,i}$, the more the i-th natural circular frequency is poorly estimated.

Considering modal damping ratios, the same approach for the estimation of the identification accuracy is adopted by defining the index $r_{\zeta,i}$

$$r_{\zeta,i} = \left|\frac{\zeta_{ID,i}}{\zeta_{AN,i}}\right| \tag{5}$$

where $\zeta_{ID,i}$ is the identified modal damping ratio of the i-th mode and $\zeta_{AN,i}$ is the modal damping ratio of the correlated mode that is assumed in the analytical model. By adopting the correction on $r_{\zeta,i}$, as already defined for the natural circular frequencies, the index $r^{*}_{\zeta,i}$ is thus defined in the range $0 < r^{*}_{\zeta,i} \leq 1$

$$r_{\zeta,i}^{*} = \begin{cases} r_{\zeta,i} & if\ r_{\zeta,i} \leq 1 \\ \dfrac{1}{r_{\zeta,i}} & if\ r_{\zeta,i} > 1 \end{cases} \tag{6}$$

4. Numerical analyses

4.1 Test structure

The test structure is a reinforced concrete (RC) plan-asymmetric frame that is constituted by one span and three stories. The structure is modelled as a shear type frame, under the assumptions of considering the beams as infinitely stiff in comparison to the columns and the slabs as rigid diaphragms.

Four columns with a rectangular cross section (0.3 × 0.4 m) are present at each interstory and three different structural configurations, as reported in Fig. 1, are taken into account by changing the dimensions of the cross section of one of the columns. These configurations are characterized by different values of the structural eccentricity (i.e., the distance e_{CG} between the center of stiffness C and the center of the mass G), as reported below:

a) small eccentricity – configuration E1: the modified cross section of one column is 0.33 × 0.44 m ($e_{CG,x}$=0.3 m; $e_{CG,y}$ =0.3 m), Fig. 1a;

b) medium eccentricity – configuration E2: the modified cross section of one column is 0.40 × 0.50 m ($e_{CG,x}$=0.86 m; $e_{CG,y}$ =0.99 m), Fig. 1b;

c) high eccentricity – configuration E3: the modified cross section of one column is 0.50 × 0.60 m ($e_{CG,x}$=1.61 m; $e_{CG,y}$ =1.79 m), Fig. 1c.

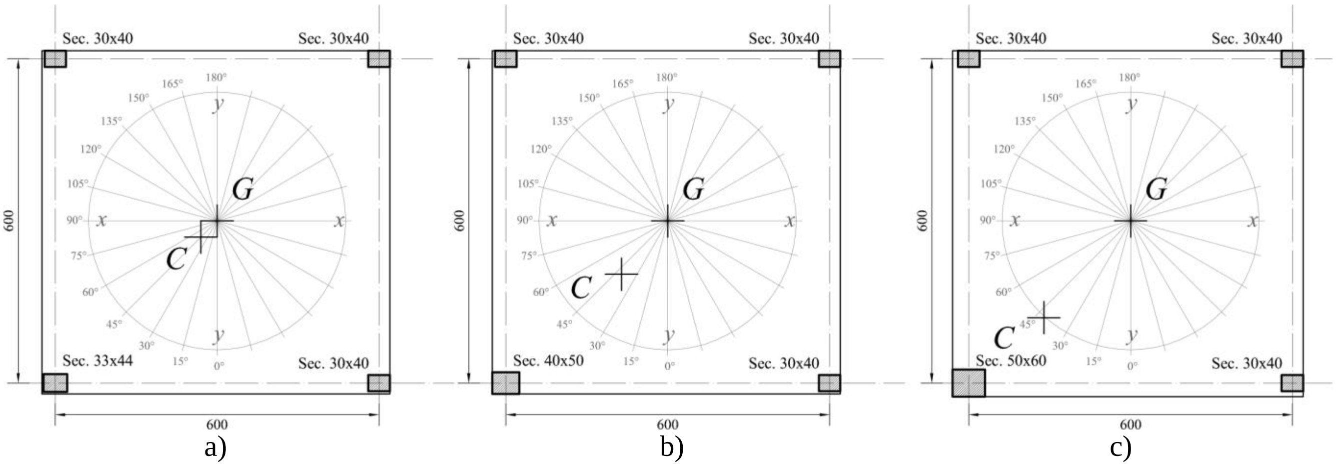

Fig. 1 – Plan views of RC frames with different configurations: a) small eccentricity - E1
b) medium eccentricity - E2 c) high eccentricity - E3

A 9 DOFs analytical model of each structure, in term mass and stiffness matrices, was assembled by considering 3 DOFs for each story. By performing a modal analysis the modal properties of the undamped systems, in terms of natural frequencies and mode shapes, were determined. The first four mode shapes of the structure in the configuration E2 are reported in Fig. 2. In addition, the modal damping ratio was assumed as ζ_i=0.05 for each i-th mode.

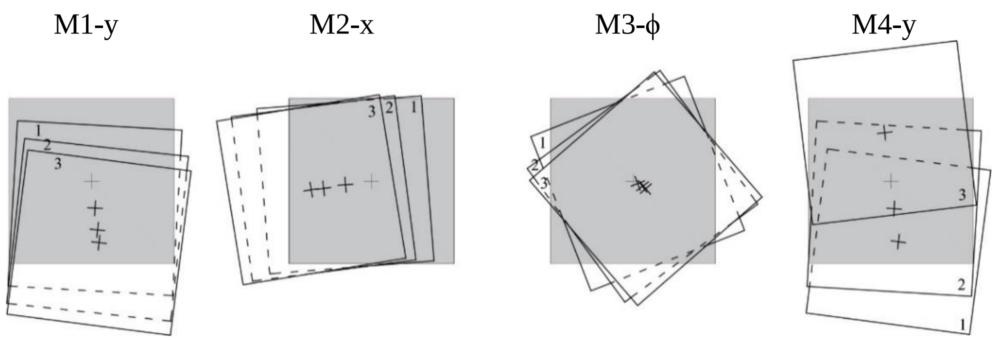

Fig. 2 – Plan views of the first four mode shapes for the configuration E2 (medium eccentricity)

4.2 Applied white noise base excitation

In order to perform the modal identification through a simulation approach the structures were excited by a white noise base excitation. The structural responses were collected at all the DOFs, as if they were recorded from a number of sensors (i.e., accelerometers) that is equal to the number of the DOFs. The white noise base excitation was generated with an acceleration, in term of the root-mean-square (RMS) amplitude, of approximately 0.01g and a 10% RMS noise was added to the obtained structural responses. The modal identification was then performed by considering these output signals and the absolute accelerations were converted to relative accelerations by subtracting the input signal.

At first, the analysis of the influence of the input duration in the modal identification was taken into account. Different cases were considered by varying the length of time of the applied white noise base excitation; they are described in Table 1.

Table 1 – Length of time (LT) of base excitation

Case	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**	**L10**	**L11**	**L12**	**L13**	**L14**	**L15**	**L16**
LT (s)	25	50	75	100	125	150	175	200	250	300	350	400	450	500	1000	2000

These analyses were performed on the structure with a medium eccentricity (configuration E2), which is characterized by a period of the first mode that is approximately T_1 = 0.5 s; in addition, it is worth mentioning that the modal damping ratio for the first mode is ζ_1=0.05. Some of the durations of the white noise input, which are equal to the durations of the output response, were selected according to the measurement requirements in OMA. Referring to case L4 (LT=100 s), the length of time of the input was determined by estimating the maximum correlation time in the response and then calculating LT = $(10/\zeta_1)\ T_1$, which is 20 times the correlation time, according to [2]. For the cases L9 (LT=250 s) and L14 (LT=500 s), the lengths of time of the base excitation were calculated according to the indication in [12] and considering recording time durations that are about 500 T_1 and 1000 T_1, respectively. Referring to case L16 (LT=2000 s), the input duration was determined, as reported in [2], according to ANSI S2.47 [13]; this length of time is equal to LT = $(200/\zeta_1)\ T_1$. The other cases were chosen in order to investigate the full range of variability from the minimum length of time (L1) to the maximum one (L16).

A second analysis has concerned the application of the modal identification starting from the structural responses in case of different directions of the applied base excitation. The full angle (360°) was divided into 24 circular sectors and each of the dividing segments was considered as a possible direction for the application of the input. The analyzed cases are reported in Table 2, in which the direction of the base excitation is indicated by an angle computed with respect to the y-axis, as reported in Fig. 1.

Table 2 – Direction of the applied base excitation (angles calculated with respect to y-axis)

Case	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**D10**	**D11**	**D12**
Angle (α)	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°

5. Results and discussion

5.1 Output-only modal identification: one case study

The results of the output-only modal identification performed using the NExT-ERA method are here reported and discussed for one case study. This case study is characterized by the structural configuration (E2) with a medium eccentricity (Fig. 1b), a duration of the applied base excitation LT = 500 s (case L14, according to Table 1) and a direction α = 135° of the input (case D10, referring to Table 2).

According to the NExT method, the correlation functions were calculated for all the response signals with respect to a reference one, which is the signal related to the DOF at the top story in the x-axis direction. These correlation functions were truncated to a time lag equal to 5 s. Indeed, according to [2], the longest correlation time, in which the function is reduced to approximately 4% of its maximum value, is defined by the period (i.e., T_1=0.5 s) and the modal damping ratio (i.e., ζ_1=0.05) of the first mode, and calculated as $T_1 / (2 \times \zeta_1)$. The ERA method was then applied starting from these estimated correlation functions. The dimension of the state space model was selected as equal to four times the number of the expected structural modes (i.e., 4 × 9 DOFs = 36), according to the indication reported in [8].

The distinction between computational and structural modes, among all the outcomes of the modal identification, was performed using an automated selection. According to the original formulation of the ERA method [6], the Modal Amplitude Coherence (MAmC) index and the Mode Singular Value (MSV) index were calculated. The true modes were selected by considering the modes with the higher values of the MSV (i.e., characterized by a high modal contribution) and with MAmC values > 0.90 (i.e., characterized by a high coherence between the data and the prediction based on the identified model). The results obtained from the mode selection were manually refined (e.g., selecting only one mode among the couple of complex conjugate modes that is identified in case of lightly damped structures) and the identified modes were correlated with the modes obtained by performing a modal analysis on the analytical model. The outcomes of the structural mode selection are reported in Table 3.

Table 3 – Selection of identified structural modes

Number of identified mode	Modal Amplitude Coherence (MAmC)	Mode Singular Value (MSV)	Correlated structural mode
7	0.999	0.048	M9-ϕ
13	0.971	0.103	M8-ϕ
17	0.974	0.120	M7-x
21	0.999	0.147	M6-y
23	0.989	0.746	M1-y
25	0.997	1.000	M2-x
29	0.997	0.296	M3-ϕ
31	0.995	0.301	M5-x
33	0.987	0.375	M4-y

The modal complexity of the identified structural modes was estimated and the polar plots of the complex-valued mode shapes related to the first four modes are reported in Fig. 3, together with the values of the Modal Phase Collinearity (MPC). It is worth noting that among the first modes, the third one (M3-ϕ), which is a torsional mode, shows the major modal complexity. This effect is not related to the dynamics of the structure (the assumed analytical model is indeed proportionally damped), but is only due to the noise added on the data and due to identification errors.

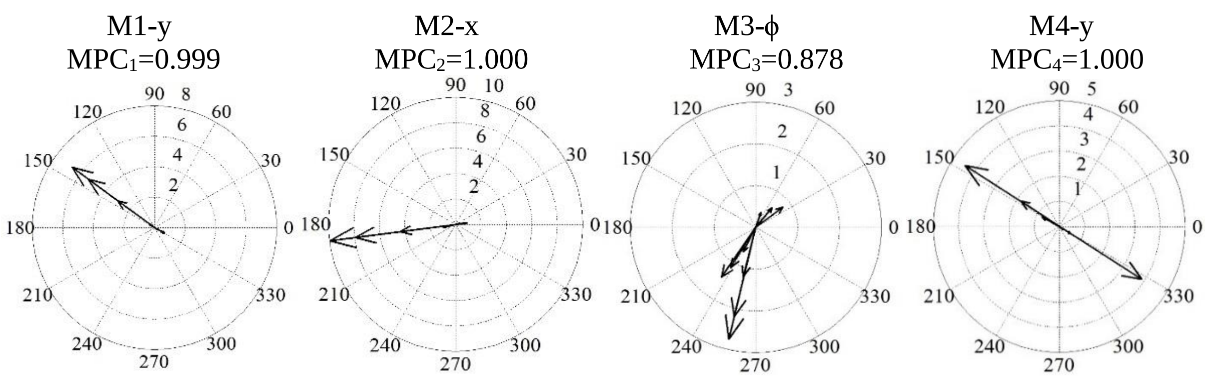

Fig. 3 – Polar plots of identified complex-valued mode shapes

Moreover, the identified complex-valued mode shapes were transformed to real-valued ones using the Standard Technique [1]. In order to validate the identified model the auto MAC matrix [11] was computed starting from the obtained real-valued mode shapes. This matrix estimates the similarities among the identified modal vectors and it is graphically reported in Fig. 4a. The consistency of the identified model is proven by the small values of the off-diagonal components of the auto MAC matrix. As expected, the diagonal elements of this matrix are equal to one.

In order to evaluate the accuracy related to the modal estimation, the identified model was compared with the analytical one. Referring to natural circular frequencies and modal damping ratios, the indices $r^*_{\omega,i}$ and $r^*_{\zeta,i}$ were calculated using Eq. (4) and Eq. (6), and the results are reported in Table 4. The natural circular frequencies are accurately identified, while more uncertainties are related to the identification of the modal damping ratios. In addition, the cross MAC matrix was calculated in order to compare the identified and the analytical mode shapes. This matrix is reported in Fig. 4b and its diagonal values are also included in the last columns of Table 4. These values are close to one, especially for the first modes.

a) b)

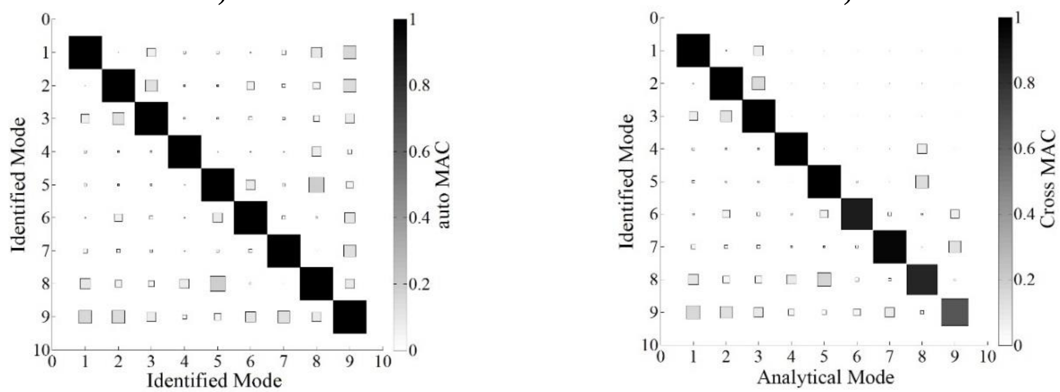

Fig. 4 – Modal Assurance Criterion matrices: a) auto MAC; b) cross MAC

Table 4 – Accuracy estimation related to the identified modal model

Structural *i*-th mode	$\omega_{ID,i}$ **(rad/s)**	$\omega_{AN,i}$ **(rad/s)**	$r^*_{\omega,i}$ **(/)**	$\zeta_{ID,i}$ **(/)**	$\zeta_{AN,i}$ **(/)**	$r^*_{\zeta,i}$ **(/)**	**Cross** MAC_{ii} **(/)**
M1-y	12.95	12.88	0.995	0.045	0.05	0.870	1.000
M2-x	16.69	16.55	0.991	0.050	0.05	0.997	0.997
M3-ϕ	27.16	27.25	0.997	0.042	0.05	0.843	0.999
M4-y	35.84	36.10	0.993	0.049	0.05	0.983	0.993
M5-x	46.62	46.36	0.995	0.052	0.05	0.957	0.990
M6-y	52.09	52.17	0.999	0.063	0.05	0.790	0.885
M7-x	66.69	67.00	0.995	0.048	0.05	0.955	0.968
M8-ϕ	76.79	76.35	0.994	0.055	0.05	0.915	0.850
M9-ϕ	110.64	110.32	0.997	0.066	0.05	0.762	0.664

5.2 Influence of the duration of the base excitation on the modal identification

Ten runs of the NExT-ERA identification algorithm were performed for each duration of the applied input (i.e., cases from L1 to L16, as reported in Table 1). For each run of the procedure a white noise signal was generated, and applied as a base excitation with a direction $\alpha = 135°$ to the structure with a medium eccentricity (configuration E2) in order to obtain the response used for the identification. The accuracy of the identification was evaluated by calculating the following parameters: the index $r^*_{\omega,i}$, the index $r^*_{\zeta,i}$, the Modal Assurance Criterion (cross MAC) and the Modal Phase Collinearity (MPC). At the end, the results for the different lengths of time of the applied base excitation, obtained through the ten runs of the algorithm, were averaged. The outcomes are reported and discussed with reference to the third mode M3-ϕ (i.e., the first torsional mode) and the fourth mode M4-y (i.e., the second longitudinal mode with prevalent mode shape components along the y-axis).

The cross MAC values related to all the performed analyses are reported in Fig. 5, where the different durations of the base excitation are conveniently reported using a logarithmic scale on the x-axis. Fig. 5a refers to the torsional mode M3-ϕ while Fig. 5b is related to the longitudinal mode M4-y. For both modes the cross MAC tends to one if longer durations of the input are considered. In addition, it is evident that the torsional mode exhibits lower values of the cross MAC with respect to the longitudinal mode, for which all the values are higher than 0.8. The cross MAC values averaged for each input duration are highlighted in Fig. 5 using a continuous line for the mode torsional M3-ϕ and a dashed line for the longitudinal mode M4-y.

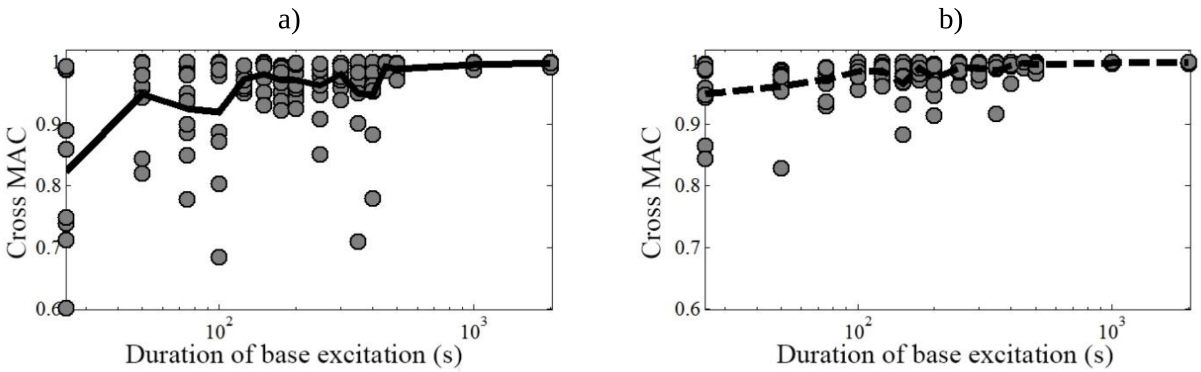

Fig. 5 – Cross MAC value vs duration of base excitation: a) M3-ϕ; b) M4-y

For the sake of brevity, the results related to the other indices (i.e., r^*_ω, r^*_ζ and MPC) are only reported in terms of averaged values (Fig. 6). All the considered indices, including the cross MAC, increase and tend to one for longer durations of the applied base excitation. However, the index r^*_ζ shows a higher variability and lower values with respect to r^*_ω. These observations are true both for the torsional mode and for the longitudinal mode. It is worth noting that the results obtained for modes M3-ϕ and M4-y are similar both considering the index r^*_ω related to natural circular frequencies and the index r^*_ζ related to modal damping ratios. On the contrary, the averaged values of both the cross MAC and the MPC are higher for the longitudinal mode with respect to the torsional mode.

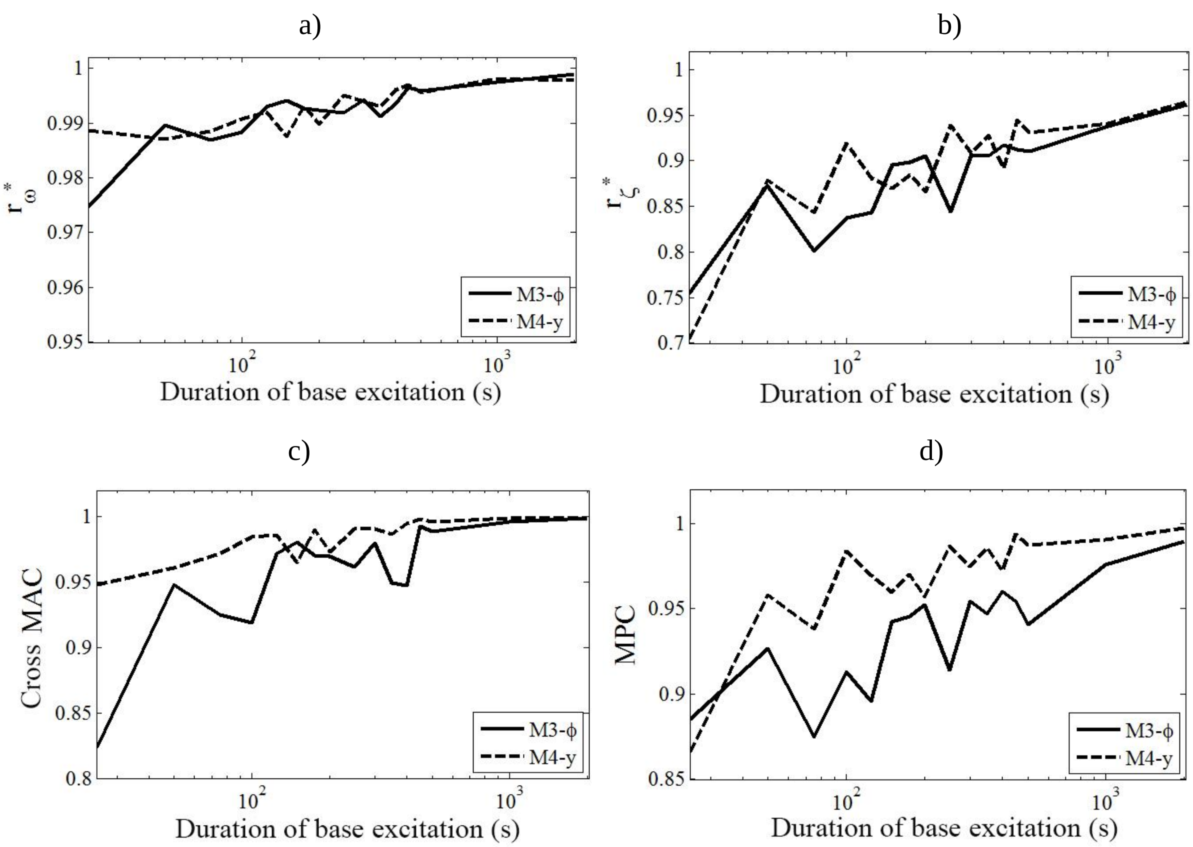

Fig. 6 – Averaged results of identification accuracy vs duration of base excitation: a) index r^*_ω; b) index r^*_ζ; c) Modal Assurance Criterion (cross MAC); d) Modal Phase Collinearity (MPC)

5.3 Influence of the direction of the base excitation on the modal identification

The results of the modal identification applied for the different directions of the base excitation, according to the cases from D1 to D12 (Table 2), are here reported and discussed, specifically addressing the problem of mode shape identification. The analyses were performed for the three structural configurations (from E1 to E3) characterized by different structural eccentricities and for a fixed length of time of the input equal to 500 s (case L14). Moreover, only one run of the NExT-ERA algorithm was performed for each direction of the base excitation.

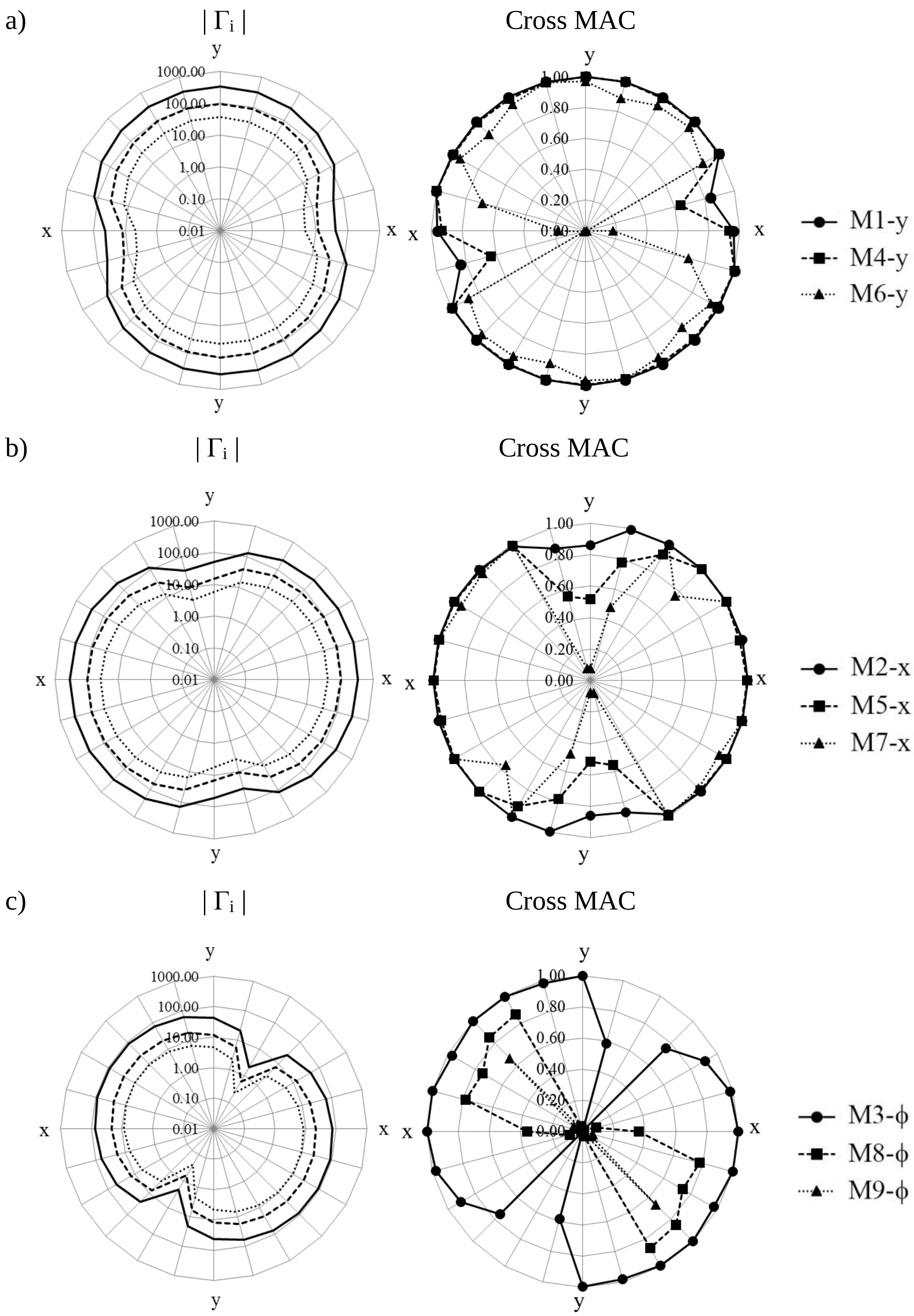

Fig. 7 – Modal participation factors and cross MAC values for the different directions of the base excitation: a) longitudinal modes along the y-axis; b) longitudinal modes along the x-axis; c) torsional modes

It is worth highlighting that the structural modes were identified using the automatic selection, as described in Section 5.1. Notwithstanding that, for this analysis when a mode was not automatically identified (e.g., as occurred for some higher modes, especially the torsional ones), the corresponding analytical mode shape was manually associated to the identified mode shape by comparing the analytical and the identified natural frequencies. In the majority of the cases, this operation led to very low or zero values of the cross MAC, proving that the modes were not completely identifiable.

The modal participation factors Γ_i of the three structures, evaluated for each direction of the applied base excitation, were calculated and compared with the cross MAC values, which express the accuracy related to mode shape identification. For the sake of brevity, the results related to all the modes are presented only for the structure characterized by a medium structural eccentricity (configuration E2), as reported in Fig. 7. In this figure, the similar modes are grouped together: Fig. 7a refers to longitudinal modes along the y-axis, Fig. 7b is related to longitudinal modes along the x-axis and the torsional modes are reported in Fig. 7c. The accuracy related to the mode shape identification is strongly dependent on the direction of the applied input, as shown in Fig. 7. In addition, there is a correlation between the absolute values of the modal participation factors $|\Gamma_i|$ and the values of the cross MAC: in case of an input direction that leads to a high participation factor for the *i*-th mode, the corresponding mode shape is identified with a cross MAC that is quite close to one. On the contrary, referring to input directions that lead to low modal participation factors, the uncertainties in the identification of the mode shapes increase, especially for the high-order modes. It is worth mentioning that the sixth mode shape (M6-y) and the seventh mode shape (M7-x) were not identified at all for input directions that are along the x-axis and the y-axis, respectively.

As evident in Fig. 7c, the identification of the torsional modes is the most challenging. The results, in terms of cross MAC values, related to the identification of the torsional modes for the structures characterized by the different structural eccentricities (configurations E1, E2 and E3) are reported in Fig. 8. For all the three configurations the third mode shape (M3-ϕ) was never identified for an input direction that is approximately parallel to the segment that connects the center of the stiffness (C) and the center of the mass (G) (i.e., for α=30° or α=45°). For the small eccentricity configuration (E1), it was not possible to identify the eighth and the ninth mode shapes at all, as shown in Fig. 8a. The possibility of identifying these mode shapes is higher for the medium (E2) and the high eccentricity (E3) configurations, however for the majority of the input directions low values of the cross MAC were obtained, as demonstrated in Fig. 8b and Fig. 8c.

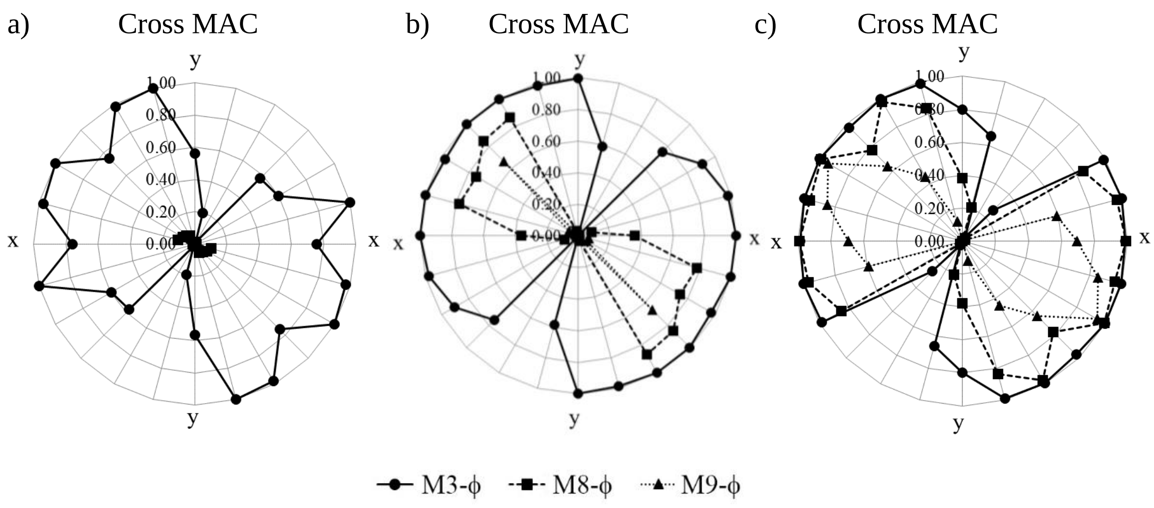

Fig. 8 – Cross MAC values related to identification of torsional mode shapes: a) small eccentricity configuration (E1); b) medium eccentricity configuration (E2); c) high eccentricity configuration (E3)

6. Conclusions

The work has concerned the application of modal identification techniques on plan-asymmetric structures subjected to base excitation. The output-only algorithm NExT-ERA was applied using numerical simulations on different structural configurations of RC plan-asymmetric frames and considering different durations and different directions of the applied white noise base excitation.

Firstly, comparing the results obtained for the first torsional mode and for a longitudinal mode, which is a high-order mode, it was observed that the accuracy related to mode shapes identification is higher for the longitudinal mode almost for each duration of the applied input. In addition, the identified torsional mode shape showed a greater modal complexity, due to the added noise on the data and identification errors, than the longitudinal mode. Secondly, it was observed that the accuracy in mode shape estimation is strongly dependent on the direction of the applied input, especially for high-order modes. Moreover, referring to the identification of the torsional mode shapes, the results showed that the number of input directions, for which this task was achieved, is higher for the structures with the greater structural eccentricities.

The experimental observations reported in [4,5] and related to the challenging problem of identifying high-order modes and, especially, torsional modes for white noise base excited structures have been investigated and confirmed using numerical simulations and parametric studies on modal identification applied to frame structures. Moreover, it has been shown that the accuracy in mode shape identification, for structures subjected to base excitation along different directions, is directly correlated with the distribution of the modal participation factors evaluated for the same directions.

Future developments of the work are related to the extension of the performed analyses to the case of non-stationary input signals, such as earthquake excitations.

7. References

[1] Alvin FK, Robertson AN, Reich GW, Park KC (2003): Structural system identification: from reality to model. *Computers and Structures*, **81**, 1149-1176.

[2] Brincker R, Ventura C (2015): *Introduction to OPERATIONAL MODAL ANALYSIS.* John Wiley & Sons, UK.

[3] Farrar R, Worden K (2013): *Structural health monitoring – A machine learning perspective*. John Wiley & Sons, UK.

[4] Moaveni B, He X, Conte JP, Restrepo JI, Panagiotou M (2011): System identification study of a 7-story full-scale building slice tested on the UCSD-NEES shake table. *Journal of Structural Engineering*, **137** (6), 705-717.

[5] Astroza R, Ebrahimian H, Conte JP, Restrepo JI, Hutchinson TC (2016): System identification of a full-scale five-story reinforced concrete building tested on the NEES-UCSD shake table. *Structural Control and Health Monitoring*, **23** (3), 535-559.

[6] Juang JN, Pappa RS (1985): An eigensystem realization algorithm for modal parameter identification and model reduction. *Journal of Guidance, Control, and Dynamics*, **8** (5), 620-627.

[7] Pappa RS, Elliott KB, Schenk A (1993): Consistent-mode indicator for the eigensystem realization algorithm. *Journal of Guidance, Control, and Dynamics*, **16** (5), 852–858.

[8] Caicedo JM (2011): Practical guidelines for the natural excitation technique (NExT) and the eigensystem realization algorithm (ERA) for modal identification using ambient vibration. *Experimental Techniques,* **35** (4), 52-58.

[9] James III GH, Carne TG, Lauffer PJ (1993): The Natural Excitation Technique (NExT) for Modal Parameter Extraction From Operating Wind Turbines. *The International Journal of Analytical and Experimental Modal Analysis*, **10** (4), 260-277.

[10] Landi L, Bernagozzi G, Diotallevi PP (2015): Operational modal analysis of a plan-asymmetric RC frame structure subjected to a simulated random ground motion along different directions. *Proceedings of the XVI conference "L'Ingegneria sismica in Italia" ANIDIS 2015*, L'Aquila, Italy.

[11] Allemang RJ (2003): The modal assurance criterion - Twenty years of use and abuse. *Sound and Vibration,* **37** (8), 14-23.

[12] Møller N, Gade S, Herlufsen H (2005): Stochastic Subspace Identification Technique in Operational Modal Analysis. *1st International Operational Modal Analysis Conference*, Copenhagen, Denmark.

[13] ANSI S2.47 (1990): Guidelines for the Measurement of Vibrations and Evaluation of Their Effects on Buildings. *American National Standard, Vibration of Buildings,* R2001.