Makara Journal of Technology

Volume 18 | Number 1 Article 1

4-1-2014

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Recommended Citation

Budipriyanto, Agung and Suprobo, Priyo (2014) "Dynamic Characteristic Identification of Seismic-Excited Multi-Story Buildings through Response-Only Technique," *Makara Journal of Technology*: Vol. 18 : No. 1 , Article 1.
DOI: 10.7454/mst.v18i1.2936
Available at: https://scholarhub.ui.ac.id/mjt/vol18/iss1/1

Makara J. Technol. 18/1 (2014), 1-10
doi: 10.7454/mst.v18i1.2936

Dynamic Characteristic Identification of Seismic-Excited Multi-Story Buildings through Response-Only Technique

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Abstract

Identifying dynamic characteristics of civil engineering structures is still a challenging task. It intends to assess behavior of the structures under time-dependent loads. This paper discusses a methodology suitable for identifying the characteristics of multi-story buildings using only their measured response under earthquake ground excitations. Appropriateness of technique used for structural identification was corroborated through coherence of the structure's responses. The methodology was applied for identifying the characteristics of 14-story and 20-story office buildings located in a high seismic region. Responses of these two buildings recorded during three different seismic ground motions were investigated. The buildings' response spectral densities and singular values were computed and utilized to identify their dynamic characteristics, viz. modal frequencies, damping factors, and mode types such as bending or torsion mode. Results of this study were validated through comparisons with the results reported using different structural identification techniques. It indicated that the methodology implemented in this study was capable of identifying the dynamic characteristics of multi-story buildings using responses under seismic ground motions.

Abstrak

Identifikasi Karakteristik Dinamik Gedung Bertingkat dengan Menggunakan Respons Seismik dari Struktur. Identifikasi karakteristik dinamik struktur sipil bertujuan untuk mempelajari perilakunya akibat beban yang bervariasi dengan waktu. Makalah ini membahas metodologi untuk identifikasi struktur gedung bertingkat dengan hanya menggunakan respons yang diukur selama terjadi gempa. Dalam makalah ini, koherensi respons struktur digunakan untuk menjustifikasi penerapan metode yang dipakai. Metodologi tersebut diaplikasikan untuk identifikasi karakteristik dinamik (frekwensi, faktor redaman, dan ragam) struktur gedung bertingkat 14 dan 20 dengan menggunakan respons percepatan yang direkam selama tiga kejadian gempa. Hasil dari studi ini dibandingkan dengan hasil studi terdahulu yang diperoleh dengan metode yang berbeda. Hasil tersebut mengindikasikan bahwa metodologi ini mampu mengidentifikasi karakteristik dinamik struktur gedung bertingkat dengan menggunakan responsnya akibat beban gempa.

Keywords: dynamic characteristic identification, multi-story building, seismic excitation, response-only technique

1. Introduction

Dynamic characteristic identification of civil engineering structures, e.g., buildings, bridges, and fixed offshore structures, needs to be carried out for assessing the structures under time-dependent loads. These dynamic characteristics include the natural frequency, damping factor, and mode shape or type. In many cases the structures' dynamic characteristics obtained from experimental investigations are required. These investigations are conducted, for instance, for updating numerical finite element structural models, studying performance of the structures under time-varying loads, and establishing baseline of vibration-based health monitoring of the structures.

In carrying out experiments on a large civil engineering structure for measuring these dynamic characteristics, it would be difficult to excite the structure using artificial excitation forces. Therefore, these characteristics are viably obtained from the structure's response under natural excitation loads, e.g., the wind, waves, traffic, or seismic loads. One of the advantages of utilizing these excitations in vibration testing is that they allow the structure undergoing testing to be in its normal operational conditions. As no excitation force data is acquired during testing, the structure's dynamic characteristics can only be identified from its response recorded during these natural excitations.

Studies on system identification of multi-story buildings under seismic ground excitations have attracted the attention of researchers. In [1-3], application of Auto-Regressive Moving Average with exogenous input technique was reported to identify dynamic characteristics of the structure. A 26-story building was studied in [1]. Its responses were measured using seismometers mounted at three locations along the building's height. Then they were employed to obtain the structure's dynamic characteristics. They stated that the technique could be utilized to identify the dynamic characteristics from few seismic response data. In [2,3], dynamic characteristics of multi-story buildings under seismic loadings were estimated from the buildings' responses measured in the basement and at the roof using the above-mentioned technique. The buildings' response spectra and spectral ratios were computed for determining their natural frequencies.

The performance of a multi-story building under seismic loadings was studied, and the results were discussed in [4,5]. In [4], the authors utilized the building's measured response to compute its dynamic characteristics using the method employed in [1-3]. Finite element analyses were carried out to obtain an appropriate numerical model for simulating the structure's time response under these loadings. The ARX method was also applied in [5] for structural system identification of a 13-story steel-moment resisting frame building to extract damping ratios and natural frequencies of the building under different earthquake excitations. Damage detection methods including frequency changes and presence of high frequencies were applied to detect fractures that occurred in the building due to the seismic ground motions.

Zhang et al. [6] reported results of investigation on dynamic characteristics of a 20-story building under ambient and earthquake loads. They pointed out that the building's natural frequencies obtained using ambient and earthquake forces were slightly different. Finite element analysis of the 20-story building was conducted, and the results were reported in [7]. The building's responses in horizontal and transverse directions obtained from the finite element analysis were calibrated using its recorded ambient responses. The calibration was conducted in order to elicit the building's finite element model having similar natural periods with those measured under the ambient forces. In their study, commercially available computer software was employed to obtain natural periods and damping factors of the building from recorded seismic and ambient responses. Incremental dynamic analysis and modal pushover analysis approaches were implemented to predict nonlinear seismic response of the building using the calibrated model.

Kim et al. [8] proposed a time domain method for identifying dynamic characteristics of a single degree of freedom system with unknown excitations. They verified the effectiveness of the method through numerically simulated data and data collected from the experiment carried out on a reinforced concrete highway bridge located in Southern California. Because their proposed method was based on the single degree of freedom approach, there would be problems when it was applied to systems having closely spaced modes. Ibrahim Time Domain identification technique was utilized in [9] for dynamic characteristic identification of a multi-story building from its seismic response. In the analysis, the response used was selected so that the identification technique could be applied to extract dynamic characteristics of the building. Selection of the input data from seismic response for the identification technique was found to be rather time consuming. The blind source separation along with random decrement method was employed in [10] to measure natural frequency and damping ratio of 1^{st} mode of the 14-story building. Responses of the building recorded during four earthquake excitations were utilized in this study.

This paper discusses a methodology applicable for dynamic characteristics identification of multi-story buildings using response data recorded during seismic ground motions. In this study, coherence function was computed prior to carrying out dynamic characteristics identification of the structure to verify whether or not nonlinearity was present in the structure. Hence, an appropriate system identification technique, viz., linear or nonlinear technique, could be selected. The coherence function was obtained from selected reference seismic response and responses measured at different structures' locations. When the structure is linear, its natural frequency can be determined through spectral density magnitude and phase of the seismic responses. This study partly adopted techniques proposed in [11,12] to obtain the damping factor and mode. Singular values of the seismic response spectrum were computed to separate possibly closely spaced modes. Then unlike the method proposed in [11,12], the singular values of the spectrum were transformed into the time domain to get responses of single degree of freedom systems from which damping factors could be elicited. Curve-fitting technique was employed to extract damping factor from the responses.

To demonstrate its efficacy, the methodology presented in this paper was applied to extract the dynamic characteristics of 14-story and 20-story instrumented office buildings located in an active seismic zone. Under United States Geological Survey National Strong

Motion Program [13], acceleration sensors were installed on different locations and floors of the buildings to measure their response under seismic loadings. Instruments mounted in the buildings could monitor horizontal, transverse, and rotational displacements; total drift; and inter-story drift of any floors in the buildings during earthquake loadings.

The 14-story building was 45.5m long, 32.3m wide, and 49.7m high (measured from the ground floor). It was a moment-resisting frame structure. Nine accelerometers were installed on the building floors. They were located in the basement, on the 8th floor, and at the roof of the building to measure the building's seismic response in the transverse, longitudinal, and vertical; and directions, viz. the x-, y-, and z-axis directions, respectively; see Figure 1(a). On the building floors, two accelerometers were deployed to measure response in the vertical direction, two accelerometers were mounted to measure the response in the longitudinal direction, and five accelerometers were deployed to measure the building's dynamic response in the transverse direction. Accelerometers deployed for measuring seismic response in the transverse direction, i.e. the x-axis or EW direction, were located at the building roof, on the 8th floor of the building, and in the basement; they were named accelerometer #1, #2, #3, #4, and #9. Responses measured using four accelerations, except that of accelerometer #3, were utilized in this study to estimate the building dynamic characteristics. Response of accelerometer #3 was not available for all seismic excitations investigated in this study; therefore it was not used for the dynamic characteristic identification.

The 20-story building was 80.5m tall, and its plan dimension was 38.5m by 38.5m. The building was a moment-resisting steel frame structure with 14.63m by 14.63 m steel shear wall core located in the center of the building. In the building a total of 30 accelerometers were installed. They were located in the basement, on the 1st, 2nd, 7th, 8th, 13th, 14th, 19th, and 20th floors and at the roof of the building. These acceleration sensors were capable of measuring the building's acceleration responses when it was being shaken by strong ground motions. There were one tri-axial and 29 uni-axial acceleration sensors in the building. The tri-axial accelerometer was deployed for measuring acceleration response in the three axis directions, viz., horizontal, vertical, and transverse directions, while the uni-axial one was mounted for measuring the response either in horizontal, vertical, or transversal direction. Figure 1(b) shows sensor locations mounted on the 20-story building. In this study, the responses of accelerometers #17, #23, #29, and #32 were employed to obtain the building's dynamic characteristics. Earthquakes shook these two buildings, and their acceleration responses during these ground motions were measured and documented.

This paper presents results of investigations on dynamic characteristics of these multi-story buildings under three earthquake ground excitations, respectively; for the 14-story building the earthquakes investigated in this study occurred on October 23, 2002; November 3, 2002; and December 15, 2003; and for the 20-story building they occurred on December 15, 2003; April 23, 2004; and May 30, 2004. Tables 1 and 2 present information regarding focal depth of the earthquake, the distance measured from the earthquake's epicenter to the building

(a) The 14-story building **(b) The 20-story building**

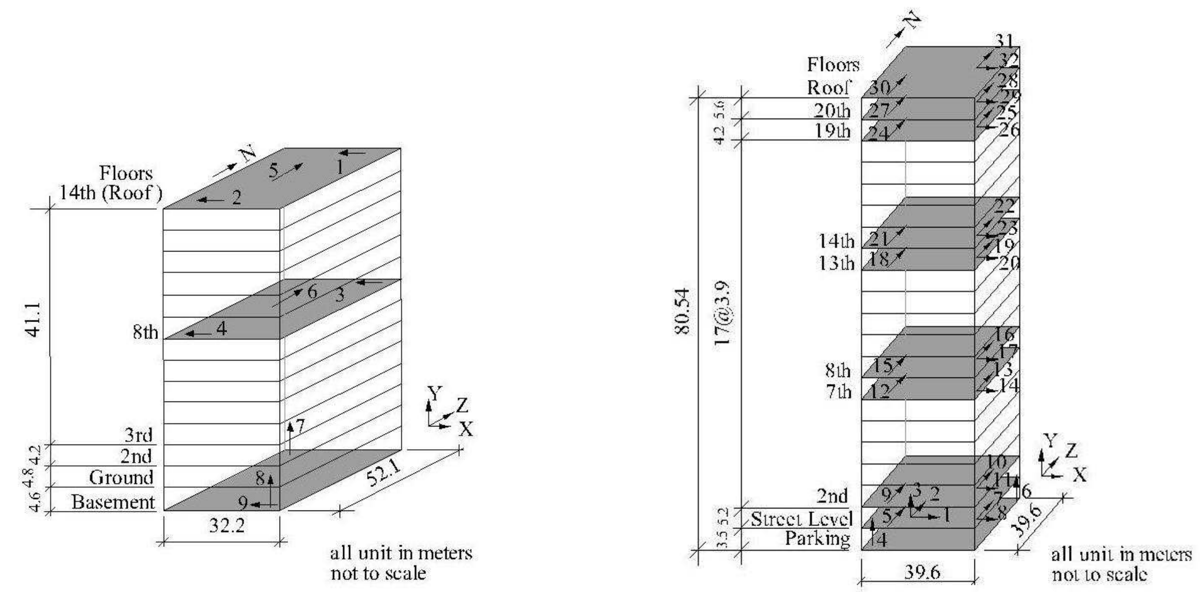

Figure 1. Locations and Directions of Acceleration Sensors Mounted on (a) the 14-Story Building and (b) the 20-Story Building (Redrawn from [2,3])

Table 1. Focal Depths, Epicentral Distances, and Peak Ground Accelerations of the Earthquakes Shook the 14-Story Building

Seismic event	Focal depth (km)	Ep. dist. [a] (km)	PGA[b] (cm/s^2)
Oct 23, 2002	10.0	278.6	3.4
Nov 3, 2002	5.0	286.0	15.6
Dec 15, 2003	37.0	20.0	6.4

[a] The epicentral distance was measured from the earthquake epicenter to the building location, [b] PGA presented in this table was peak acceleration measured in the basement of the building in the E-W direction [2,6]

Table 2. Focal Depths, Epicentral Distances, and Peak Ground Accelerations of the Earthquakes Shook the 20-Story Building

Seismic event	Focal depth (km)	Ep. dist. [a] (km)	PGA[b] (cm/s^2)
Dec 15, 2003	37.0	18.6	6.4
April 23, 2004	41.3	23.4	1.47
May 30, 2004	127.6	126.1	1.96

[a] The epicentral distance was measured from the earthquake epicenter to the building location, [b] PGA presented in this table was peak acceleration measured in the basement of the building in the E-W direction [2,6]

investigated in this study, and peak acceleration response recorded in the building's basement in the EW direction [2-6]. These buildings' seismic responses were chosen since these response data have been well documented so that they were readily available for the study presented in this paper.

It should be noted that finite element analyses of the buildings under these seismic ground motions could not be carried out in this study because detailed structural dimensions of the buildings could not be obtained. However, finite element analyses of the buildings investigated in this study had been conducted in studies reported in [4,5,7]. Those studies were performed with the intent of obtaining numerical models for the buildings where their time responses were similar to the buildings' time responses recorded during earthquake excitations. Investigation carried out in this study was aimed at implementing a methodology applicable for dynamic characteristic identification of multi-story building using its responses measured when the building was being shaken by earthquake ground motions. Dynamic characteristics of two multi-story buildings under respectively three different seismic loadings were investigated, and the results are reported in this paper. Results of this study were verified by comparing them with results of studies reported in [2-4,6,7].

2. Methods

For two response measurements, $x_i(t)$ and $y_i(t)$, the cross-spectral density function can be obtained using [11]

$$S_{xy}(f) = \frac{2}{n_d N\Delta t}\sum_{i=1}^{n_d} X_i^* Y_i \ . \qquad (1)$$

i=1,2,3…N, Δt is sample time interval, n_d is number of records, X_i and Y_i are Fourier transforms of $x_i(t)$ and $y_i(t)$ respectively. In this study these responses were obtained when the multi-story building structure was excited by earthquake forces. The spectrum was used for estimating dominant frequency of the structure.

The phase angle of the cross spectral density is computed using the expression below:

$$\theta_{xy} = \tan^{-1}\left[\frac{\operatorname{Im} S_{xy}(f)}{\operatorname{Re} S_{xy}(f)}\right]. \qquad (2)$$

Re S_{xy} and Im S_{xy} are respectively the real and imaginary parts of the spectrum.

To check linearity of the structure, the coherence function can be obtained using [11] as follows:

$$\gamma_{xy}^2 = \frac{\left|S_{xy}(f)\right|^2}{S_{xx}(f)S_{yy}(f)} \ . \qquad (3)$$

$S_{xy}(f)$ and $S_{xx}(f)$ denote the cross-spectral density of input and output responses and the auto spectral density of the input, respectively.

The coherence function can be utilized to discriminate linear and nonlinear structural systems [14]. This function value ranges from 0.0 to 1.0. When the coherence function value is about 0.0, it indicates that the system is not linear. The system is designated to be linear when the function value is close to 1.0.

As the input excitation was not measured, a reference response needed to be determined. In this study, the coherence function was obtained for determining a reference response. Coherence functions of any combination of two responses measured at different building locations were computed and examined. Response measured at a location of the structure was selected to be a reference if coherence function values obtained using the reference and any other investigated response recorded at different building locations were good, i.e., close to unity, or resulted in higher coherence values. When a reference response had been determined, dynamic characteristic identification of the building could be accomplished.

When the building structure behaves linearly and its modes are well separated, natural frequencies of the structure can be roughly estimated using auto and cross-spectrum of the measured seismic responses. It can be conducted by examining the frequencies that corresponds to the peak magnitudes of spectrum. However for a system having closely spaced modes, effects of the adjacent modes would lead to erroneous identified dynamic characteristics. Therefore in this study singular values of the spectrum were computed to decompose the response spectrum into response of single degree of freedom systems where the dynamic modal characteristics could be extracted [12]. In addition, the phase of the structure's response spectrum under these excitations was obtained to distinguish the type of vibration mode, viz., bending mode or torsion mode.

Auto spectral density of the output, $S_{yy}(f)$, and spectral density of the input, $S_{xx}(f)$, can be related using the expression given below [12]:

$$S_{yy}(f) = H^{*}(f)\, S_{xx}(f)\, H^{T}(f) \tag{4}$$

where $H(f)$ and $H^{*}(f)$ denote frequency response function and its conjugate, respectively. Suppose the inputs are uncorrelated and their spectra are flat in the vicinity of the structure's natural frequency, $S_{xx}(f)$ is a diagonal matrix having constant magnitude. In this case Eq. (4) can be written

$$S_{yy}(f) = \mathrm{S}\, H^{*}(f)\; H^{T}(f). \tag{5}$$

S denotes the spectral density, and it may be omitted because its values are constant. Accordingly, the spectrum can be computed using the expression

$$S_{yy}(f) = \sum_{j=1}^{n} \frac{\phi_j \phi_j^{T}}{(i \cdot f - \lambda_j)} + \frac{\phi_j^{*} \phi_j^{*T}}{(i \cdot f - \lambda_j^{*})} \tag{6}$$

where n is the number of modes, ϕ is the eigenvector, λ and λ^{*} are the complex pole and its conjugate, respectively, f denotes frequency, superscript T denotes matrix transpose, and $i = \sqrt{-1}$. In matrix form, the spectrum can be expressed as the multiplication of three matrices as

$$S_{yy}(f) = \Phi \Lambda \Phi^{T}\ . \tag{7}$$

Φ is matrix of spectral eigenvalues, where natural frequencies and damping factors can be extracted, and Λ is matrix of eigenvectors, where mode shapes can be obtained.

Unlike the method proposed in [11,12], in the study reported in this paper the singular values were transformed into the time domain, and damping factor was then estimated in a least square sense using the expression given below:

$$y = Ae^{-\zeta 2\pi f_n t}\left(\cos(2\pi f_d\, t) + \frac{\zeta}{\sqrt{1-\zeta^2}}\sin(2\pi f_d\, t)\right) \tag{8}$$

where A is a constant, f_n and f_d are natural frequency and damped natural frequency, respectively, ζ is damping factor, and t denotes time.

The methodology described above was applied for identifying dynamic characteristics of the 14-story and 20-story office buildings in the EW direction using their responses under three different earthquake ground motions, respectively.

3. Results and Discussion

To implement the methodology proposed in this study, cross spectra of the structure response were computed so that the structure's predominant frequency under the investigated earthquake excitations could be estimated. Dominant frequency corresponds to largest response amplitude in a frequency range of interest. Then coherence functions computed using responses measured on different building floors were plotted to examine the building's dynamic response characteristics, i.e. linear or nonlinear, under these seismic loadings.

Figures 2 to 4 show cross-spectrum, coherence, and phase spectrum obtained from responses of the 14-story and 20-story buildings under the earthquake loadings investigated in this study. The 14-story building responses employed for computing the spectra were those recorded from accelerometers #4 & #1, #4 & #2, #4 & #9, and #1 & #2; see Fig. 1(a) for the accelerometer numbers. For the 20-story building, the responses recorded using accelerometers #17, #23, #29, and #32 were employed to obtain the spectra and its dynamic characteristics in the EW direction.

Figures 2(a) to (f) and Figs. 3(a), (b), and (c) show the spectrum, coherence, and phase spectrum of the 14-story building seismic response. As seen in Figs. 2(a) and (b), frequency at predominant peak spectrum magnitudes under the October 23, 2002, and November 3, 2002, earthquake excitations were about 0.4 Hz. Smaller spectral amplitude at higher frequency was also observed; see Fig. 2(d). Under the December 15, 2004, earthquake loadings, however, the response spectrum had the predominant frequency of 1.51 Hz. Larger amplitude at the higher frequency might be due to relatively short distance of the epicenter to the building and the earthquake magnitude such that higher frequency mode of the building was excited. Under the earthquake motions, smaller peak spectrum magnitude corresponding to lower modal frequency of about 0.4Hz was also observed; see Fig. 3(a). In Fig. 3(a), the peak response magnitude existed between 0.5 and 1.0 Hz; however, it seemed that it was not a modal frequency as the coherence value at this frequency was very low. It might be due to noise embedded in the response.

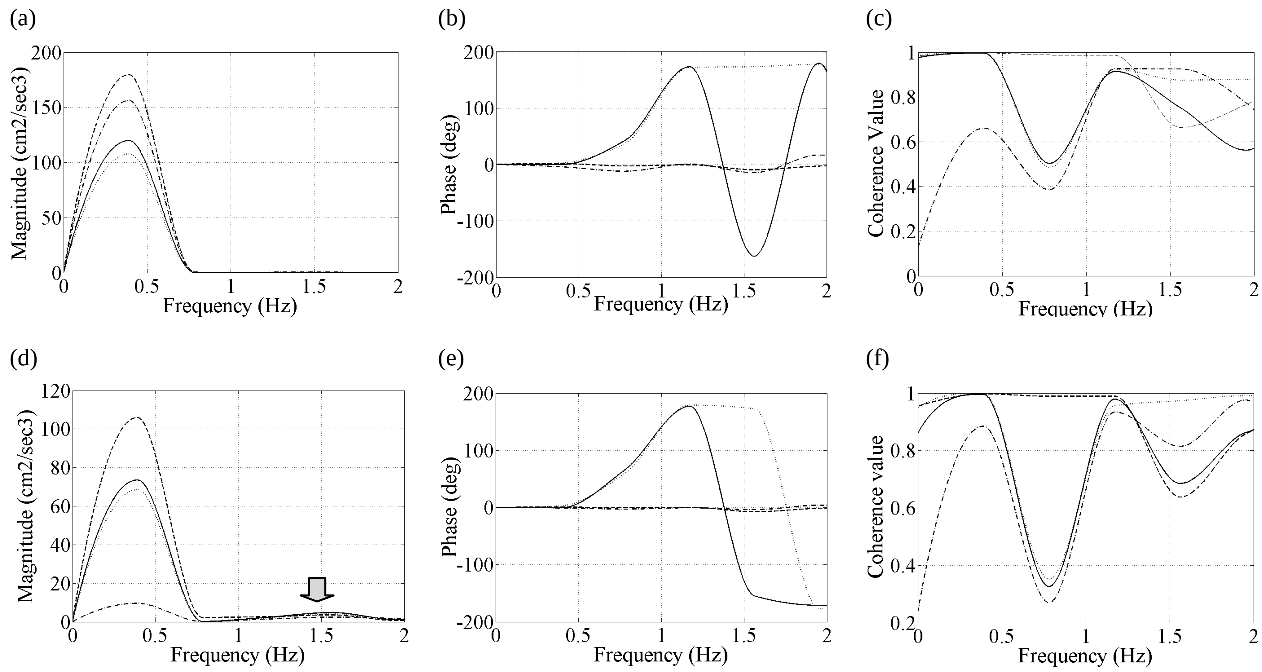

Figure 2. Cross Spectrum, Phase Spectrum, and Coherence of the 14-Story Building (a), (b), (c) under the October 23, 2002, and (d), (e), (f) under the November 3, 2002, Earthquake Loadings (These were Computed using Response of Accelerometers: #4 & #1 —— , #4 & #2 ········ , #4 & #9 - · - , #1 & #2 - - -)

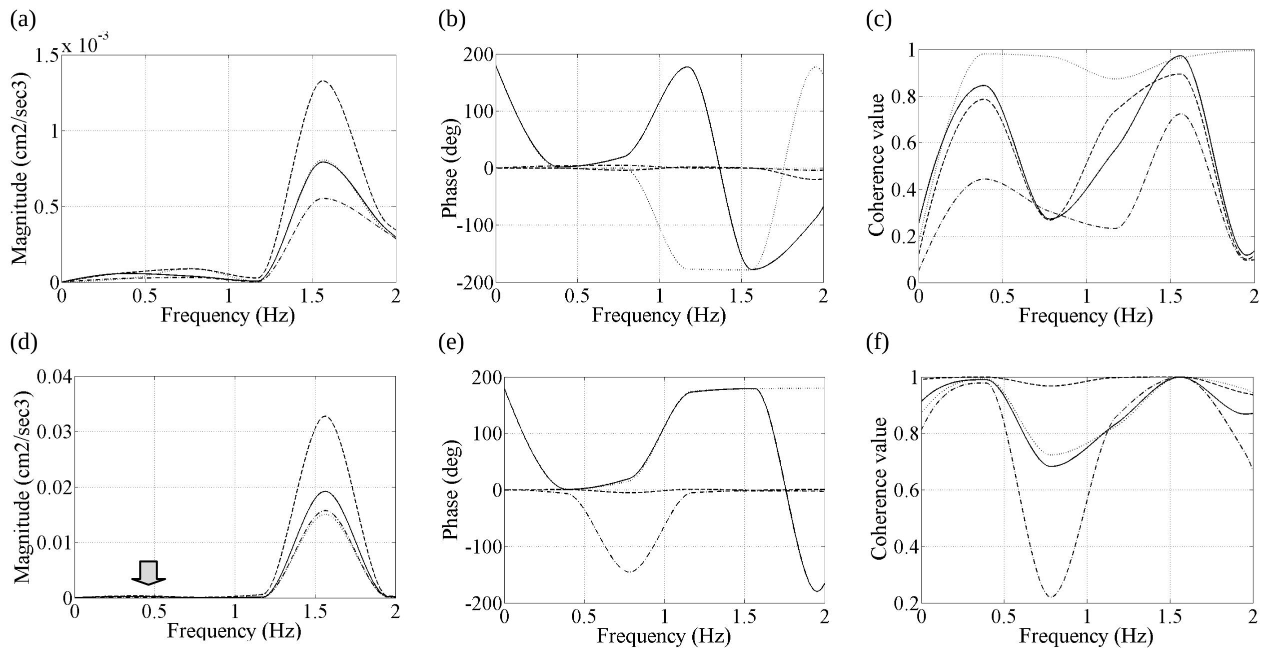

Figure 3. Cross Spectrum, Phase Spectrum, and Coherence of Response under the December 15, 2003, Earthquake Loadings of (a), (b), (c) the 14-Story Building (These were Computed using Response of Accelerometers: #4 & #1 ——, #4 & #2 ········, #4 & #9 - · -, #1 & #2 - - -), and (d), (e), (f) the 20-Story Building (These were Computed using Response of Accelerometers: #23 & #32 ——, #23 & #29 ········, #23 & #17 - · - , #29 & #32 - - -)

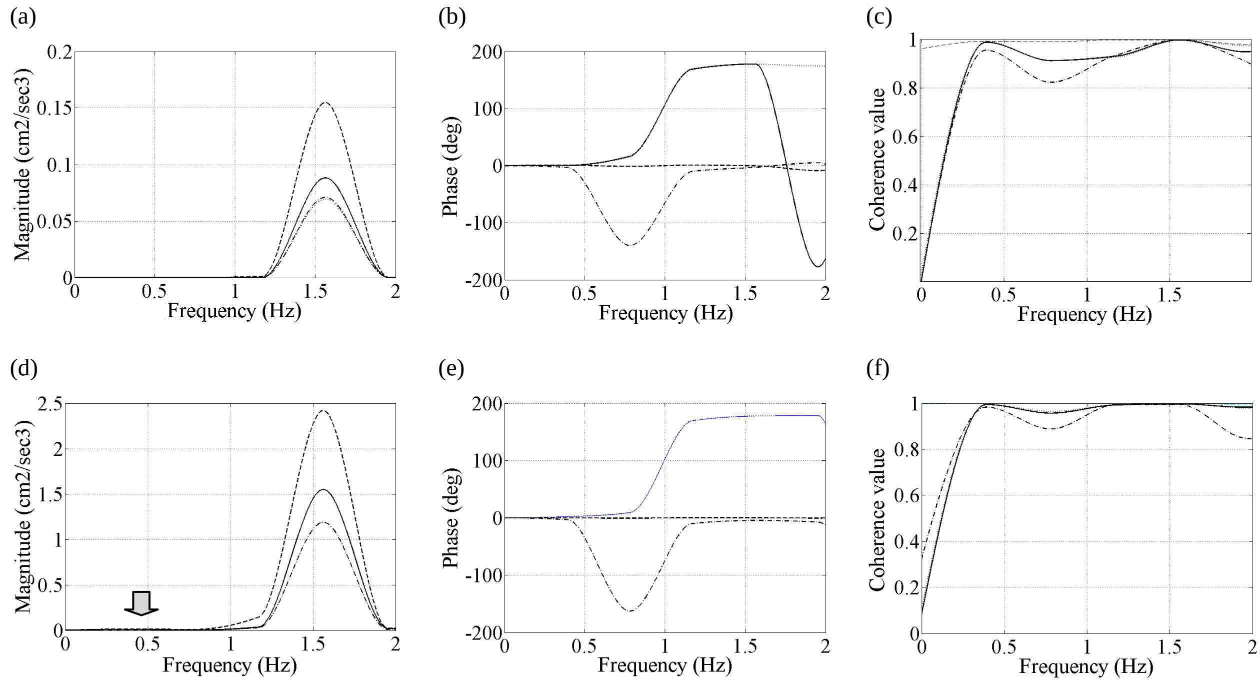

Figure 4. Cross Spectrum, Phase Spectrum, and Coherence of the 20-Story Building (a), (b), (c) under the April 23, 2004, and (d), (e), (f) under the May 30, 2004, Earthquake Loadings (These were Computed using Accelerometers: #23 & #32 ——, #23 & #29 ·········, #23 & #17 - · - , #29 & #32 - - -)

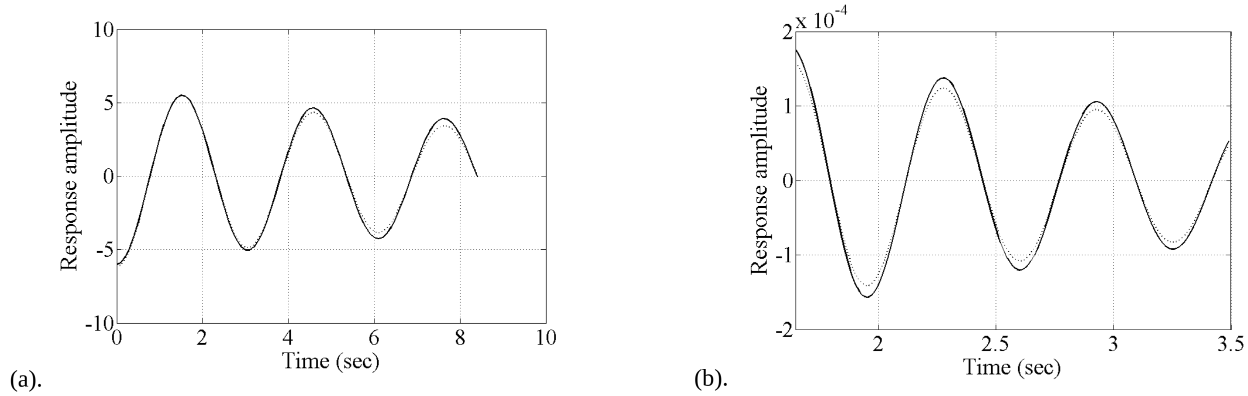

Figure 5. Fitted Response of the 14-Story Building under the November 3, 2002, Earthquake Excitations for the First Mode, and (b) the 20-Story Building under the May 30, 2004, Earthquake Excitations for the Second Mode

Cross spectra of the 20-story building response under the investigated earthquake loadings are shown in Figs. 3(f), 4(c), and 4(f). As seen in these figures, large spectrum amplitude was observed; it corresponded to the frequency of 1.56 Hz. Small peak magnitude of spectrum of the building at a frequency of about 0.45Hz was also observed when the structure was excited under the December 15, 2004, earthquake; see Fig. 3(d). Phase angle values of these building responses at the modal frequencies were examined in this study. It was observed that most of the phase spectrum values at the predominant peak spectrum magnitudes investigated in this study were either nearly 0^o (in phase) or 180^o (out of phase). From the phase values, the building's mode type, viz., bending or torsion, could be identified.

Coherence magnitudes of the 14-story and 20-story buildings' seismic responses at the dominant frequencies were examined for identifying nonlinearity, which would be present in the structure. In the preliminary investigation carried out for this study the coherence was also utilized to select a reference response. The reference response was selected when coherence of the response and any other response investigated gave high coherence magnitudes. Results of the preliminary study were not reported in this paper for brevity. In this study, the response of accelerometer #4 located at the fourth floor was selected to be the reference for identifying dynamic characteristics of the 14-story building, whereas the response of accelerometer #23 was selected as the reference for the 20-story building.

Figures 2(c), 2(f), and 3(c) show coherence values of the 14-story building seismic response in the frequency range of 0.0 Hz to 2.0 Hz, whereas Figures 3(f), 4(c), and 4(f) show the values of the 20-story building response in the frequency of interest. It was observed that most of these coherence values were good; they were close to unity at the modal frequencies. Thus it could be justified that the structures behaved linearly when they were excited by the investigated earthquake ground motions. Response which did not result in good coherence values was not utilized for dynamic characteristics identification. For instance, when the 14-story building was excited by the December 15, 2003, earthquake, the coherence values obtained from the reference and accelerometer #9 responses at the modal frequencies were low; see Fig. 3(c). This might be due to the presence of noise in the response. Therefore the acceleration response was not further employed for the identification. In this study, to ensure the system linearity, the acceleration responses having coherence values lower than 0.8 were not employed for dynamic structural identification as described in the methodology.

The cross spectrum was then decomposed using the singular value decomposition method to obtain the spectrum of damped single degree of freedom systems. These values were utilized to extract natural frequency and damping factor of the building. In this study to measure the modal frequency and damping factor of the building structure, the singular values were transformed into time domain so that damped response of single degree of freedom systems could be acquired. The functions were fitted in least square sense so that the natural frequency and damping factor could be estimated. Fitted response of the 14-story building under the November 3, 2002, seismic ground motions and the one of the 20-story building under the May 30, 2004, ground motions are shown in Figs. 5(a) and 5(b). Responses of the building under other seismic ground motions were fitted in a similar manner; for the sake of brevity, however, they are not presented in this paper.

Natural frequencies and damping factors of these two buildings under the earthquake ground excitations were extracted using the methodology discussed in this paper, and the results are presented in Tables 3 and 4. The dynamic characteristics of these buildings obtained from studies reported in [2-4,6,7] are presented in these tables for comparison. As seen in Tables 3 and 4, natural frequencies and damping factors obtained using the methodology employed in this study were in fairly good agreement with those reported in [2-4,6,7]. These buildings' dynamic characteristics varied slightly under these seismic ground motions. The 14-story building's dynamic characteristics obtained from this study changed slightly under the investigated seismic ground motions. Under the December 15, 2003, earthquake ground motions, the structure's natural frequency changed

Table 3. Modal Frequencies and Damping Factors of the 14-Story Building under Three Earthquake Excitations

Seismic event	Study reported in this paper: Modal freq. (Hz) 1st	2nd	Damping factor (%) 1st	2nd	Studies reported earlier: Modal freq. (Hz) 1st	2nd	Damping factor (%) 1st	2nd	Reference
Oct 23, 2002	0.40	1.46	3.7	4.0	0.42-0.48	1.40	3.9	N/A	[2]
					0.46	N/A	3.1	N/A	[4]
Nov 3, 2002	0.40	1.47	3.1	3.9	0.42-0.48	1.40	3.9	N/A	[2]
					0.45	N/A	4.0	N/A	[4]
Dec 15, 2003	0.42	1.51	3.6	4.1	N/A	N/A	N/A	N/A	

N/A : Data were not reported

Table 4. Modal Frequencies and Damping Factors of the 20-Story Building under Three Earthquake Excitations

Seismic event	Study reported in this paper: Modal freq. (Hz) 1st	2nd	Damping factor (%) 1st	2nd	Studies reported earlier: Modal freq. (Hz) 1st	2nd	Damping factor (%) 1st	2nd	Reference
Dec 15, 2003	0.45	1.56	3.20	4.2	0.45	1.56	N/A	N/A	[6]
April 23, 2004	0.46	1.56	3.26	4.1	0.47	1.56	4.2	2.7	[3]*
May 30, 2004	0.45	1.56	3.24	3.9	0.46	1.52	N/A	N/A	[7]*

*) The study performed using the response of earthquake different from that in this paper. N/A: Data were not reported.

Table 5. Phase Spectrum at the Identified Modes of the 14-Story Building

Seismic event	Mode #	Phase of spectrum of accel. #			
		4&1	4&2	4&9	1&2
Oct 23, 2002	1	in [a)]	in	in	in
	2	out [b)]	out	in	in
Nov 3, 2002	1	in	in	in	in
	2	out	out	in	in
Dec 15, 2003	1	in	in	in	in
	2	out	out	in	in

[a)] in: in phase; the phase was equal or close to 0^{o},

[b)] out: out of phase; the phase was equal or close to 180^{o}

Table 6. Phase Spectrum at the Identified Modes of the 20-Story Building

Seismic event	Mode #	Phase of spectrum of accel. #			
		23&32	23&29	23&17	29&32
Dec 15, 2003	1	in [a)]	in	in	in
	2	out [b)]	out	in	in
April 23, 2002	1	in	in	in	in
	2	out	out	in	in
May 30, 2003	1	in	in	in	in
	2	out	out	in	in

[a)] in: in phase; the phase was equal or close to 0^{o},

[b)] out: out of phase; the phase was equal or close to 180^{o}

slightly; this might be due to effects of the earthquake magnitude and its epicentral distance, which was relatively close to the building.

The damping factors were also changed; the changes in the dynamic characteristics of the 20-story building were observed to be marginal. Tables 5 and 6 present phase of the spectrum obtained using response of accelerometers investigated in this study. From these tables it can be indicated that the first mode identified for these buildings was a bending mode, whereas the second one was a higher-order bending mode. A similar procedure could be carried out for the dynamic characteristics identification of these buildings using response recorded at different acceleration locations. Results of this study demonstrated that the methodology discussed in this paper was capable of extracting dynamic characteristics of these buildings using their recorded seismic responses.

4. Conclusions

In this paper a methodology applicable for identifying dynamic characteristics of multi-story buildings excited by earthquake forces is discussed. Prior to carrying out dynamic identification of the structure, coherence function was obtained so that the behavior of the structure under the ground motions, viz., linear or nonlinear, could be verified. Thus, the appropriate system identification technique could be selected. For linear structural system, the structure's natural frequency could be estimated through its seismic response spectral density magnitude and phase of the responses. To extract its dynamic characteristics, viz., the mode type and modal frequency techniques proposed in [11,12] were applied so that closely spaced modes could be separated; then, unlike the techniques presented in [11,12] in this study, the curve-fitting technique of time response was implemented to extract the damping factor.

To demonstrate usefulness of the methodology proposed in this study, dynamic characteristics of 14-story and 20-story moment-resisting frame office buildings were identified. These buildings' acceleration responses recorded respectively under three different earthquake excitations were employed for the identification. First two modes of the buildings are reported in this paper. Results of this study were encouraging; the dynamic characteristics of the investigated buildings were successfully identified. Moreover, natural frequency and damping factor values were reasonably good when they were compared to the results of studies reported in [2-4,6,7]. It indicated that the methodology implemented in this study could be advantageously applied for dynamic characteristic identification of multi-story buildings using only their responses under seismic ground excitations.

Acknowledgments

The authors would like to thank reviewers for their valuable suggestions and comments. Professor A.S.J. Swamidas' comments on this paper are also appreciated.

References

[1] T. Saito, H. Yokota, J. Wind Eng. Indust. Aerodyn. 59 (1996) 299.
[2] M. Celebi, Earthq. Spectra. 20 (2004) 693.
[3] M. Celebi, Earthq. Spectra. 22 (2006) 847.
[4] H. Liu, Z. Yang, M. Gaulke, Eng. Struct. 27 (2005) 463.
[5] J.E. Rodgers, M. Çelebi, J. Struct. Eng. 132 (2006) 1543.
[6] Z. Yang, U. Dutta, M. Celebi, H. Liu, N. Biswas, T. Kono, H. Benz, 13th World Conf. on Earthquake Eng., Vancouver, B.C., Canada, 2004, Paper No. 1136.
[7] H. Liu, R. Goel, F. Bai, W. Scott, T. Kono, 4th Int. Conf. on Earthquake Eng., Taipei, Taiwan, 2006, Paper No. 279.

[8] B.W. Kim, N. Stubb, T. Park, J. Sound Vib. 282 (2005) 215.
[9] A. Budipriyanto, Proc., Int. Sem. on App. Tech., Sci, and Art (APTECS), Surabaya, 2010, p.12.
[10] A. Budipriyanto, Procedia Engr. 54 (2013) 299.
[11] J.S. Bendat, A.G. Piersol, Random Data: Analysis and Measurement Procedures, John Wiley and Sons Inc., New York, 1986, p.407.
[12] R. Brincker, P. Andersen, L. Zhang, Proc. 18th Int. Modal Analysis Conf., San Antonio, 2000, p.625.
[13] United States Geological Survey, National Strong-Motion Project, *http://nsmp.wr.usgs.gov/*, 2011.
[14] C.R Farrar, K. Worden, M.D. Todd, G. Park, J. Nichols, D.E. Adams, M.T. Bement, K. Farinholt, Nonlinear System Identification for Damage Detection, LA-14353 LANL, 2007, p.143.