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Modal Identification Results of RC Frames at Different Damage Levels

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ABSTRACT: This study presents the modal parameter estimation results of an experimental program conducted on two half-scale reinforced concrete (RC) frames with and without infill conditions. Modal parameters were estimated using operational modal analysis methods which have been widely used in civil engineering structures. Frames were progressively damaged in in-plane direction by applying increasing drifts with the usage of displacement controlled actuator at floor level. Three different types of dynamic tests at pre-determined damage states were conducted for modal parameter identification purposes; namely (i) in-plane wideband dynamic excitation tests by an electro-dynamic shaker, (ii) impact excitation tests by an impact hammer and (iii) ambient vibration tests. For modal parameter estimations, NExT-ERA, ERA, and EFDD methods were used. The purpose of the paper is multifold: (i) follow the evolution of the changes in modal parameter estimations under increasing damage levels, and (ii) investigate the differences in modal parameter estimation by using different excitation and identification types.

1 INSTRUCTION

Over recent years, modal analysis has been used both in design processes and structural health monitoring. Operational modal analysis provides to identify the modal characteristic parameters of structures that are excited randomly by environmental loading conditions, overcoming the inability to measure the input forces. Therefore, using output-only (operational modal analysis) methods have been widely used in assessment of civil engineering structures and especially acquired increased attention in the last two decades. These methods are used to extract modal parameters (natural frequencies, mode shapes and damping ratios) as well as structural damage identification, quantification and localization problems. In literature, there are numerous surveys exist on the recent developments of structural health monitoring techniques applied to civil engineering structures based on changes in their dynamic characteristics, Fan and Qiao (2010). Accordingly, it is of interest to determine the modal parameters which forms the preliminary part of vibration-based structural damage identification.

For that purpose, an experimental program has been conducted on two half scale reinforced concrete frames (RC) with and without infill conditions under quasi-static tests. The specimens were subjected to a dynamic test program at specific drift ratios which includes ambient vibration, impact hammer and white-noise (WN) tests using an electro-dynamic shaker. Output-only methods, namely NExT-ERA, ERA and EFDD were used for operating these various dynamic data to modal parameter estimation. Objectives of this study are following the changes in modal parameters under increasing damage levels and comparing the impact hammer test results with different methods. Results were given in following sections.

2 TEST SETUP AND PROGRAM

Quasi-static tests were carried out on two RC specimens namely, one-story, one-bay, half scale with and without infill wall conditions with partial slab. Column and beam members have same dimensions, 150 x 250 mm^2. The compressive strength of concrete was around 50 MPa and the yield strength of the reinforcement was 420 MPa. Approximately 10% of the axial load capacity of columns (185 kN) which represents the axial load due to upper stories, was applied to each column by two hydraulic pistons to conduct the experimental study in realistic conditions. Displacement-controlled actuator was attached to specimen at slab level and used to provide the lateral in-plane deformation. In Figure 1, general view of specimen 2 (S2) is shown. Only infill wall existence, differs S2 to S1 specimen.

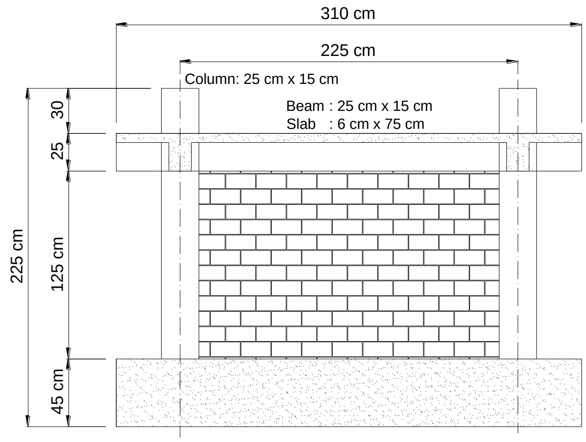


Figure 1. General view of specimen 2 (S2)

Specimens were subjected to cyclic, incremental displacement pattern which is shown in Figure 2b. Each drift level includes three full cycles in order to induce strength degregation. Dynamic tests were performed at 0.20%, 0.50%, 1.00%, 1.40%, 2.20% and 3.50% drift levels. At each dynamic test points, specimens were subjected to a sequence of 71 dynamic tests including ambient vibration tests, free vibration tests with impact hammer and WN tests. Measurement duration was selected as about 8 minutes for ambient and WN tests to ensure the reliability of the test data. WN tests were performed by an electro-dynamic shaker which was placed on slab level. A control scheme called "Offline Tuning Technique" was used to improve the signal reproduction fidelity of the shaker so that truly broad-band excitation was achieved. This type of excitation is required to excite the modes of specimens properly and obtain accurate modal parameters. In this technique, the desired input signal is multiplied by the inverse of the estimated transfer function of the shaker in frequency domain, and then transferred back to time domain to obtain a modified input signal. Hereby, by the usage of this signal as command, broad-band excitation can be obtained, Yucel (2014).

During the tests, 4 tri-axial and 6 uni-axial piezoelectric accelerometers were mounted on specimens in in-plane (x), out-of-plane (y) and vertical (z) directions (Figure 2a). Note that one uniaxial accelerometer was deployed on the shaker to measure the excitation. In order to capture vibration motion properly, sampling frequency values were taken as 1000 Hz except the hammer test for S2 (it was 8000 Hz) which were significantly higher than the modal frequencies of interest in this study. Also 12 displacement transducers and 2 string potentiometers were placed on the columns, beam and wall elements to measure the static response. Besides, 2 string potentiometers and a displacement transducer were used to measure the top and base displacements of the specimens, respectively.

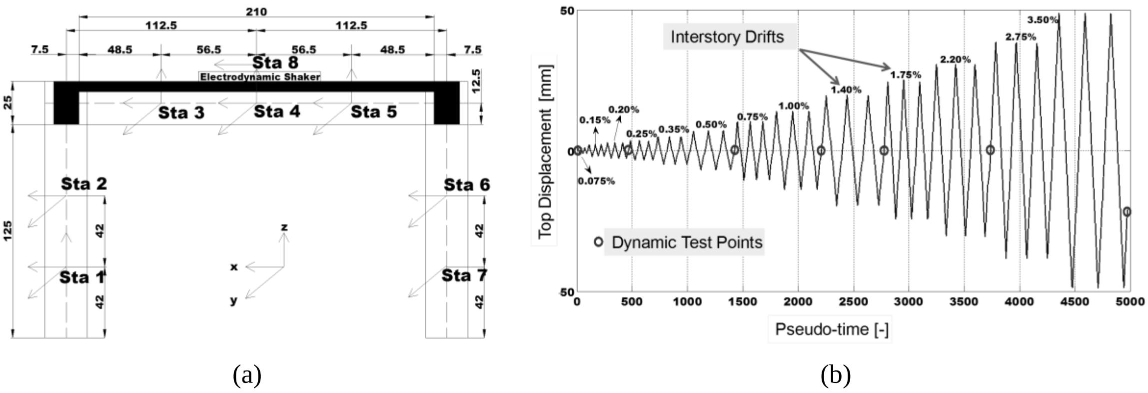


Figure 2. (a) Accelerometer layout, (b) sequence of static and dynamic tests.

3 SYSTEM IDENTIFICATION METHODS USED FOR THE MODAL PARAMETER ESTIMATION

Many different system identification methods and techniques have been developed, analyzed and tested for modal parameter identification. In this study, three different output-only system identification methods were used to estimate the modal parameters of specimens at different damage levels namely (i) Eigensystem Realization Algorithm (ERA), (ii) Natural Excitation Technique with Eigensystem Realization Algorithm (NExT-ERA), and (iii) Enhanged Frequency Domain Decomposition (EFDD). These methodologies are based on the assumptions that the structure behaves within a linear range, the structure is time invariant, and the forces applied to the structure are uncorrelated with the response of the system. In the scope of this study, these methods were programmed in Matlab® programming environment.

3.1 Eigensystem Realization Algorithm (ERA) and Natural Excitation Technique with Eigensystem Realization Algorithm (NExT-ERA)

The eigensystem realization algorithm (ERA) uses the principles of minimum system realization to obtain a state-space representation of the structure, Juang and Pappa (1985). ERA is originally deployed for impulse excitation, enabling the use of impact hammer test data for modal parameter identification. The system realization begins by forming the generalized Hankel matrix, as shown in Equation 1:

$$H(k-1) = \begin{bmatrix} Y(k) & Y(k+1) & \cdots & Y(k+z) \\ Y(k+1) & Y(k+2) & & \vdots \\ \vdots & & \ddots & \vdots \\ Y(k+r) & \ldots & \ldots & Y(k+z+r) \end{bmatrix} \tag{1}$$

where Y(k) is the pulse response matrix at the k^{th} discrete time which becomes a vector for single input multi output case. For good results, z should be selected to be approximately ten times the number of modes to be identified, and r should be selected to be 2-3 times z (Juang and Pappa, 1985). Singular value decomposition (SVD) to the Hankel matrix, separates the noise and physical spaces and enables the model order determination by sorting the singular values in descending order. Once the model order is determined, based on the realization algorithm, discrete time linear state-space matrices are constructed. From the reduced order state-space realization modal parameters is extracted.

ERA method can be performed in conjunction with the NExT. The underlying principle of NExT method is that cross-correlation functions calculated between two output measurements from a structure excited by broadband excitation has the same analytical form as the free vibration (or impulse response) of the structure, enabling the use of white noise and ambient vibration measurements for modal parameter identification, James et al (1993). Therefore, modal parameters can be estimated using cross-correlation functions. In this study, auto- and/or cross-power spectral density functions were estimated by modified periodogram method, Welch (1967), then correlation functions in time-domain were obtained by discrete inverse Fourier transform.

3.2 Enhanged Frequency Domain Decomposition Technique (EFDD)

As an output-only method EFDD, is an extension of classical peak-picking technique and is based on the classical frequency domain approach. The classical peak-picking technique has shortcomings such as identifying closely spaced modes and furthermore frequency estimates are limited by the frequency resolution of power spectral density estimates and damping estimations are highly uncertain. EFDD method is based on the evaluation of the spectral matrix G(f) in the frequency domain, Brincker et al (2001). The spectral matrix can be defined as shown in Equation 2:

$$G(f) = E\,[Y(f)\,Y^H(f)] \tag{2}$$

where the vector Y(f) collects the responses in the frequency domain, the superscript H denotes complex conjugate matrix transpose and E denotes expected value. The EFDD technique involves the singular value decomposition (SVD) of the spectral matrix at each frequency and the inspection of the curves representing the singular values to identify the resonant frequencies and estimate the corresponding mode shape using the information contained in the singular vectors of the SVD. Technique is based on the fact that the first singular value in the neighbourhood of a resonant peak is the auto spectral density (ASD) of a modal coordinate. Hence, taking back the partially identified ASD of the modal coordinate in time domain by inverse FFT yields a free decay time domain function, which represents the autocorrelation function of the modal coordinate. The natural frequency and the related damping ratio are thus simply found by estimating crossing times and logarithmic decrement.

4 MODAL PARAMETER ESTIMATION RESULTS

Modal parameter identification results obtained from different excitations and methods were given comparatively in Tables 1 and 2. It should be mentioned that authors experienced some difficulties to obtain a proper free vibration motion from impulse response in impact hammer tests. In order to minimize this problem, a convenient part of this impulse response was considered by defining specific initial-end points. Therefore, identification process was repeated by selecting 10 different initial-end points at each damage state and obtained results for natural frequencies were given in Figure 3. In order to make comparisons, mean and standard deviation values of these different parts were calculated and represented in Table 3. Here, damping ratio values for seperate identification processes were estimated in a wide scatter which caused to obtain relatively high standart deviation. Impact hammer test result is presented separately due to inconsistencies in mode shape and damping ratio identifications, if one compare to other methods.

Table 1. Modal parameter estimation results for S1 under different excitation and method conditions

Excitation Type & Identification Method	Modal Parameters	No Damage	0.20%	0.50%	1.00%	1.40%	2.20%	3.50%
Ambient Vibration (NExT-ERA)	f [Hz]	-	14.1	13.33	12.32	11.8	10.54	9.02
	ξ [%]	-	0.78	0.62	0.63	0.62	0.6	0.54
	MAC	-	1.00	0.99	0.98	0.98	0.96	0.93
White Noise (NExT-ERA)	f [Hz]	14.28	13.74	12.96	11.99	11.53	10.27	8.68
	ξ [%]	1.22	1.03	1.78	1.82	1.02	0.98	1.28
	MAC	1.00	0.99	0.98	0.96	0.96	0.94	0.91
White Noise (EFDD)	f [Hz]	14.29	13.77	12.96	12.13	11.55	10.34	8.73
	ξ [%]	1.04	1.12	1.77	1.88	1.94	1.29	1.49
	MAC	1.00	0.99	0.98	0.97	0.96	0.94	0.91
Impact Hammer (ERA)	f [Hz]	-	13.62	12.86	11.52	11.08	9.97	8.41
	ξ [%]	-	1.61	2.12	2.63	2.58	2.20	2.21
	MAC*	-	0.62*	0.62*	0.65*	0.61*	0.66*	0.67*

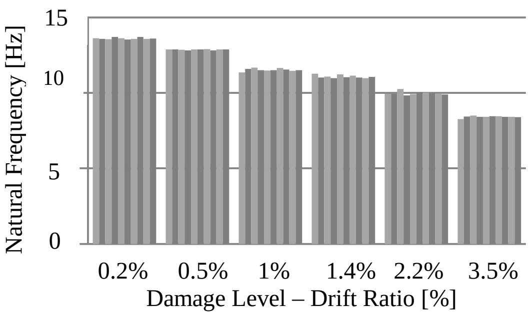
Table 2. Modal parameter estimation results for S2 under different excitation and method conditions

Excitation Type & Identification Method	Modal Parameters	No Damage	0.20%	0.50%	1.00%	1.40%	2.20%	3.50%
Ambient Vibration (NExT-ERA)	f [Hz]	18.2	17.74	17.73	17.42	-	16.55	11.99
	ξ [%]	0.80	2.32	0.84	1.17	-	1.45	2.02
	MAC	1.00	0.82	0.95	0.97	-	0.87	0.85
White Noise (NExT-ERA)	f [Hz]	18.04	17.54	17.67	17.33	17.26	16.19	11.58
	ξ [%]	1.10	0.71	1.48	1.30	2.34	1.72	1.80
	MAC	1.00	0.99	0.95	0.98	0.96	0.83	0.77
White Noise (EFDD)	f [Hz]	18.01	17.58	17.58	17.39	17.06	16.11	11.64
	ξ [%]	1.08	0.67	1.06	1.33	1.54	1.11	1.11
	MAC	1.00	0.99	0.95	0.98	0.97	0.97	0.77
Impact Hammer (ERA)	f [Hz]	23.52	21.34	21.67	23.87	22.79	23.29	22.69
	ξ [%]	1.60	1.63	3.37	2.65	4.11	1.96	3.11
	MAC*	0.66	0.39	0.39	0.39	0.70	0.25	0.27

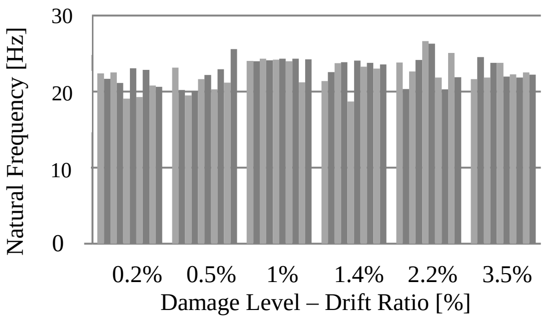
It can be concluded from the tables that, natural frequencies had decreasing trend for all methods with increasing damage level which is also consistent with the stiffness degredation due to damage. It is clear that NExT-ERA and EFDD methods gave very similar results except damping ratio estimations and ambient tests gave higher frequency values than other ones. ERA was capable to capture the decreasing trend in natural frequencies successfully as the damage increases but there exist a wide deviation in modal damping ratios for S1 specimen. Standard deviation level in ERA identification results showed that variation in modal parameters for S2 is larger than S1. MAC* values indicate that mode shapes identified at ERA process are not matching obtained from NExT-ERA (or EFDD) method for both specimens. Undamaged state natural frequencies for S1 and S2 were estimated to be 14.28 and 18.04, respectively. Inclusion of the infill wall stiffens the frame, resulted a rise in the natural frequency about %26 at undamaged case. For S2 specimen, lateral stiffness contribution to the frame due to infill wall, was lost considerably at 2.2% and suddenly dropped after 3.5% drift ratio. At 3.5% drift level, estimated natural frequencies for S1 and S2 are 8.68 Hz and 11.58 Hz, respectively. Therefore percent reduction in modal frequencies calculated as %39 and 36%, respectively. The total change in natural frequency for S2 was slightly lower than S1. Also S1 specimen lost its lateral stiffness faster than S2 specimen, that is somewhat an expected condition since, although gets damaged, the infill wall contributes substantially to the lateral stiffness of the frame.

The undamaged case data of impact and ambient vibrations is unavailable for S1. Although ambient vibration data at 1.4% drift ratio is available for S2, modal parameters couldn't be estimated with the identification methods used. Therefore the results for these tests were indicated as "-" in tables. Modal Assurance Criterion (MAC) values were also provided in order to compare the mode shapes identified at each damage state with the corresponding mode shapes identified at undamaged state. In order to check the mode shape consistency obtained at ERA method, MAC was compared with white-noise (NExT-ERA) case corresponding at the same damage states (shown as MAC*).

Figure 4 gives information about the relationship between damage levels and estimated damping ratios with different methods. Here, damping estimations by ERA method is consistently larger than the estimations with other methods. Also note that under ambient vibration case identified damping ratio is in the lowest range for both specimens if one compares with other methods.



(a)



(b)

Figure 3. Identified natural frequencies at different damage levels using ERA based on impact hammer data for 10 different initial-end points (a) S1 (b) S2

Table 3. Mean / Standard deviation values of natural frequencies and damping ratios at different damage levels using ERA based on impact hammer data for 10 different initial-end points

Damage State	S1 (Mean / Std. Dev.)		S2 (Mean / Std. Dev.)	
	f [Hz]	ξ [%]	f [Hz]	ξ [%]
Undamaged	-	-	23.52 / 1.74	1.6 / 0.85
0.2%	13.62 / 0.06	1.61 / 0.31	21.34 / 1.35	1.63 / 1.69
0.5%	12.86 / 0.03	2.12 / 0.13	21.67 / 1.76	3.37 / 1.12
1.0%	11.52 / 0.10	2.63 / 0.84	23.87 / 0.90	2.65 / 2.38
1.4%	11.08 / 0.11	2.58 / 0.51	22.79 / 1.56	4.11 / 2.44
2.2%	9.97 / 0.11	2.20 / 0.94	23.29 / 2.16	1.96 / 2.56
3.5%	8.41 / 0.06	2.21 / 0.81	22.69 / 0. 96	3.11 / 3.53

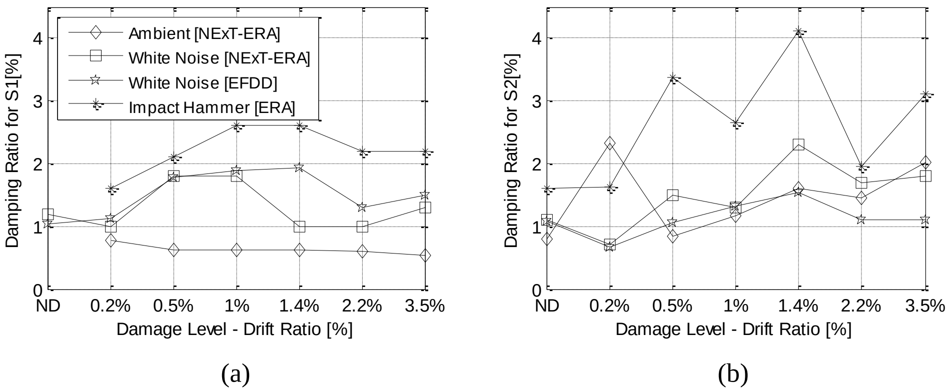


Figure 4. Damping ratio-damage level relationship with different methods (a) S1 (b) S2

It should also be noted that fundamental mode for both S1 and S2 are in-plane lateral mode due to the fact that main motion is along x-direction, but they have also components along y- and z-directions. In other words, there is no purely in-plane lateral mode but all the estimated modes are coupled modes.

5 CONCLUSIONS

In this study, an experimental program was conducted on two half-scale reinforced concrete frame system with and without infill conditions. The frames were progressively damaged in in-plane direction by applying increasing drifts by a displacement controlled actuator at the floor level. At each pre-determined damage level, dynamic tests were performed. The dynamic test results obtained from different output-only system identification methods, namely NExT-ERA, ERA and EFDD. Main outcomes of the presented study are as follows: (i) NExT-ERA and EFDD methods gave very close results with regard to natural frequency, even though the specimens were subjected to different excitation sources namely, white noise and ambient vibration. (ii) From MAC* results, it was inferred that the mode shapes identified with ERA method is not matching with others and couldn't identify the same natural modal parameters successfully for both specimens. Difference in modal identification results may arise from the amplitude of the motion. The measured vibrations, which yields low viscous damping ratio, were linear perturbations of the damaged state in ambient and white noise vibration cases. At much higher excitation level, which is not possible to induce with the available shaker in hand, the increasing trend in damping ratio may then exist as the specimens get damage. The hysteretic damping, which is a function of the area under the hysteretic force-displacement curves, Chopra (2007) is also evaluated in a referenced paper, Ozcelik et al (2015), but a direct relation couldn't be found between the equivalent viscous damping evaluated in this study. Effort on nonlinear system identification should be performed on future studies to associate damage with damping values. (iii) Identified modal parameters obtained from ERA has shown wide variation especially for infilled (S2) specimen. (iii) Decreasing trend in natural frequency for S2 is slower than S1 as the specimens get damaged. (iv)Lateral stiffness imparted by infill wall constituted 26% increase in natural frequency at undamaged state. (v) Decrease in natural frequencies at 3.5% drift ratio with respect to undamaged state is 39% and 36% for S1 and S2, respectively.

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REFERENCES

Brincker, R, Zhang, L, Andersen, P, 2001, Modal identification of output only systems using frequency domain decomposition. *Smart Materials and Structures*, S0964-1726(01), p 441-445.

Chopra AK, 2007, Dynamics of structures, New Jersey: *Prentice Hall*

Fan, W, Qiao, P, 2010, Vibration-based damage identification methods: A review and comperative study. *Structural Health Monitoring*

James, GH. III, Carne, TG, Lauffer, JP, 1995, The natural excitation technique for modal parameter extraction from operating wind turbines. *Sandia Report,* SAND 92-1666, UC-261.

Juang, JN, Pappa, RS, 1985, Eigensystem realization algorithm for modal parameter identification and model reduction. *Journal of Guidance, Control and Dynamics*, 8(5), p 620-627.

Ozcelik, O, Misir, IS, Amaddeo, C, Yucel, U, Durmazgezer E, 2015, Model identification results of quasi-statically tested RC frames at different damage levels. *Conference and Exposition on Structural Dynamics XXXIII.*

Yucel, U, 2014, Developing offline-tuning technique to be used for damage level assessment of a model frame type structure and application of system identification methods. *Master of Science Thesis, Dokuz Eylul University.*

Welch PD, 1967, The use of Fast Fourier Transform for the estimation of power Spectra: a method based on time averaging over short modified periodograms. *IEEE Trans*, AU-15:70–3.