

Chapter 13

Modal Identification of a 5-Story RC Building Tested on the NEES-UCSD Shake Table

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Abstract A full scale five-story reinforced concrete building was built and tested on the NEES-UCSD shake table. The purpose of this experimental program was to study the response of the structure and nonstructural systems and components (NCSS) and their dynamic interaction during seismic excitation of different intensities. The building specimen was tested under base-isolated and fixed-based conditions. In the fixed-based configuration the building was subjected to a sequence of earthquake motion tests designed to progressively damage the structure. Before and after each seismic test, ambient vibration data were recorded and additionally, low amplitude white noise base excitation tests were conducted at key stages during the test protocol. A quasi-linear response of the building can be assumed due to the low intensity of the excitation and consequently modal parameters might change due to the structural and nonstructural damage. Using the vibration data recorded by 72 accelerometers, three system identification methods, including two output-only (SSI-DATA and NExT-ERA) and one input-output (DSI), are used to estimate the modal properties of the fixed-base structure at different levels of structural and nonstructural damage. Results allow comparison of the identified modal parameters obtained by different methods as well as the performance of these methods and studying the effect of the structural and nonstructural damage on the dynamic parameters. The results show that the modal properties obtained by different methods are in good agreement and that the effect of structural/nonstructural damage is clearly evidenced via the changes induced on the estimated modal parameters of the building.

Keywords System identification • Full-scale specimen • Shake table test • Structural damage • Non-structural components

13.1 Introduction

Vibration-based damage detection has attracted attention in the field of earthquake engineering over the past 30 years because it potentially allows to identify and locate the damage by means of studying the variation of the dynamic characteristics of a structure from an initial state to a state after the structure has been excited by natural or human-made loads, or simply because the structure has suffered aging or cumulative deterioration in some components. Experimental and operational modal analyses are the main techniques to estimate the modal parameters (natural frequencies, damping ratios and mode shapes) from recorded structural vibration data. The identification results can be further used to apply vibration-based damage detection techniques, comparing the modal properties at different damage states of a structure. A comprehensive and detailed literature review on vibration-based damage detection can be found in [1, 2].

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In the case of buildings structures, because of the high risk and difficulty to perform progressive damage tests as well as the scarcity of heavily damaged and densely instrumented buildings, shaking table tests have produced important, high quality and unique data to assess the dynamic properties of buildings at different states of damage [3–6].

In this study the measured vibration response of a full-scale five-story reinforced concrete (RC) frame building outfitted with a wide range of nonstructural components and systems (NCSs), built and tested on the Network for Earthquake Engineering Simulation at the University of California San Diego (NEES-UCSD) shake table, is analyzed. The modal properties of the test specimen are identified using output-only and input-output methods with ambient vibration and low amplitude white noise base excitation data at different damage states, which were induced by seismic base excitations of increasing amplitude.

13.2 Description of the Specimen

The test building is a full-scale 5-story cast-in place reinforced concrete frame building (special moment resisting frame). It has two bays in the longitudinal direction (direction of shaking) and one bay in the transversal direction, with plan dimensions of 6.6 by 11.0 [m]. The building has a floor-to-floor height of 4.27 m, a total height, measured from the top of the foundation to the top of the roof slab, of 21.34 [m] and an estimated total weight of 4420 [kN], including the structure and all nonstructural components but excluding the foundation (which has a weight of 1870 [kN] approximately). A pair of identical moment resisting frames in the North and South bays provides the seismic resisting system. Different structural detailing is adopted for the beams located at the different floors, however, their strengths are consistent at each floor. The specimen has six 66×46 [cm] columns reinforced with 6#6 and 4#9 longitudinal bars and a prefabricated transverse reinforcement grid (baugrid). The floor system consists of a 20.3 [cm] thick conventionally reinforced concrete slab at all levels. There are two main openings on each slab to accommodate a steel stair assembly and a functioning elevator, each of which run the full height of the building. Two transverse concrete walls 15.2 [cm] thick provide the support for the elevator guiderails. Detailed information about the structural system, nonstructural components and their design considerations can be found in [7]. Figure 13.1 shows the test specimen and schematic plan and elevation views.

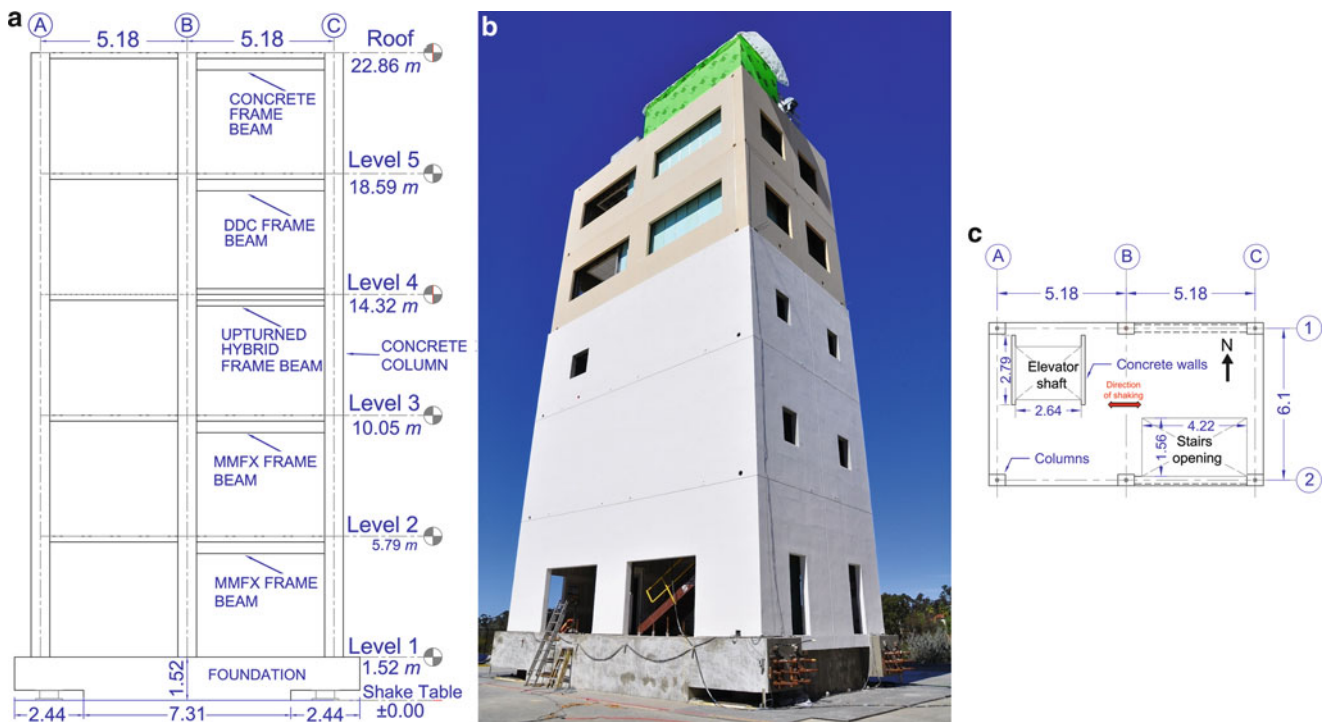


Fig. 13.1 Test specimen (a) schematic South elevation view, (b) completed structure, (c) schematic plan view

13.3 Instrumentation Plan and Dynamic Tests

13.3.1 Instrumentation Plan

A dense accelerometer array is deployed in the building, consisting of four triaxial accelerometers per floor (one at each corner). In addition, two triaxial accelerometers are installed on the platen of the shake table and one at the bottom of the foundation block of the shake table. In this study, the acceleration response of the building measured by the 72 accelerometers is used to identify the dynamic properties of the test specimen. The data are sampled at 200 Hz and the acceleration time series are detrended and filtered using a band-pass order 4 IIR Butterworth filter with cut-off frequencies at 0.15 and 25 Hz, frequency range which covers all the modes participating significantly in the response of the system.

13.3.2 Dynamic Tests

A sequence of dynamic tests is applied to the building during the period of seismic testing of the fixed-base structure (May 2012), including ambient vibration and forced vibration tests (low amplitude white noise and seismic base excitations) using the NEES-UCSD shake table. The seismic input motions correspond to spectrally matched motions, except the ICA motion, which were defined using different seed records. The input motions are defined based on global and local performance criteria with selection and order of application targeted towards progressively damaging the building-nonstructural system. Ten minutes of ambient vibration data are collected before and after each seismic test. In addition, white noise base excitation is imposed on the structure at key states of damage. Table 13.1 summarizes the seismic test protocol and the recorded data used in this study.

13.4 System Identification Methods

In order to estimate the modal properties of the building specimen at different damage states, two state-of-the-art output-only system identification methods, both assuming broad-band excitation, are used for the ambient data: Data-Driven Stochastic Subspace Identification (SSI-DATA) and Natural Excitation Technique combined with Eigensystem Realization Algorithm (NExT-ERA). For the low amplitude white noise base excitation data, in addition to the two abovementioned output-only methods, one input-output method is considered: Combined Deterministic-Stochastic Subspace Identification (DSI).

Table 13.1 Dynamic data used in this study

Date	Description	Name	Damage state
May 7, 2012	Ambient vibration 1	AMB1	DS0
	6 min WN (1.5%g RMS)	WN1A	DS0
	<i>Canoga Park (1994 Northridge earthq.)</i>	<i>FB:1-CNP100</i>	
May 9, 2012	Ambient vibration 2	AMB2	DS1
	<i>LA City Terrace (1994 Northridge earthq.)</i>	<i>FB:2-LAC100</i>	
	Ambient vibration 3	AMB3	DS2
May 11, 2012	<i>ICA 50% (2007 Pisco earthq.)</i>	<i>FB:3-ICA50</i>	
	Ambient vibration 4	AMB4	DS3
	<i>ICA 100% (2007 Pisco earthq.)</i>	<i>FB:4-ICA100</i>	
May 15, 2012	6 min WN (1.5%g RMS)	WN2A	DS4
	Ambient vibration 5	AMB5	DS4
	<i>TAPS Pump Station 67% (2002 Denali earthq.)</i>	<i>FB:5-DEN67</i>	
May 15, 2012	6 min WN (1.5%g RMS)	WN3A	DS5
	Ambient vibration 6	AMB6	DS5
	<i>TAPS Pump Station 100% (2002 Denali earthq.)</i>	<i>FB:6-DEN100</i>	
	Ambient vibration 7	AMB7	DS6

The three methods used in this paper work with the state-space formulation of the equation of dynamic equilibrium (state equation), which, in conjunction with the measurement equation, define the state-space model:

$$x_{k+1} = A_d \times x_k + B_d \times u_k + w_k \quad (13.1)$$

$$y_k = C_d \times x_k + D_d \times u_k + v_k \quad (13.2)$$

Where x_k : state vector at time k

y_k : output vector at time k

w_k : process noise vector at time k

B_d : discrete input matrix

D_d : discrete direct feed-through matrix

u_k : input vector at time k

v_k : measurement noise vector at time k

A_d : discrete state matrix (dynamical system matrix)

C_d : discrete output matrix

From the relationship between the discrete and continuous state matrices ($A_d = e^{A_c \times \Delta t}$, where Δt is the sampling time) it can be proven that their eigenvectors (Ψ) are identical, while the continuous and discrete eigenvalues (λ_i and μ_i respectively) satisfy the condition:

$$\lambda_i = \frac{\ln(\mu_i)}{\Delta t} \quad (13.3)$$

Then, from the eigenvalues and eigenvectors of the discrete state matrix (A_d) and the discrete output matrix (C_d), the modal frequencies, modal damping ratios and mode shapes of the system can be obtained by using respectively:

$$\omega_i = |\lambda_i| \quad \xi_i = -\frac{\text{Re}(\lambda_i)}{|\lambda_i|} \quad \Phi = C_d \times \Psi \quad (13.4)$$

SSI-DATA and NEX-T-ERA correspond to output-only system identification methods ($u_k = 0$ in Eq. 13.1) while DSI is an input-output method. The three methods assume that v_k and w_k are zero-mean white vectors. The order of the model is defined by using stabilization diagram, with criteria of $\Delta f \leq 1\%$, $\Delta \xi \leq 5\%$ and $(1-\text{MAC}) \leq 2\%$. Exhaustive explanations for SSI-DATA, DSI and NEX-T-ERA can be found in [8] and [9].

13.5 System Identification Results

13.5.1 System Identification Based on Ambient Vibrations

Figures 13.2 and 13.3 show the natural frequencies and damping ratios obtained for the ambient vibration data recorded at different damage states using SSI-DATA and NEX-T-ERA. It can be seen that the natural frequencies estimated by SSI and NEX-T-ERA are in very good agreement for all the damage states. Also, the natural frequencies decrease as the damage increases in the system. The higher modes seem to be less sensitive to low levels of damage than lower modes, which begin to decrease from the initial states of damage.

The damping ratios have a good agreement, being better at lower modes than higher modes, however their variability is larger than those of the natural frequencies. The estimated damping ratios do not show a clear trend as the damage progresses, but they are in the range 0–5%, which is in agreement with previous studies in similar structures.

It is important to note that in the undamaged state (DS0), the lowest frequency corresponds to the mode 1–T+To. Because the seismic motions excite the building along its longitudinal direction, from DS1 onwards, mode 1-L has the lowest associated natural frequency (see Fig. 13.2). This is because most of the structural and nonstructural damage is produced in the direction of seismic excitation; therefore the lateral stiffness in this direction degrades faster than the transversal direction. A similar observation can be observed for the higher modes (2–T+To, 2–L and 2–L+To).

Since the mode shapes identified with the methods used in this work are complex-valued, the realized modes are computed using the method proposed by [10]. The polar plot of the mode shapes are shown in Fig. 13.4, while the realized modes are

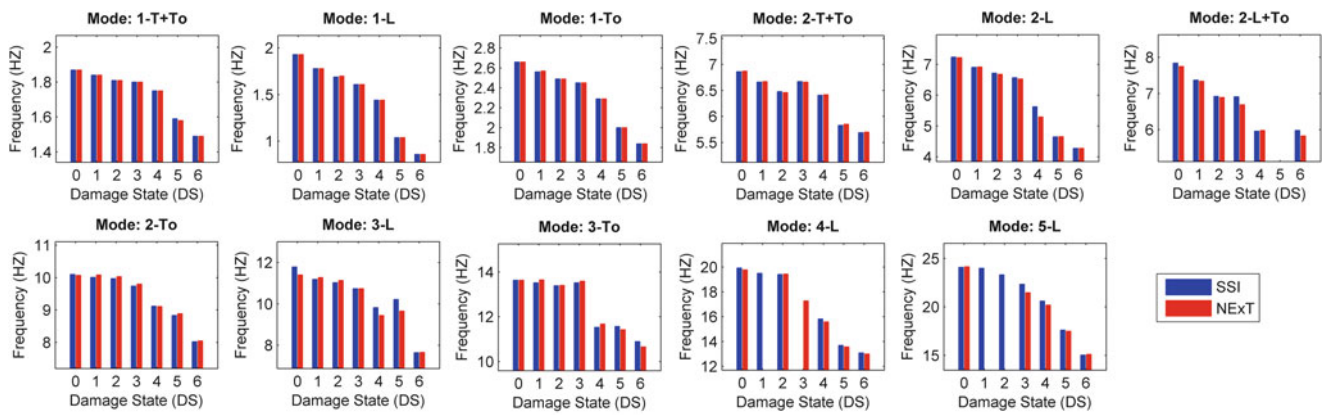


Fig. 13.2 Natural frequencies identified using ambient vibration data at different damage states

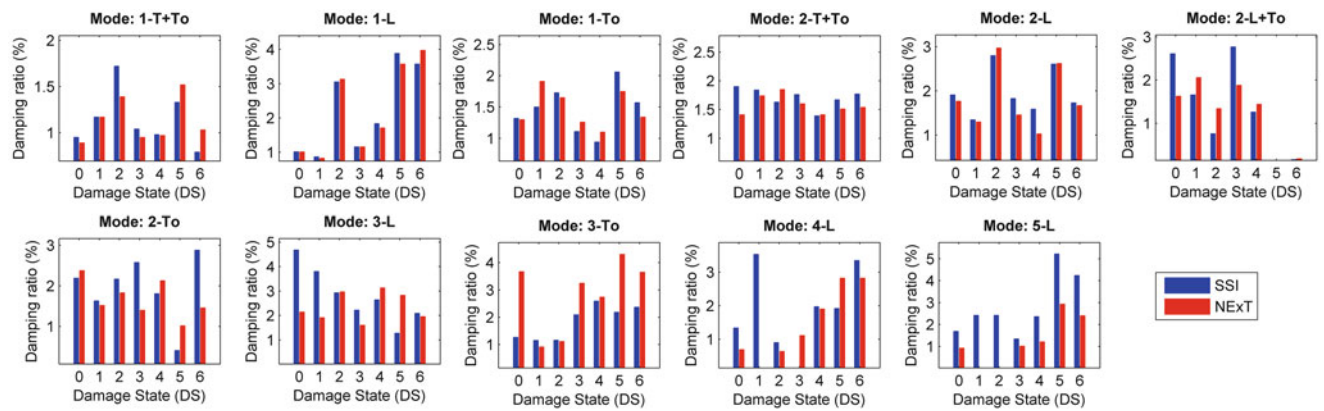
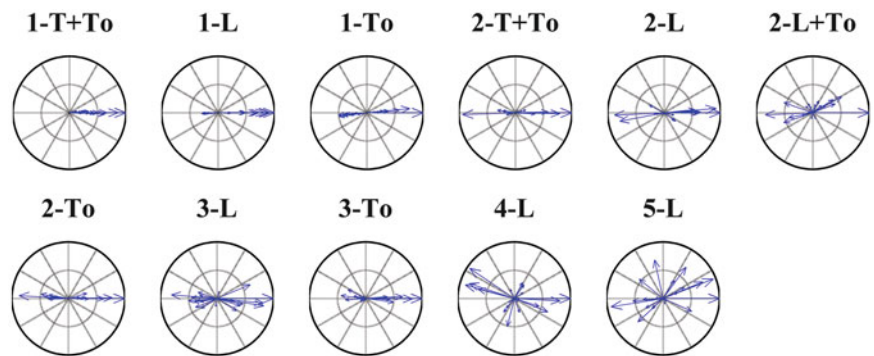


Fig. 13.3 Damping ratios identified using ambient vibration data at different damage states

Fig. 13.4 Polar plot for AMB1 (undamaged structure DS0) using SSI-DATA



presented in Fig. 13.5. It is observed that the first five longitudinal, the first three torsional and two coupled translational-torsional modes can be identified using the ambient vibration data, and most of these mode shapes are identified as almost perfectly classically-damped.

The MAC coefficient proposed by [11] is used to compare the modes shapes estimated by SSI and NExT-ERA for the test AMB1 (Fig. 13.6). Most of the values in the diagonal (corresponding modes) reach values close to one, therefore it can be concluded that the mode shapes between both methods are consistent. A similar pattern is repeated for all the states of damage. In the same way to the damping ratios, the agreement between mode shapes is better for the lower modes than for the higher modes. This is due to the fact that the participation of the higher modes is less compare to the lower modes and consequently the signal-to-noise-ratio (SNR) is lower for the higher modes.

Fig. 13.5 Mode shapes identified for AMB1 (undamaged state DS0) using SSI-DATA

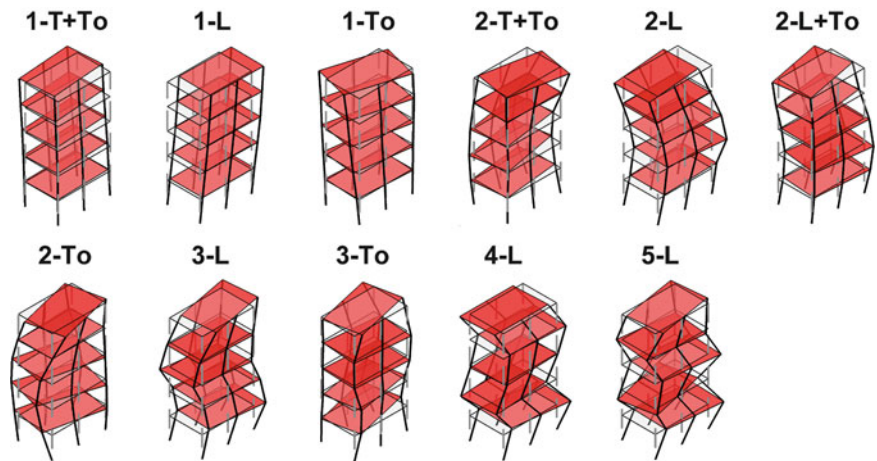
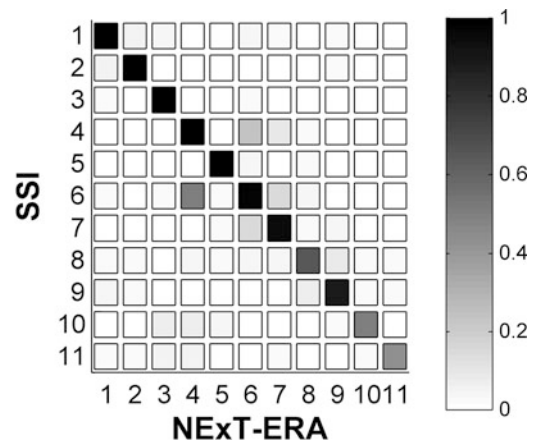


Fig. 13.6 MAC values for AMB1 (undamaged state DS0)



13.5.2 System Identification Based on White Noise RMS = 1.5 %g

At damage states DS0, DS4 and DS5, 6 min of white noise base excitation with a RMS acceleration of 1.5 %g was applied to the test specimen. Figures 13.7 and 13.8 show the natural frequencies and damping ratios obtained for the white noise data recorded at the three damage states using SSI-DATA, NExT-ERA and DSI. Similar to the case of ambient vibrations, the natural frequencies estimated by the different methods are in very good agreement and they decrease as the damage progresses in the system, however frequencies associated with the longitudinal modes have greater reductions than the other modes. This is because, as explained before, most of the structural and nonstructural damage is produced in the direction of the excitation. It is noticed that for all the white noise tests, the mode with the lowest natural frequency corresponds to the first longitudinal mode (1-L). Comparing the natural frequencies obtained by ambient vibration and white noise data at the same damage states, it is seen that they decrease in a similar percentage if they are normalized with the respective undamaged state DS0.

The damping ratios are higher than the corresponding values obtained using ambient vibrations, but the discrepancies between the methods are also larger, especially between the output-only and input-output methods. The estimated damping ratios do not show a clear trend as the damage progresses and they are in the range of 0–10%. The longitudinal modes present higher values of damping ratio.

The polar plot of the mode shapes are shown in Fig. 13.9, while the realized modes are presented in Fig. 13.10. Most of the mode shapes, especially the lower modes, are practically classically damped and by comparing the mode shapes obtained from ambient vibration and white noise data it can be seen that they are in good agreement. Because the excitation of the white noise is only in the longitudinal direction of the building, the identification process of the modes having components in the transversal direction (including torsional modes) is more difficult than the identification of the longitudinal modes.

The MAC coefficient is used to compare the modes shapes identified by the three different methods (Fig. 13.11). Most of the values in the diagonal (corresponding modes) reach values close to one, therefore it can be concluded that the mode

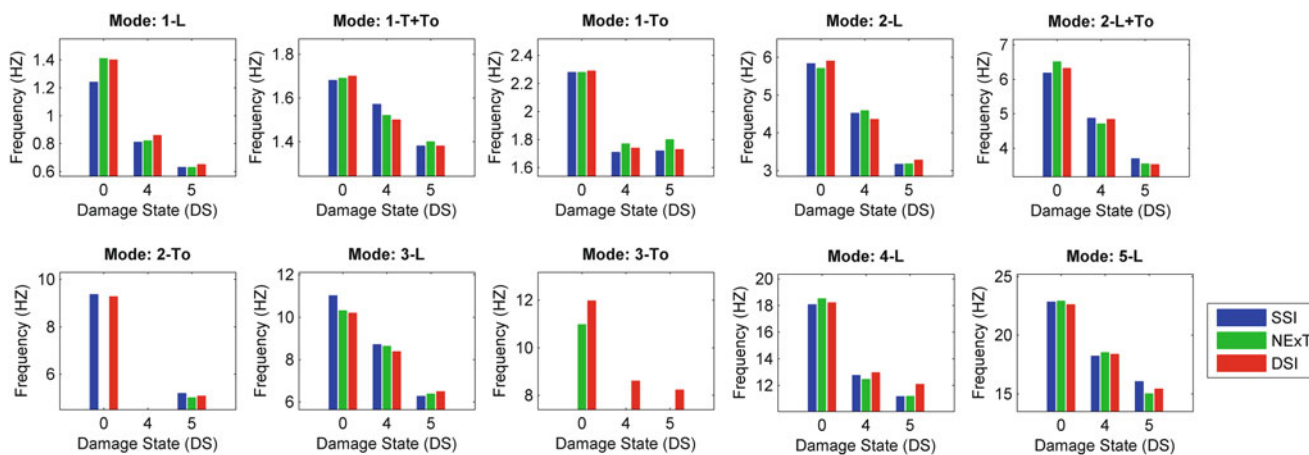


Fig. 13.7 Natural frequencies identified using ambient WN data ($RMS = 1.5\%g$) at different damage states

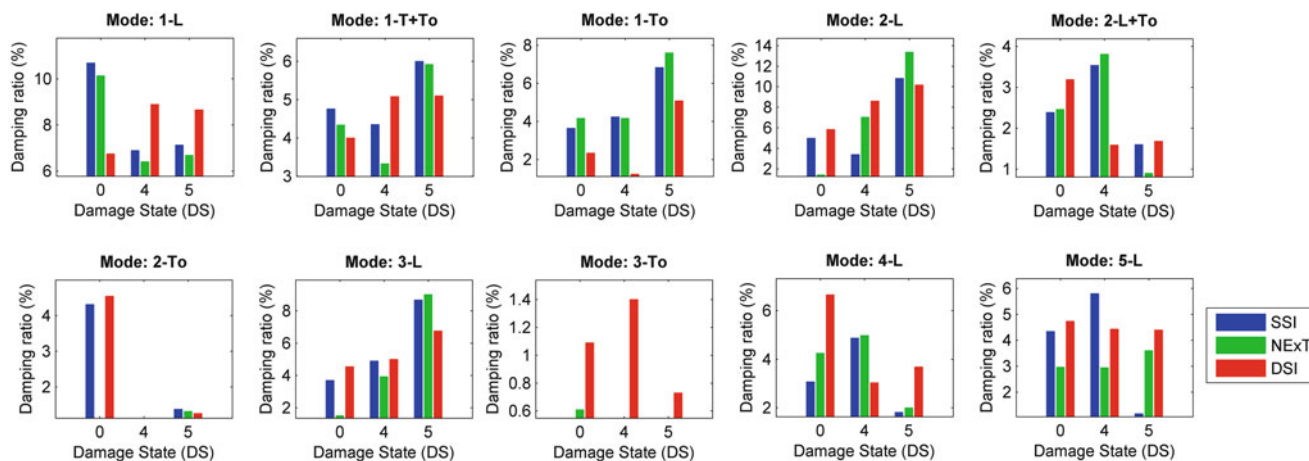
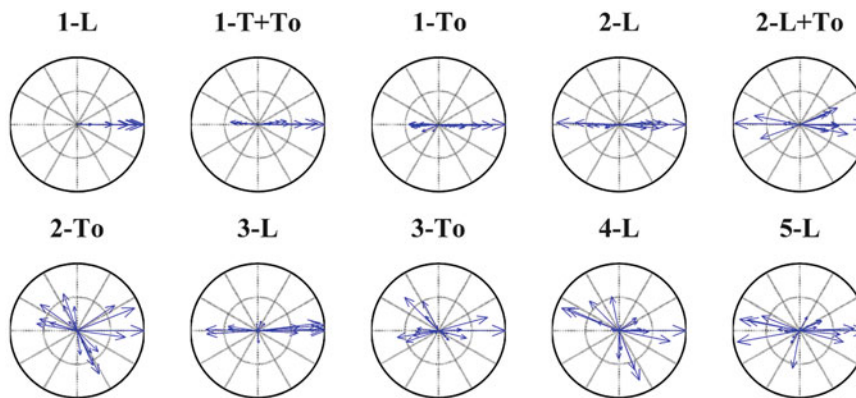


Fig. 13.8 Damping ratio identified using ambient WN data ($RMS = 1.5\%g$) at different damage states

Fig. 13.9 Polar plot of mode shapes identified using WNIA (undamaged state DS0) using DSI



shapes between the methods are consistent. A similar pattern is valid for all the states of damage. Similarly to the damping ratios, the agreement between mode shapes is better for lower modes than for higher modes. As explained previously, this is due to the fact that the participation of the higher modes is less compared to the lower modes and consequently the signal-to-noise-ratio (SNR) is lower for higher modes.

Fig. 13.10 Mode shapes identified for WN1A (undamaged state DS0) using DSI

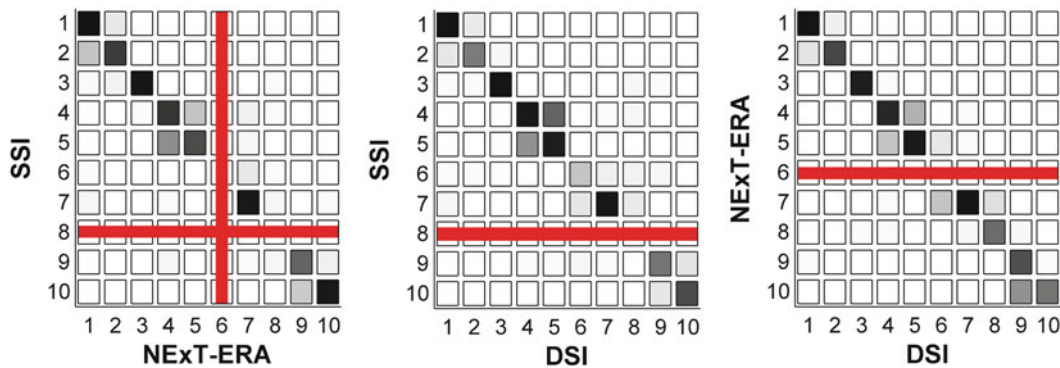
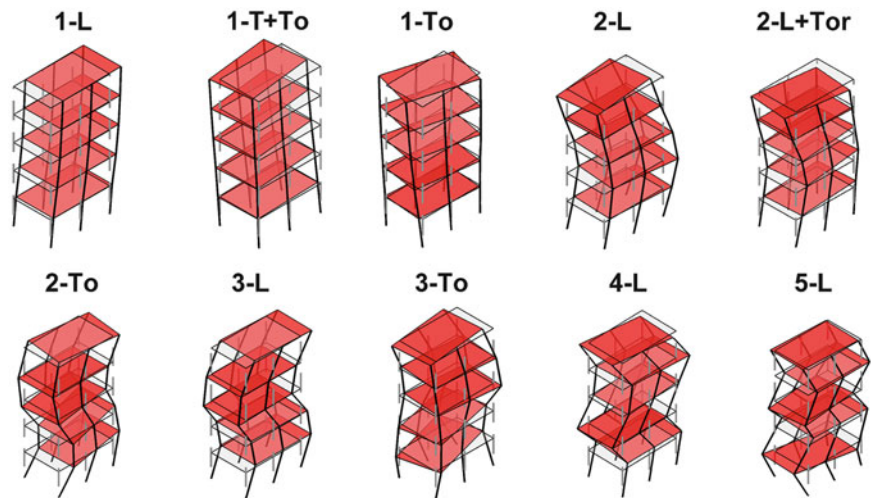


Fig. 13.11 MAC values for WN1A

13.6 Conclusions

A full-scale five-story RC frame building outfitted with a wide range of NCSs was built and tested on the NEES-UCSD shake table. While it was rigidly fixed to the shake table, the building was subjected to a sequence of earthquake motion tests designed to progressively damage the structure and NCSs. By using the ambient vibration data recorded before and after each seismic test and low amplitude white noise base excitation data conducted at key states of damage, the modal properties of the test specimen are identified using output-only (SSI-DATA) and (NEXt-ERA) and input-output (DSI) methods. Because of the low intensity of the excitations, a quasi-linear response is assumed and consequently the identified modal parameters basically change due to the structural and nonstructural damage induced by the seismic motions.

The results show that the natural frequencies decrease as more damage is induced in the nonstructural and structural components. The magnitude of reduction, which is due to the degradation of the stiffness of the system, is greater in the longitudinal modes, which correspond to the direction of the excitation. The damping ratios do not show a clear trend as a function of the damage, but longitudinal modes reach higher values compared to coupled translational-torsional and torsional modes.

Finally, the correlation between the mode shapes obtained by different methods is studied using the MAC coefficient. The results show a good agreement between different methods for each state of damage.

Acknowledgements This project was a collaboration between four academic institutions: The University of California at San Diego, San Diego State University, Howard University, and Worcester Polytechnic Institute, four major funding sources: The National Science Foundation, Englekirk Advisory Board, Charles Pankow Foundation and the California Seismic Safety Commission, and over 40 industry partners. Additional details may be found at bncs.ucsd.edu. Through the NSF-NEESR program, a portion of funding was provided by grant number CMMI-0936505 with Dr. Joy Pauschke as program manager. The above support is gratefully acknowledged. Support of graduate students Consuelo Aranda, Michelle Chen, Elias Espino, Steve Mintz, Elide Pantoli and Xiang Wang, the NEES@UCSD and NEES@UCLA staff, and consulting contributions of Robert

Bachman, Chair of the project's Engineering Regulatory Committee, are greatly appreciated. Design of the test building was led by Englekirk Structural Engineers, and the efforts of Dr. Robert Englekirk and Mahmoud Faghihi are greatly appreciated in this regard. Opinions and findings in this study are those of the authors and do not necessarily reflect the views of the sponsors.

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