Forced Vibration Testing

An Earthquake Damaged Reinforced Concrete Building

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Figure 1a: Eccentric mass shaker installed on the roof of the Four Seasons Building.


Figure 1b: Linear shaker installed on the roof of the Four Seasons Building.

Rapid advances in technology have provided engineers with powerful tools for predicting the structural behavior of complex buildings. A prerequisite to validation of analytical predictions is comparison of test data. Generally, most data available comes from examining the behavior of building elements. However, full-scale building test data that are archived typically suffer from poor quality (high instrument noise) and perhaps more importantly, insufficient spatial resolution (number of sensors). Additionally, data from instrumented structures shaken into the non-linear range (permanent damage) are rare which significantly limits the ability of earthquake engineers to improve their understanding of the behavior of real structural systems. An opportunity to address these shortcomings occurred recently because the University of California, Los Angeles, NEES Equipment Site was able to procure, instrument and test a four-story reinforced concrete frame building that was damaged during the 1994 Northridge Earthquake. This article documents this testing program, and how the data can be used to further our understanding of the behavior of this type of building.

The NSF-funded George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program was established with the goal of transforming the nation's ability to carry out earthquake engineering research. In particular, NEES seeks to shift the emphasis from current reliance on physical testing to integrated experimentation, computation, theory, databases and model-based simulation. To support this goal, 15 different advanced testing facilities, termed Equipment Sites, are being developed that will be geographically distributed across the United States. The Equipment Sites will consist of (a) structural laboratories, (b) shaking tables, (c) geotechnical centrifuges, (d) mobile and permanent field testing facilities, and (e) a tsunami wave basin.

The University of California, L.A. NEES Equipment Site (nees@UCLA) is the only field equipment site dedicated to field testing of full-scale structural systems among 15 NEES equipment sites. The nees@UCLA equipment portfolio includes shakers for exciting structural systems, numerous sensors for monitoring accelerations and deformations within the excited structure (e.g., accelerometers and strain gauges), and real-time data acquisition and dissemination capabilities.

The advanced field testing capabilities of the nees@UCLA site were recently demonstrated on forced vibration testing of a four-story reinforced concrete building in Sherman Oaks, California, termed the Four Seasons Project. The principal research objective of the Four Seasons Project was to collect high quality field test data to significant levels of shaking, which would provide insight into the dynamic response of a real building and its components. The dataset will be archived in the NEES data repository, and can potentially form the basis of detailed analytical studies in the future. In the sections that follow, we provide an overview of the nees@UCLA equipment and testing capabilities, and describe the testing plan and some preliminary results of the Four Seasons Building Project.

NEES@UCLA Project Overview

The nees@UCLA equipment site provides state-of-the-art equipment for forced vibration testing and seismic monitoring of full-scale structural and geotechnical systems. This equipment is useful for identifying system properties through system identification analyses of recorded data, studying the nonlinear responses of systems with limited mass, and evaluating the interactions of various system components for realistic sets of boundary conditions. The major equipment components of the site include the following:


Figure 2a: West face of the Four Seasons Building

A) **Eccentric mass shakers** (*Figure 1a*) that can apply harmonic excitation across a wide frequency range in one or two horizontal directions. These shakers can induce weak to strong forced vibration of structures. For small structures, excitation into the nonlinear range is possible when the shakers are operated near their maximum force capacity (100kips each). The shakers can be operated in a wired or wireless mode.

B) **Linear shaker** (*Figure 1b*) that can apply broadband excitation at low force (15kips) levels. This shaker can be programmed to approximately reproduce the seismic structural response that would have occurred for any specified base-level acceleration time history (assuming the properties of the structure are known). The shaker can be controlled in a wired or wireless mode.

C) **Above-ground sensors** that can be installed at the ground surface or on a building, bridge, or geo-structures to record acceleration or deformation responses. Accelerations are recorded with uni-directional or triaxial accelerometers. Deformations (i.e., relative displacements between two points) are recorded with LVDTs or by using fiber-optic sensors.

D) **Retrievable subsurface accelerometers** (RSAs) that can be deployed below-ground to record ground vibrations in three directions. The sensors and their housing are specially designed to be retrievable upon the completion of testing.

E) **Wireless field data acquisition system** that efficiently transmits data in wireless mode from the tested structure to the high performance mobile network (see following item).

F) **High performance mobile network** that (a) receives and locally stores data at a mobile command center deployed near the test site; (b) transmits selected data in near real time via satellite to the UCLA global backbone; and, (c) broadcasts data via the NEESpop server into the NEESgrid for tele-observation of experiments.

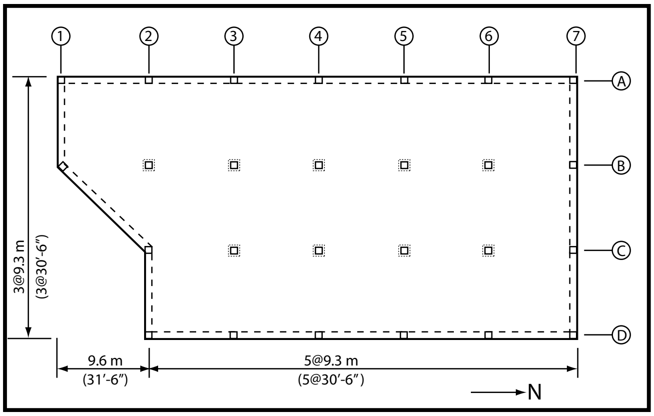

Figure 2b: Four Seasons Building – Typical floor plan.

Testing Program of Four Seasons Project

The Four Seasons building, shown in *Figures 2a* and *2b*, is a four-story reinforced concrete office building located in Sherman Oaks, California. This building was constructed in 1977 and the structural system includes a perimeter moment frame with an interior post-tensioned slab-column "gravity" system with drop panels, which represents a fairly common structural system used on the west coast of the United States. The Four Seasons building was significantly damaged in the 1994 Northridge Earthquake, and post-earthquake studies of the building provide somewhat conflicting reasons for the observed damage. The building has since been yellow-tagged and is scheduled for demolition. Damage was particularly severe at slab-column connections, due to slab punching

shear failure around the perimeter of the drop panels. The most dramatic failures were observed at the south end of the 2nd floor level (column B2) and the north end of the 3rd floor level (column B6). (*Figure 2c*) In addition to the slab punching failures, significant joint diagonal cracks, column flexural cracks, and some minor spalling near beam-column joints were observed on the perimeter frame. (*Figure 2d*)

Figure 2c: Punching shear failure (Column B6 at the 3rd floor level).

Figure 2d: Shear crack on beam-column joint (Column A4 at the 3rd floor level).

The testing consisted of a series of forced vibration tests using the linear shaker and eccentric mass shakers, respectively, and ambient vibration tests, as shown in *Table 1*. The linear shaker was used to generate broadband excitations, which are useful to assess modal properties of the building from acceleration measurements by time domain system identification techniques. During relatively high-amplitude sinusoidal vibrations obtained by synchronized operation of two large capacity eccentric mass shakers, interstory displacements were obtained from both displacement measurements by LVDTs and the differences between story accelerations divided by the square of circular frequency. Also, curvature distributions of slabs and columns during the eccentric mass shaker test were investigated using strain measurements. In addition to forced vibration testing, ambient vibrations were measured before and after each test to investigate potential drifts of modal properties resulting from the forced vibrations.

A dense array of sensors was deployed prior to the test. A total of 16 triaxial and 27 uniaxial force-balance accelerometers (Kinemetrics ES-T and ES-U, respectively) were provided for acceleration measurements, 26 linear variable displacement transducers (Trans-Tek, Series 240, DC LVDT) were used to measure interstory displacements and beam curvatures, and 96 strain gauges (TML, PL-60-11-5L) were affixed to slab and column surfaces to monitor curvature distributions. The data acquisition was performed using two separate systems: a Kinemetrics system using Antelope and a National Instrument system using LabView. Data from both systems were GPS time-stamped to ensure data compatibility. *Figure 3* (*page 29*) shows a schematic of the data acquisition system and data flow through the system.

System Identification Results From Test Data

Natural frequencies and damping ratios identified by system identification analyses are presented in *Table 2* and *Table 3*. The first six or seven modes could be identified by linear shaker test and ambient vibration test data.

Table 1: Test sequence

Date (mo/day/yr)	**Test**
07/02/04	Ambient vibration measurement – Run1
06/22/04 to 07/13/04	E-W translational / Torsional excitation with *empty* baskets
07/14/04 to 07/19/04	E-W translational / Torsional excitation with *half-full* baskets
07/19/04	Ambient vibration measurement – Run2
07/19/04	Linear shaker test – Run1
07/22/04	N-S translational excitation with *half-full* baskets
07/28/04	N-S translational excitation with *empty* baskets
08/02/04	N-S translational excitation with *empty* baskets
08/02/04	Linear shaker test – Run2
08/03/04	E-W translational / Torsional excitation with *empty* baskets
08/03/04	Ambient vibration measurement – Run3

Table 2: Natural Frequencies from System Identification.

Identified Natural Frequency (Hz)							
	1st	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**
Ambient 0702,(a)	1.09	1.25	1.55	3.23	3.63	4.16	5.38
EMS, (b)	0.81	0.87	1.1~1.2				
Ambient 0719, (c)	1.06	1.20	1.50	3.11	3.51	3.99	
LS 0728, (d)	0.87	0.94	1.25	2.73	2.91	3.43	
LS 0802, (e)	0.88	0.94	1.26	2.73	2.94	3.44	4.54
Ambient 0803 (f)	1.06	1.21	1.49	3.11	3.48	3.96	
Normalized to LS 0802, (e)							
(a)/(e)	124%	133%	123%	118%	124%	121%	119%
(b)/(e)	92%	93%	87%~95%				
(c)/(e)	120%	128%	119%	114%	119%	116%	
(d)/(e)	99%	100%	100%	100%	99%	100%	
(f)/(e)	120%	129%	119%	114%	118%	115%	
Normalized to their 1st frequency							
Ambient 0702	100%	115%	142%	295%	332%	380%	491%
EMS	100%	108%	135%~148%				
Ambient 0719	100%	113%	142%	293%	331%	376%	
LS 0728	100%	108%	144%	315%	335%	395%	
LS 0802	100%	107%	143%	310%	334%	391%	516%
Ambient 0803	100%	115%	141%	294%	329%	374%	

Table 3: Identified Damping Ratios.

	1st	2nd	3rd	4th	5th	6th	7th
Ambient 0702	2.93%	4.87%	1.78%	1.86%	3.18%	2.29%	3.68%
EMS	4.4%	6.6%					
Ambient 0719	3.35%	3.10%	2.14%	2.98%	3.07%	2.14%	
LS 0728	5.90%	6.88%	6.17%	5.84%	8.24%	6.19%	
LS 0802	5.66%	6.94%	6.01%	5.61%	7.69%	6.14%	13.50%
Ambient 0803	2.92%	2.98%	1.31%	2.24%	2.98%	2.60%	

The frequencies identified with the data from the eccentric mass shaker tests and ambient vibrations were, on average, 8% lower and 14 to 35% higher than those obtained using the linear shaker test data. Since there was no change in building mass during the tests, these differences are attributed to changes in stiffness properties either due to the contribution of nonstructural elements and/or stiffness degradation of structural members. However, for this building, the contribution of non-structural elements was thought to be relatively minor since most of the drywall partitions were already separated from neighboring structural members due to earthquake damage, and no in-filled or exterior brick veneer walls exist. Consequently, stiffness degradation of the structural members may be the more likely cause of the frequency drop.

Table 2 also shows the ratios of identified natural frequencies to the lowest fundamental frequency for each direction. Frequency ratios for the forced vibration and ambient vibration tests follow different trends, that is, the 1st N-S frequency is 7 to 8 % higher than the 1st E-W frequency for the forced-vibration tests (EMS test and linear shaker tests), and 13 to 14% higher for the ambient vibration tests. Again, considering that the mass of the building is fixed, the change in the frequency indicates that stiffness degradation occurs

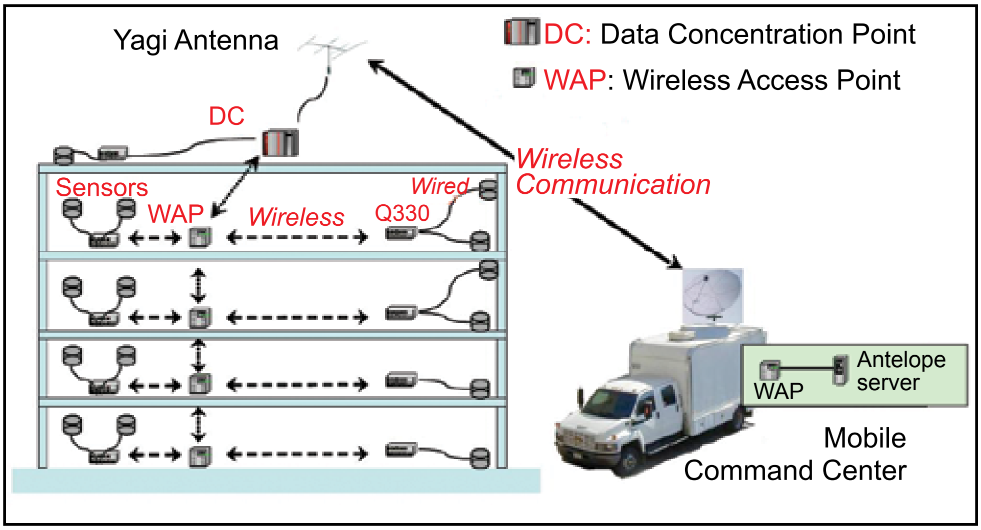

Figure 3: Data acquisition system.

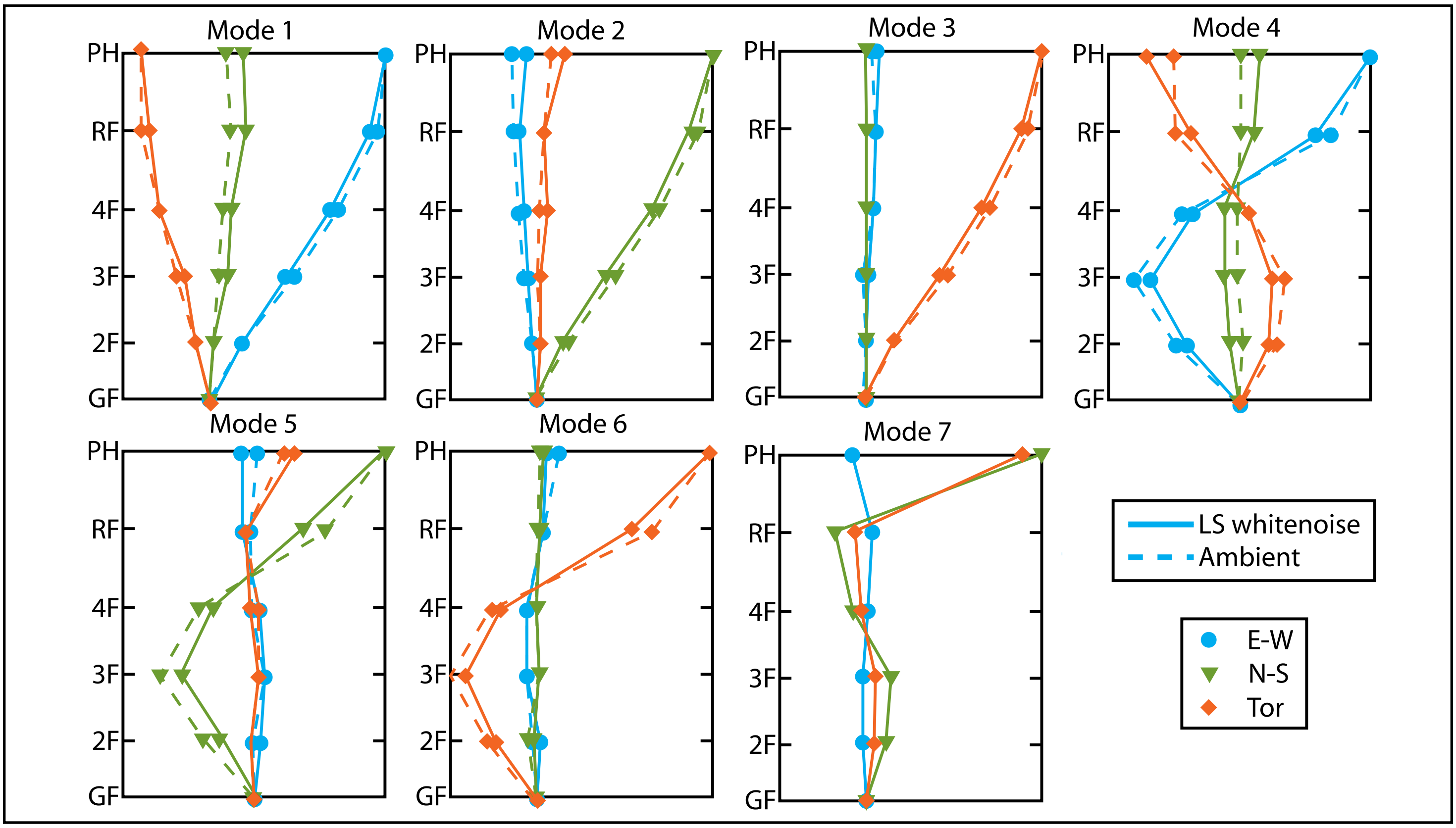

Figure 4: Mode shapes (Linear Shaker test run 2 and Ambient vibration run 2).

for larger amplitude vibrations, and is more severe in the structural members contributing to stiffness in the N-S direction. One possible reason for the noted discrepancy in frequency ratios could be the pre-existing condition of the building, which was damaged in the Northridge earthquake.

As shown in row (*a*) and (*f*) of *Table 2 (see page 28)*, identified frequencies for ambient vibration measurements collected after the half-full basket EMS test showed a 3 to 4% reduction in frequencies relatively to the ambient vibration results identified prior to the test. Permanent stiffness reduction in structural members, exterior cladding at typical stories or foundation/soil supporting the building may be the possible reason. Further research is needed to clarify this phenomenon.

The ratios of the identified frequencies for the 2nd modes to identified frequency for the 1st modes in each direction are in the range of 2.7 to 3.1 (*Table 2, see page 28*), which is very close to 3.0, which is the theoretical frequency ratio of the 2nd to the 1st mode in the case of a cantilever beam in shear deformation [Trifunac, 1972]. Damping ratios identified from linear shaker tests and ambient vibrations are shown in *Table 3(see page 28)*. Mode shapes determined by linear shaker test (run2) and ambient vibration test (run2) are shown in *Figure 4*. The first six mode shapes correspond to the first and second modes in the order of transverse (E-W), longitudinal (N-S), and torsional direction, respectively. But, in the 7th mode, the N-S translational and torsional components are mixed. The mode shapes do not change as much with the type of testing (i.e. vibration amplitude) as do the natural frequencies.

Conclusions

A series of forced and ambient vibration tests were performed on a four-story reinforced concrete building damaged by the Northridge earthquake using the nees@UCLA mobile field laboratory. Two eccentric mass shakers and a linear inertia shaker were used as vibration sources. Global frequency response of the test building and detailed behavior of structural components were monitored with a dense instrumentation array using 75 accelerometer channels, 26 displacement transducers, and 96 concrete strain gauges.

From the acceleration measurement, drift of modal properties of the building was investigated using system identification techniques. Approximately the first 6 frequencies and mode shapes for the building could be identified using the test results. From the ambient vibration data collected before and after the eccentric mass shaker test, a drop about 3% in the natural frequencies was observed. Fundamental frequencies during eccentric mass shaker test were 70 to 75% of those by ambient vibration data, and 92 to 93% of those by linear shaker test.

Collected vibration data and modal properties can form a basis of the analytical model predicting the response of the building. A study on the construction of an analytical FE model using a model updating technique was conducted [Yu, 2005]. An ongoing aspect of the study involves assessing reasons and the degree of building damage that resulted from the Northridge earthquake by a nonlinear dynamic analysis.▪

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