IOMAC'15

6th International Operational Modal Analysis Conference
2015 May12-14 Gijón - Spain

AMBIENT VIBRATION RECORDS IN REPRODUCING THE FORCED VIBRATION TEST RESULTS OF A FOUR-STORY REINFORCED CONCRETE BUILDING WITH TWO BASEMENT FLOORS

Ozan Cem Celik[1]

[1] Assist. Prof. Dr., Middle East Technical University, Northern Cyprus Campus, Kalkanli, Guzelyurt, KKTC, Mersin 10, Turkey, occelik@metu.edu.tr.

ABSTRACT

In forced vibration testing, a vibration generator bolted to one of the top floors excites the building with a known sinusoidal force. Sweeping the frequency of the vibration generator, steady-state structural responses are recorded at each operated frequency by accelerometers deployed throughout the building. Dynamic properties of the structural system are then identified from acceleration-frequency response curves by using well-established methods in the structural dynamics area, which do not require sophisticated system identification algorithms. Its drawbacks; however, have long made ambient vibration testing an attractive alternative. This study uses the ambient vibrations recorded following the forced vibration test of a four-story reinforced concrete school building with two basement floors, which is the first permanently instrumented building in Turkey and in close proximity to the North Anatolian Fault, to determine its natural vibration frequencies, modal damping capacities, and natural vibration modes. System identification using frequency domain decomposition methods yields structural system dynamic properties that are comparable to the forced vibration test results. Ambient vibration testing will be used as an alternative when building owners do not permit forced vibration testing of their buildings. The identified structural system dynamic properties will be used in calibrating the finite element structural models of the instrumented buildings in earthquake prone areas of Europe as part of a European Union project, which ultimately aims to assess their seismic fragilities.

Keywords: Buildings, Dynamic properties, Dynamic tests, Field tests, Identification, Structural dynamics

Figure 1. View of the building from its southwest corner.

1. INTRODUCTION

Forced vibration testing provides the most direct means of determining the structural system dynamic properties. Input excitation is known and how the acceleration-frequency responses, obtained upon digital signal processing of the raw data, are used in determining the dynamic properties is well established in the structural dynamics area [1]. Its drawbacks; however, have long made ambient vibration testing an attractive alternative [2–6]. Building owners, whether public or private entities, are unwilling to have their buildings tested when they learn that their buildings will be subjected to forced vibrations although these low-amplitude vibrations definitely do not damage buildings. Natural frequencies that can be identified are also limited within the operating frequency range of the vibration generator. Moreover, transportation and installation of the vibration generator is not a trivial task and interferes with the daily building function [7].

In this study, ambient vibrations recorded following the forced vibration test of a four-story reinforced concrete building were used to determine its structural system dynamic properties. A dense network of 18 uniaxial accelerometers was used for monitoring the structural responses. Natural vibration frequencies, modal damping capacities, and natural vibration modes of the building were identified using the frequency domain decomposition methods [8, 9] employed in the ARTeMIS software [10] and were subsequently compared with the forced vibration test results. Ambient vibration testing will be used as an alternative to forced vibration testing to determine the structural system dynamic properties that will be used in calibrating the finite element structural models as part of a European Union project, which aims to assess the seismic fragility of instrumented buildings in earthquake prone areas of Europe.

2. BUILDING DESCRIPTION

Dynamic tests were performed on a four-story reinforced concrete school building with two basement floors, which is in close proximity to the surface rupture that occurred during the 1944 M_w 7.4 Gerede earthquake in Bolu, Turkey. The building was permanently instrumented to record the structural responses in the case of earthquakes that may occur along the nearby North Anatolian Fault and is the first instrumented building in Turkey [11]. Figure 1 shows the building from its southwest corner. The building was originally a six-story building and its structural system consisted of moment resisting frames along both North-South (N-S) and East-West (E-W) directions, with 4.2 m long shear walls along the N-S direction on each side of the staircase. Its top two floors were later shaved off during its

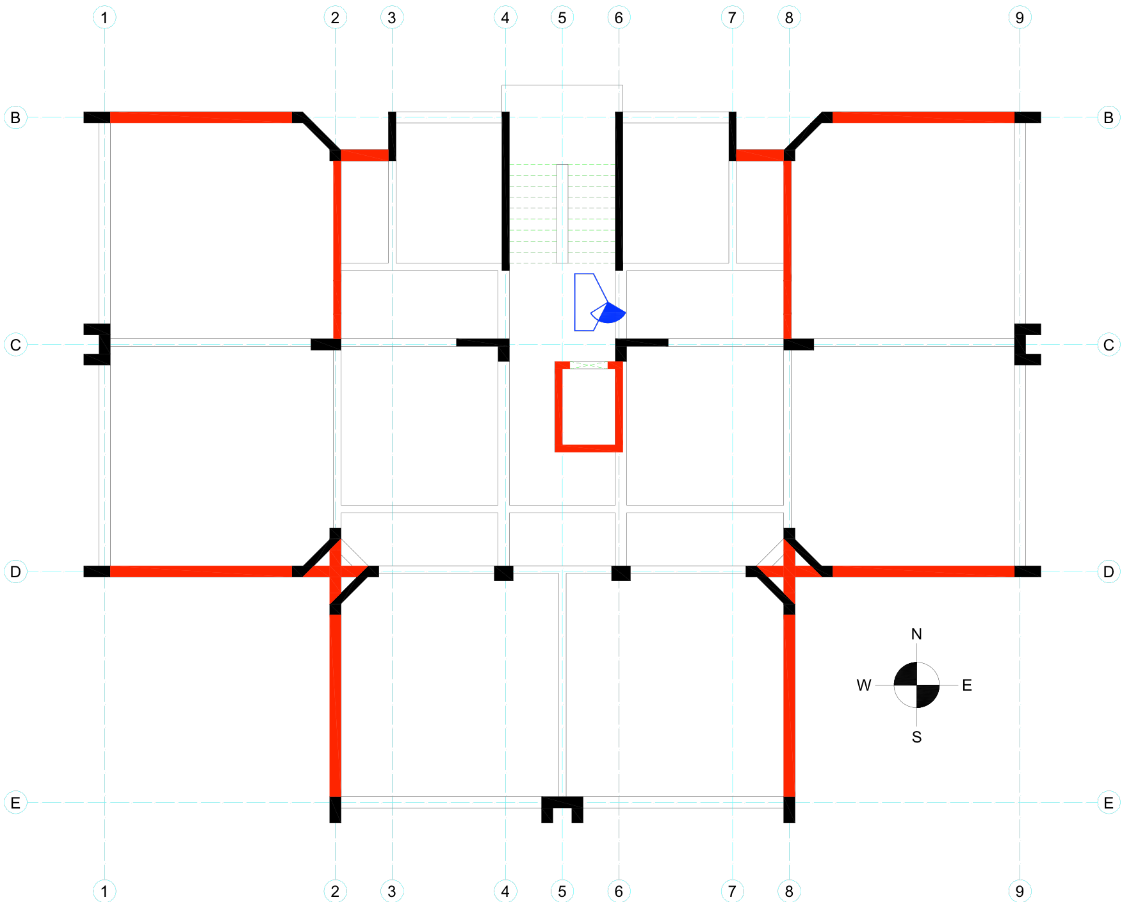
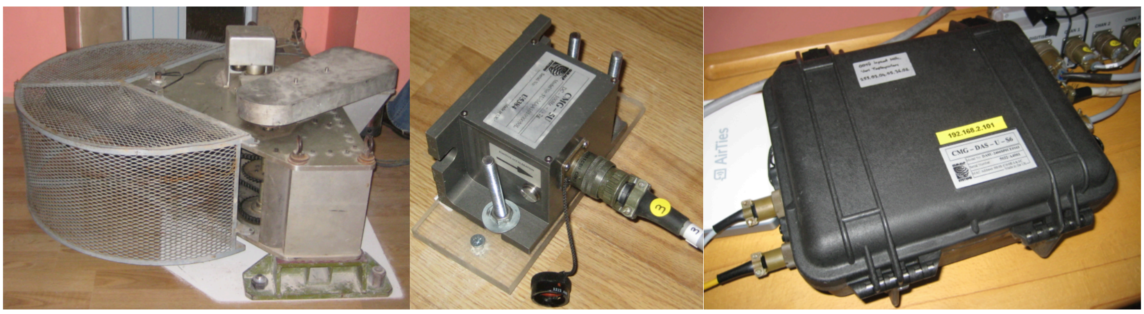


Figure 2. Fourth floor plan; Vibration generator location.



(a) (b) (c)

Figure 3. (a) Vibration generator, (b) accelerometer #3, (c) data acquisition system.

strengthening with cast-in-place reinforced concrete infill walls along both directions as shown in Fig. 2. The total height of the building up to the roof is 22.4 m including the basements. The story height is 3.6 m. Concrete grade is C25; TS 500 [12] defines its characteristic compressive strength as 25 MPa. The building has spread footings and rests on a soil medium consisting of dense sand and clay.

3. INSTRUMENTATION SCHEME

In forced vibration test, the building was excited by a vibration generator (Model VG-1 [13]; Fig. 3a) bolted to the fourth floor (one floor below the roof) slab between the elevator shaft and the stairs (Fig. 2). The vibration generator applied a horizontal sinusoidal force (in kN):

Table 1. Accelerometer locations and directions.

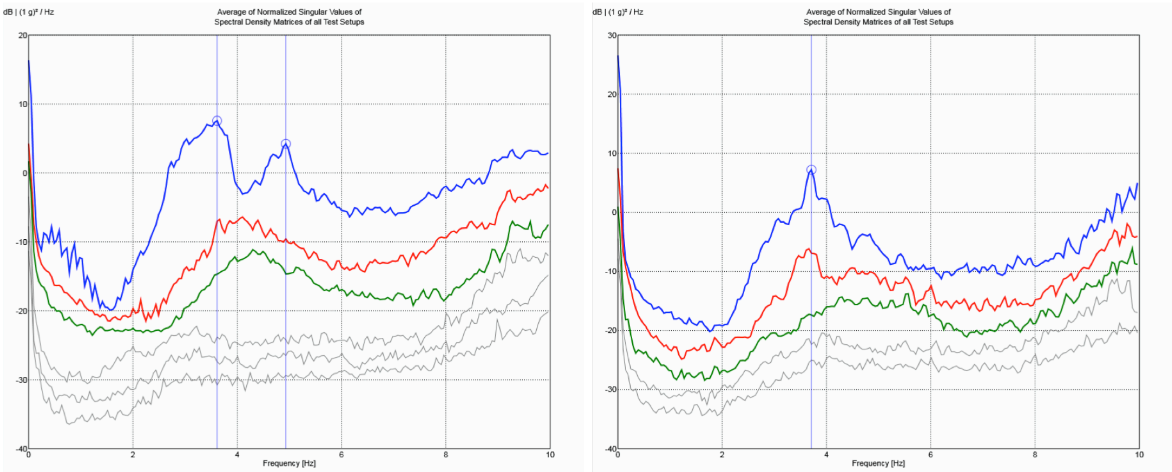
		E-W excitation				N-S excitation			
Acc. #	Floor #	Loc.	Dir.	Setup 1	Setup 2	Loc.	Dir.	Setup 1	Setup 2
1	4	B3	S		•	B3	S	•	•
2	4	B7	W	•	•	B7	S	•	•
3	4	D7	W	•	•	D7	W	•	
4	3	D7	W	•		B3	S		•
5	3	B7	W	•		B7	S		•
6	2	D8	W	•		B2	S		•
7	2	B8	W	•		B8	S		•
8	1	D7	W	•		B3	S		•
9	1	B7	W	•		B7	S		•
10	B1	B2	S		•	B2	S	•	
11	B1	B8	W	•	•	B8	S	•	•
12	B1	D8	W	•	•	D8	W	•	
13	B2	B3	S		•	B3	S	•	•
14	B2	B8	W	•	•	B8	S	•	•
15	B2	D8	W	•	•	D8	W	•	
16	B2	B3	+Z		•	B3	+Z	•	
17	B2	B8	+Z		•	B8	+Z	•	
18	B2	D8	+Z		•	D8	+Z	•	

$$p(t) = 0.24f^2 \sin 2\pi f t \qquad (1)$$

where f is the excitation frequency (in Hz) and t is the time (in s), along the E-W and N-S directions, respectively. Note that the operating frequency range of the vibration generator is up to 9.7 Hz. A dense network of 18 uniaxial accelerometers (CMG-5U [14]; see Fig. 3b for accelerometer #3) was used for monitoring the structural responses. Three horizontal accelerometers were placed on the fourth and two basement floors, two parallel along the excitation direction and the third in the perpendicular direction, which made possible to record the translational and torsional responses of each of these floors. The first three floors were instrumented by two horizontal accelerometers, parallel along the excitation direction. The second basement floor was further instrumented by vertical accelerometers placed at three corners of the building to record the rocking responses of the building, if any. Two six-channel digital recorders (CMG-DM24 [15]; Fig. 3c) were used. Accelerometers placed along the excitation direction on the fourth and two basement floors were used as reference accelerometers and records from all 18 accelerometers were taken in two setups for each excitation direction. Table 1 shows the accelerometer locations and directions for all test setups. The digital recorders were set to record accelerations at 100 samples per second, which gives a frequency range up to 50 Hz according to the Nyquist frequency criterion.

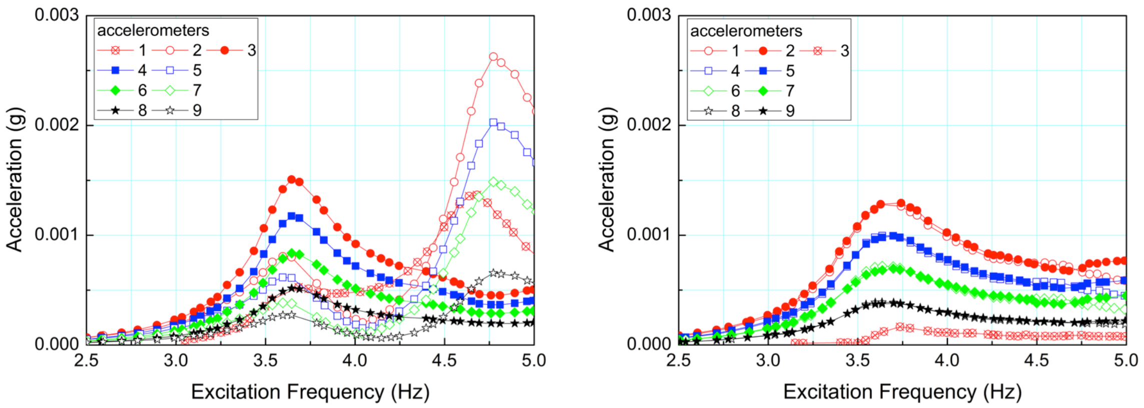
4. AMBIENT VIBRATION RECORDS

Ambient vibrations were recorded for at least 15 minutes following each forced vibration test setup with the same configuration of accelerometers. Structural system dynamic properties were identified from the ambient vibration records using the ARTeMIS software. Figure 4 shows the singular values of the power spectral density matrices of the ambient responses recorded by accelerometers for E-W and N-S setups [8]. Natural vibration frequencies were identified using the Frequency Domain Decomposition (FDD) and Enhanced Frequency Domain Decomposition (EFDD) methods whereas modal damping capacities were identified using the EFDD method [8, 9]. These structural system dynamic properties are subsequently compared with those determined from the forced vibration test of the building.



(a) (b)

Figure 4. Singular values of the power spectral density matrices of the ambient responses: (a) E-W and (b) N-S setups.



(a) (b)

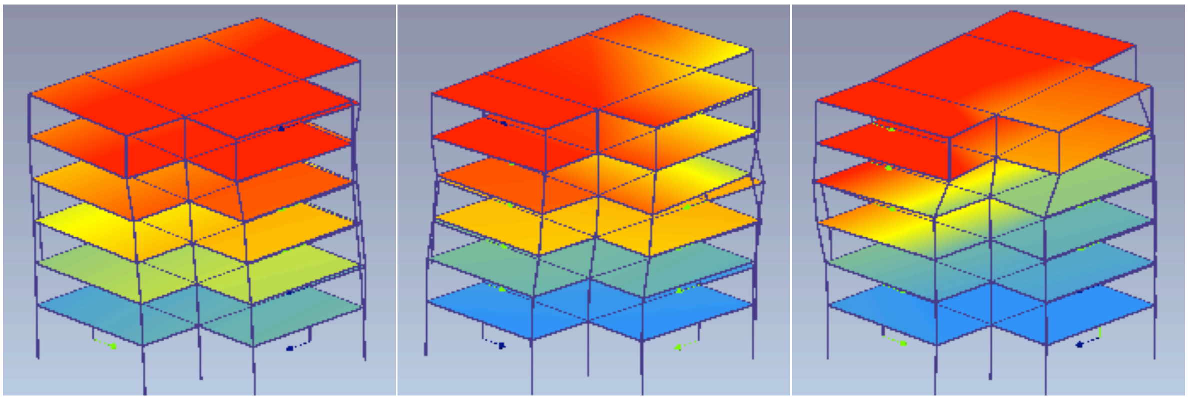
Figure 5. Acceleration-frequency response curves for (a) E-W and (b) N-S excitations.

Table 2. Structural system dynamic properties identified from forced and ambient vibration tests.

	Natural frequency (Hz)			Modal damping (%)		
		Ambient				
Mode	Forced	FDD	EFDD	Forced	Ambient	Description
1	3.7	3.6	3.5	6	7	E-W translation
2	3.7	3.7		9		N-S translation
3	4.8	4.9	4.9	6	6	Torsion

5. COMPARISON WITH FORCED VIBRATION TEST RESULTS

A frequency sweep up to 5.0 Hz with increments of typically 0.05 Hz was performed in the E-W and N-S directions, respectively. Upon digital signal processing of the records, plotting the steady-state response amplitudes at each frequency, after the transient response damped out, resulted in frequency-response curves in the form of acceleration amplitude versus excitation frequency [1, 16] as shown in Fig. 5 for the E-W and N-S excitations. Natural vibration frequencies are essentially equal to resonant frequencies and associated modal damping capacities can be determined using the half-power bandwidth method [16, 17]. Table 2 compares the forced and ambient vibration test results. The differences in natural frequencies and damping capacities are marginal. However, it was not possible



(a) (b) (c)

Figure 6. Mode shapes: (a) E-W translational, (b) N-S translational, (c) torsional.

to identify the damping capacity for the first translational mode along the N-S direction and damping values were sensitive to the set of records used (those reported in Table 2 are for the first E-W setup). Figure 6 shows the natural vibration mode shapes of the building for the first translational modes in both directions and the torsional mode as determined from the ARTeMIS software.

6. CONCLUSIONS

System identification performed using ambient vibration records reproduced the forced vibration test results of a four-story reinforced concrete building with two basement floors. Hence, possible use of ambient vibration testing as an alternative to forced vibration testing is justified when building owners do not permit forced vibration testing of their buildings. The identified structural system dynamic properties will be used in calibrating the finite element structural models of the instrumented buildings in earthquake prone areas of Europe as part of a European Union project, which ultimately aims to assess their seismic fragilities.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the Middle East Technical University (METU) Northern Cyprus Campus under *grant* BAP-FEN-14-D-3 and the European Union Seventh Framework Programme (*FP7/2007-2013)* under *grant agreement* n° 268428. These supports are gratefully acknowledged. The research funded by the European Union was conducted at the METU Ankara Campus.

REFERENCES

[1] Celik, O. C., Sucuoglu, H., & Akyuz, U. (2013). Forced vibration testing and finite element modeling of a nine-story reinforced concrete flat plate-wall building. *Earthquake Spectra*, in press. doi:10.1193/091212EQS287M

[2] Carder, D. S. (1936). Observed vibrations of buildings. *Bulletin of the Seismological Society of America*, 26, 245–277.

[3] Crawford, R., & Ward, H. S. (1964). Determination of the natural periods of buildings. *Bulletin of the Seismological Society of America*, 54, 1743–1756.

[4] Stephen, R. M., Hollings, J. P., & Bouwkamp, J. G. (1973). *Dynamic behavior of a multistory pyramid shaped building*. Report No. EERC 73-17, University of California, Berkeley, CA.

[5] Ivanovic, S. S., Trifunac, M. D., Novikova, E. I., Gladkov, A. A., & Todorovska, M. I. (2000). Ambient vibration tests of a seven-story reinforced concrete building in Van Nuys, California,

damaged by the 1994 Northridge Earthquake. *Soil Dynamics and Earthquake Engineering*, 19, 391–411.

[6] Skolnik, D., Lei, Y., Yu, E., & Wallace, J. W. (2006). Identification, model updating, and response prediction of an instrumented 15-story steel-frame building. *Earthquake Spectra*, 22, 781–802.

[7] Celik, O. C. (2002). *Forced Vibration Testing of Existing Reinforced Concrete Buildings*. M.Sc. Thesis, Civil Engineering Department, Middle East Technical University, Ankara, Turkey.

[8] Brincker, R., Zhang, L., & Andersen, P. (2001). Modal identification of output-only systems using frequency domain decomposition. *Smart Materials and Structures*, 10, 441–445.

[9] Brincker, R., Ventura, C. E., & Andersen, P. (2001). Damping estimation by frequency domain decomposition. In: *Proc. of the 19th International Modal Analysis Conference (IMAC)* (pp. 698–703). Kissimmee, FL.

[10] Structural Vibration Solutions (2014). *ARTeMIS Modal 3.5*. http://www.svibs.com [20 February 2015], Aalborg, Denmark.

[11] Gulkan, P., Sucuoglu, H., Sonuvar, O., Incekara, C. O., Bayulke, N., & Mengi, Y. (1994). *Analysis of Instrumented Building Response to Strong Ground Motions at Very Short Distances to the Causative Fault*. Project No. INTAG 506 (YAG-40), The Scientific and Technical Research Council of Turkey, Ankara, Turkey.

[12] Turkish Standards Institute (2000). *Requirements for Design and Construction of Reinforced Concrete Structures*, *TS 500*. Ankara, Turkey.

[13] Kinemetrics (1975). *Operating Instructions, Vibration Generator System, Model VG-1*. San Gabriel, CA.

[14] Guralp Systems (2013). *CMG-5U, Single-axis accelerometer, Operator's Guide*. Document No. MAN-050-0002, Aldermaston, England.

[15] Guralp Systems (2009). *CMG-DM24, Mk3 Digitizer, Operator's guide*. Part No. MAN-D24-0004, Aldermaston, England.

[16] Rea, D., Bouwkamp, J. G., & Clough, R. W. (1968). *Dynamic properties of McKinley school buildings*. Report No. EERC 68-4, University of California, Berkeley, CA.

[17] Chopra, A. K. (1995). *Dynamics of Structures*. Prentice Hall, Upper Saddle River, NJ.