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DYNAMIC CHARACTERISTICS OF FIVE TALL BUILDINGS DURING STRONG AND LOW-AMPLITUDE MOTIONS

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SUMMARY

The objectives of this paper are to present (1) a comparison of dynamic characteristics of five buildings determined from recorded strong-motion response data and from low-amplitude (ambient vibration) tests, and (2) a description of the low-amplitude ambient testing and PC-based data-acquisition approach that is integrated with the permanent strong-motion instrumentation in the five buildings. All five buildings are within the San Francisco Bay area and the strong-motion dynamic characteristics are extracted from the October 17, 1989 Loma Prieta earthquake response records. Ambient vibration tests on the same five buildings were conducted in September 1990. Analyses of strong-motion response and low-amplitude test data have been performed by many investigators. The present study differs from numerous previous investigations because (1) in this study, accelerometers in the five permanently-instrumented buildings were used during the low-amplitude testing, and (2) rapid screening of the strong-motion response data was achieved with a concerted use of system identification software. The results show for all cases that the fundamental periods and corresponding percentages of critical damping determined from low-amplitude tests are appreciably lower than those determined from strong-motion response records. The data set collected during this study is a useful contribution to the data base of dynamic characteristics of engineered structures and reconfirms the differences between the dynamic characteristics identified from strong-motion records and from low-amplitude tests.

1. INTRODUCTION

1.1. General remarks

This paper provides a comparative investigation on the dynamic characteristics of five buildings in the San Francisco Bay area. The dynamic characteristics discussed are identified from two sources of data:

(1) the recorded responses of the five buildings to the Loma Prieta earthquake [LPE] of October 17, 1989 ($M_s = 7{\cdot}1$);
(2) records from low-amplitude ambient vibration tests performed after the LPE.

One of the differences of this study compared to others, too numerous to cite herein (because of the large number of available references, the authors prefer to limit the references only to those relevant to the subject matter of this paper) is the unique low-amplitude (ambient) testing and data acquisition procedure. The testing of each building was conducted from a recording

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room that contained the junction box (of the cables of the force-balance-accelerometers permanently deployed throughout the superstructure) which was hooked up with the digital (PC-based) data acquisition system used in this investigation. This facilitated easy access to various floors of the building without actually going to those floors and without having to provide temporary cables and sensors.

Furthermore, during this study, a rapid screening analysis procedure using commercially available system identification and signal processing software was employed in order to process and analyse the vast amount of strong-motion and low-amplitude test data.

The main objective of the study was to compare the dynamic characteristics of buildings extracted from strong-motion and low-amplitude responses. Although past investigations have shown that there are significant differences of dynamic characteristics determined from strong-motion and low-amplitude responses, this study presents the results of a concerted study of five permanently instrumented buildings that will be useful to (a) provide a comparative discussion of the results, (b) present the approach to testing of the instrumented structures with a digital data acquisition system and related analyses of the data, and (c) add to the database.

1.2. Selected buildings and particulars

In selection of the buildings, the basic criteria (not necessarily in order of priority) were that (a) the selected buildings have permanent strong-motion instrumentation, (b) the buildings had

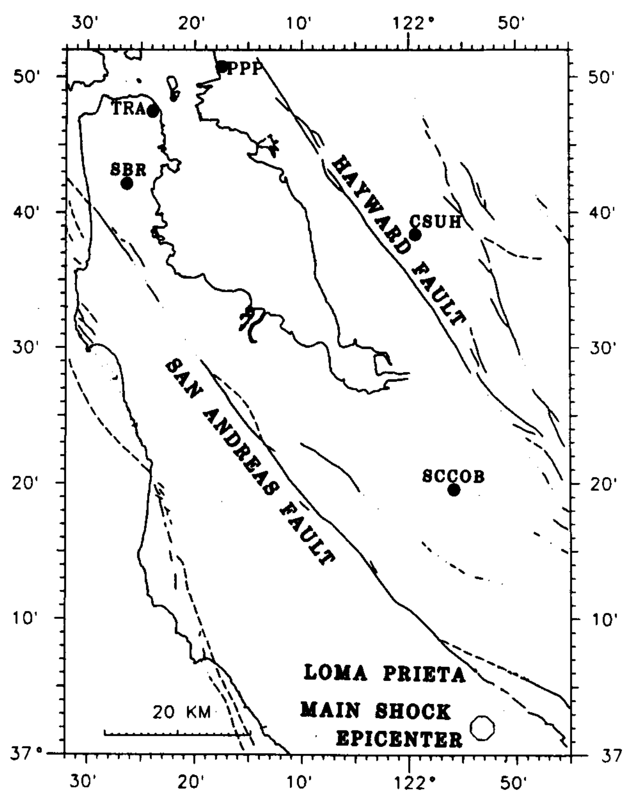

Figure 1. General location map of the five buildings relative to the epicenter of the Loma Prieta earthquake

not suffered visible structural damage during the LPE, (c) the LPE processed records would be available, (d) the buildings represent a range of different structural systems and construction materials, and (e) the structural drawings of the buildings would be available for further studies.

After considering several candidate structures that met the criteria, five buildings were selected: (1) the administration building of California State University at Hayward (CSUH); (2) the Santa Clara county office building (SCCOB); (3) an office building in San Bruno (SBR), (4) the Transamerica building in San Francisco (TRA); and (5) the Pacific Park Plaza building in Emeryville (PPP).

The general location map of the five buildings relative to the epicenter of the LPE is shown in Figure 1. The general dimensions and instrumentation schemes of the selected buildings are shown in Figures 2 to 6. Significant characteristics of the selected buildings (structural type, foundation type and general dimensions), distances from the Loma Prieta earthquake epicenter, number of channels of strong-motion sensors within the superstructure and the peak accelerations at ground level (or foundation level) and at roof level are summarized in Table I. Also indicated in the table is the agency, U.S. Geological Survey (USGS) or California Division of Mines and Geology (CDMG), responsible for the instrumentation in each building, and the reference north building orientation. The orientation is important in identifying the direction of recorded motions and resulting evaluations and is provided in degrees clockwise from true north.

Results from dynamic analyses and slow-amplitude tests performed on the Transamerica building and the Pacific Park Plaza building, available prior to the LPE (for TRA, see Stephen *et al.*[1] and Kinemetrics,[2] and for PPP, see Stephen *et al.*[3]), and dynamic characteristics for the SCCOB extracted from response data of two earthquakes that occurred prior to the LPE (Darragh[4]) are also included in this comparative study.

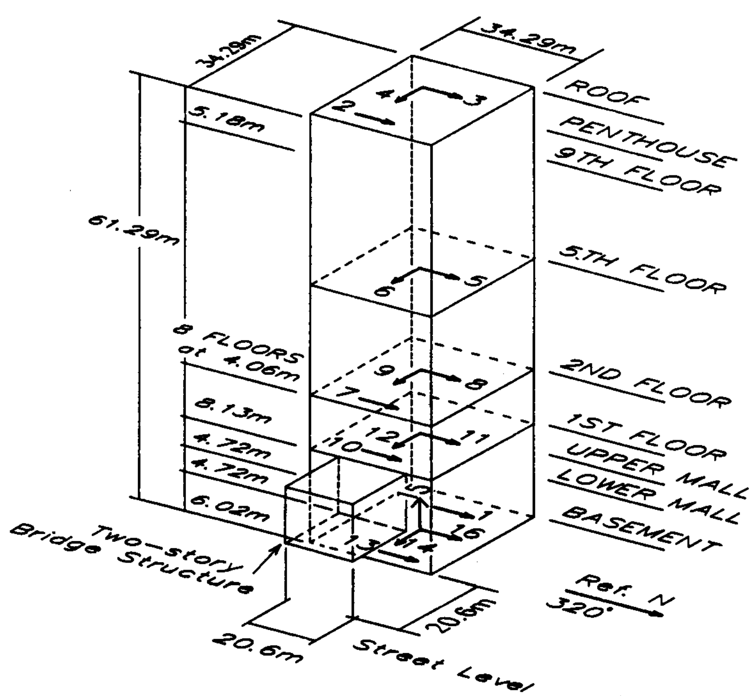

Figure 2. General instrumentation scheme of administration building, California State University, Hayward

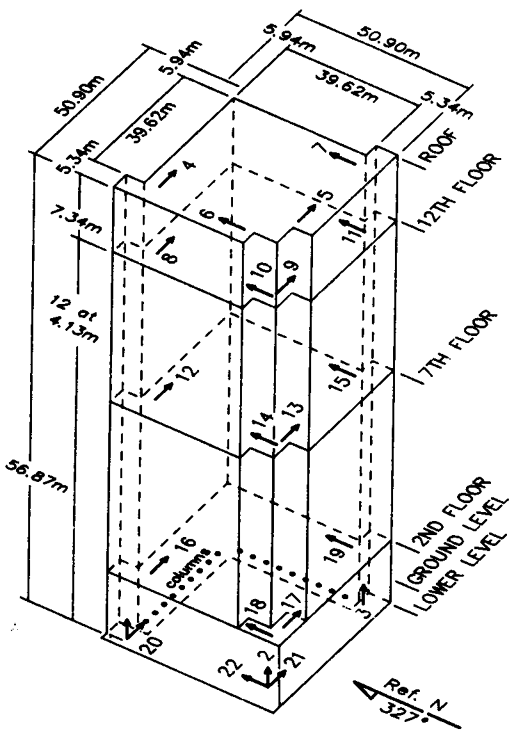

Figure 3. General instrumentation scheme of 13-story Santa Clara county office building, San Jose

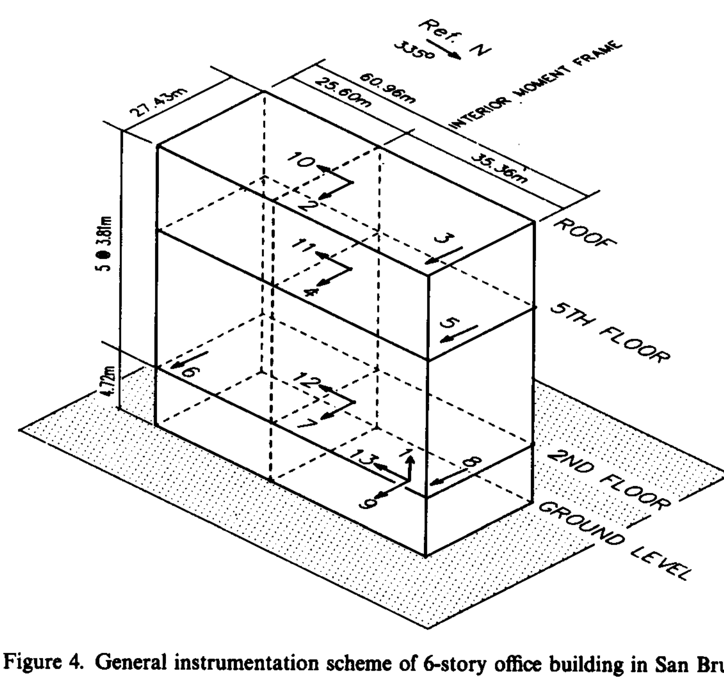

Figure 4. General instrumentation scheme of 6-story office building in San Bruno

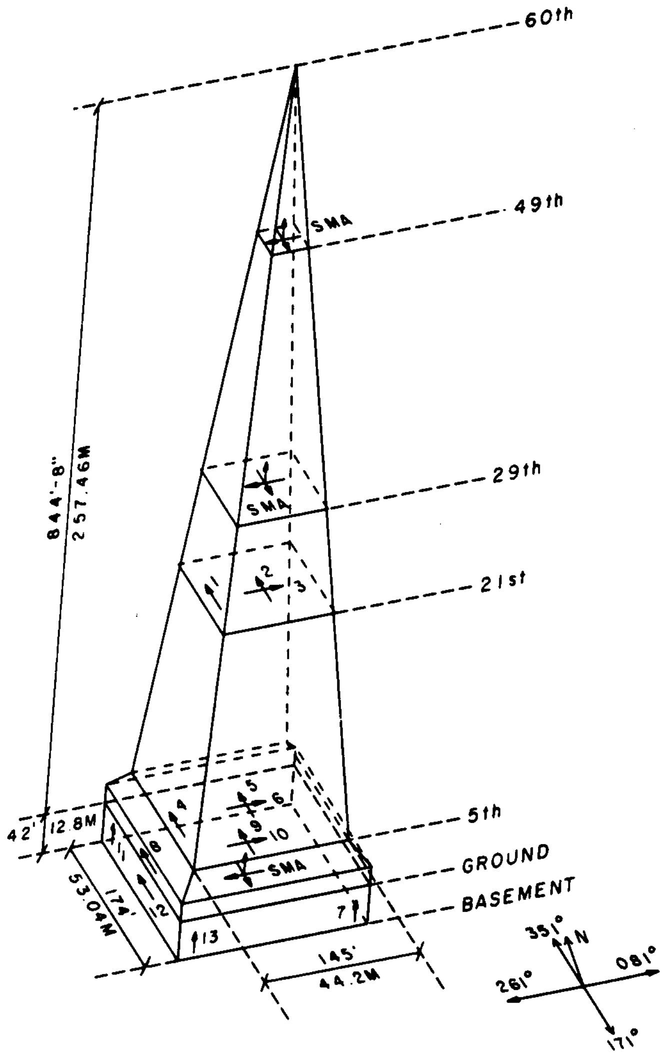

Figure 5. General instrumentation scheme of Transamerica building in San Francisco

1.3. Scope of paper

The scope of this paper includes analyses and comparative study of the LPE and ambient test data but does not cover time-history analyses. Results are given only for the fundamental modes of the buildings. For TRA and PPP, other pertinent analyses of the LPE data are presented elsewhere (for TRA see Çelebi and Şafak,[5] and for PPP see Çelebi and Şafak,[6] and Anderson *et al.*[7]).

2. LOW-AMPLITUDE TESTING

The digital data acquisition system used to carry out the ambient vibration tests accommodates 16 sample-and-hold data channels, has an input range of ± 10 V and uses a 12-bit A/D converter

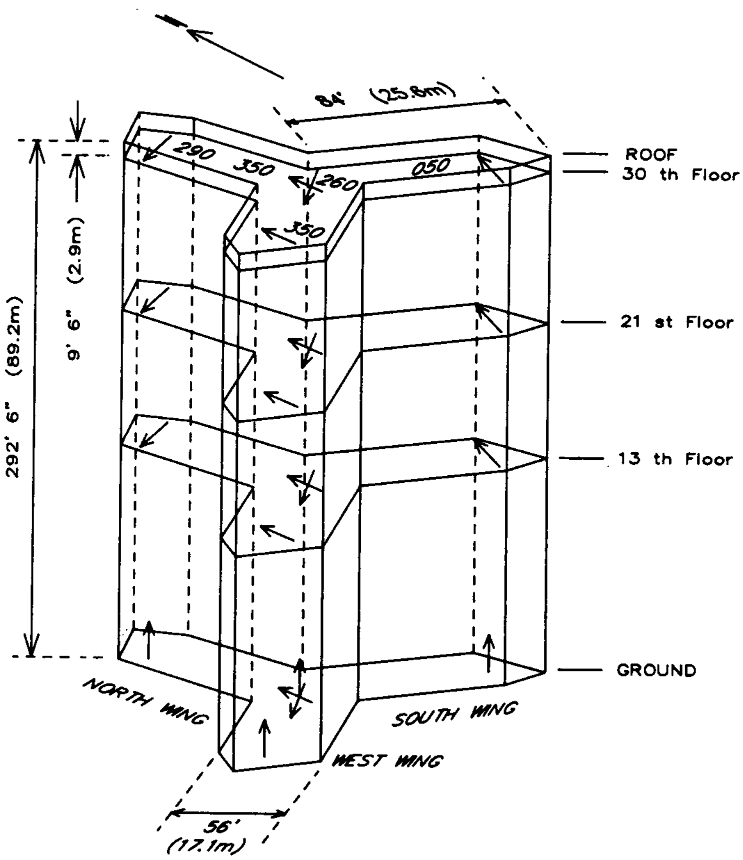

Figure 6. General instrumentation scheme of Pacific Park Plaza building in Emeryville

capable of performing up to 250 000 conversions per second. Amplifiers provided system gains of up to 4000 times. Low-pass filtering was accomplished with 3-pole Butterworth filters set at a cut-off frequency of 10 Hz. The sampling rate was 50 samples per second per channel.

In performing the tests, permanently-installed force-balance accelerometers were used as the sensors. This allowed easy access to motion data without having to provide temporary cables or sensors and made it possible to compare the ambient and strong-motion response directly. Nominal accelerometer sensitivity is $2{\cdot}5\ \mathrm{V\,g^{-1}}$. However, the ambient vibration data obtained in this study were acquired and analysed in terms of microvolts rather than as a percentage of g. Further details of the testing techniques are provided by Marshall *et al.*[8]

3. ANALYSES OF DATA

Commercially available system identification and signal processing software was used (Mathworks[9]) for the analyses of the strong-motion data. The procedures used in system identification analyses estimate a model based on observed input–output data (Ljung[10]). Simply stated, the input is the recorded basement or ground floor motion and the output is the response at roof level or at one of the levels where the structural response is detectable. The extra input

Table I. Building characteristics and Loma Prieta peak accelerations

Building	H† (m)	N_A/N_B‡	D† (km)	n†	LPE peak accel. (g) Nom. Dir.	Grnd.	Roof	Comments
(1) Administration building (CSUH) Hayward, Calif. (CDMG) $N = 320°$§	61	13/0	70	16	NS EW Vert.	0·07 0·09 0·05	0·15 0·24	Steel moment-frame core. Exterior reinforced concrete moment-frame. Concrete shear walls around elevator shafts to second floor. (0·45 m slab on grade and bearing piles)
(2) Santa Clara cty. office building, San Jose, Calif. (CDMG) $N = 337°$§	57	12/1	35	22	NS EW Vert.	0·10 0·09 0·10	0·34 0·34	Moment-resisting steel frame. (Concrete mat)
(3) Office building, San Bruno, Calif. (CDMG) $N = 335°$§	24	6/0	81	13	NS EW Vert.	0·14 0·11 0·12	0·25 0·32	Reinforced concrete moment-resisting frame. (Individual spread footings)
(4) Transamerica building, San Francisco, Calif. (USGS) $N = 351°$§	257	60/3	97	22	NS EW Vert.	0·11 0·12 0·07	0·29 0·31	Steel frame. 48th floor is top occupied floor. (2·75 m thick concrete mat) (No piles)
(5) Pacific Park Plaza, Emeryville, Calif. (USGS) $N = 350°$§	94	30/1	97	21	NS EW Vert.	0·17 0·21 0·06	0·24 0·38	Reinforced concrete moment-resisting frame. (1·50 m thick concrete mat on friction piles)

† N_A = number of floors above ground level, N_B = number of floors below ground level.
‡ H = height of the building, D = distance to epicenter, n = number of data channels.
§ Orientation of reference North measured clockwise from true North.

(ARX) model, based on the least squares method for single-input–single-output (Ljung[10] and Mathworks[9]), was used throughout this study.

The low-amplitude (ambient) vibration data were analysed by conventional spectral analysis techniques. System identification techniques were not applied to the ambient vibration data because of the unknown system input characteristics.

3.1. Sample analysis of data from one building

Due to space limitations, analytical results for only one building, the CSUH building, are provided. The detailed results for all buildings are reported by Marshall *et al.*[8]

The instrumentation scheme of the CSUH is provided in Figure 2. The location and orientation of each accelerometer is indicated by an arrow in the figure. The processed horizontal LPE acceleration records are provided in Figure 7. This CDMG-instrumented building is square in plan and sits on an 0·45 m (18 in) thick mat foundation supported by bearing piles. The 13-story building has a steel moment-frame core and exterior reinforced concrete frame (Shakal *et al.*[11]). Prior to LPE, low-amplitude tests of the building were not performed.

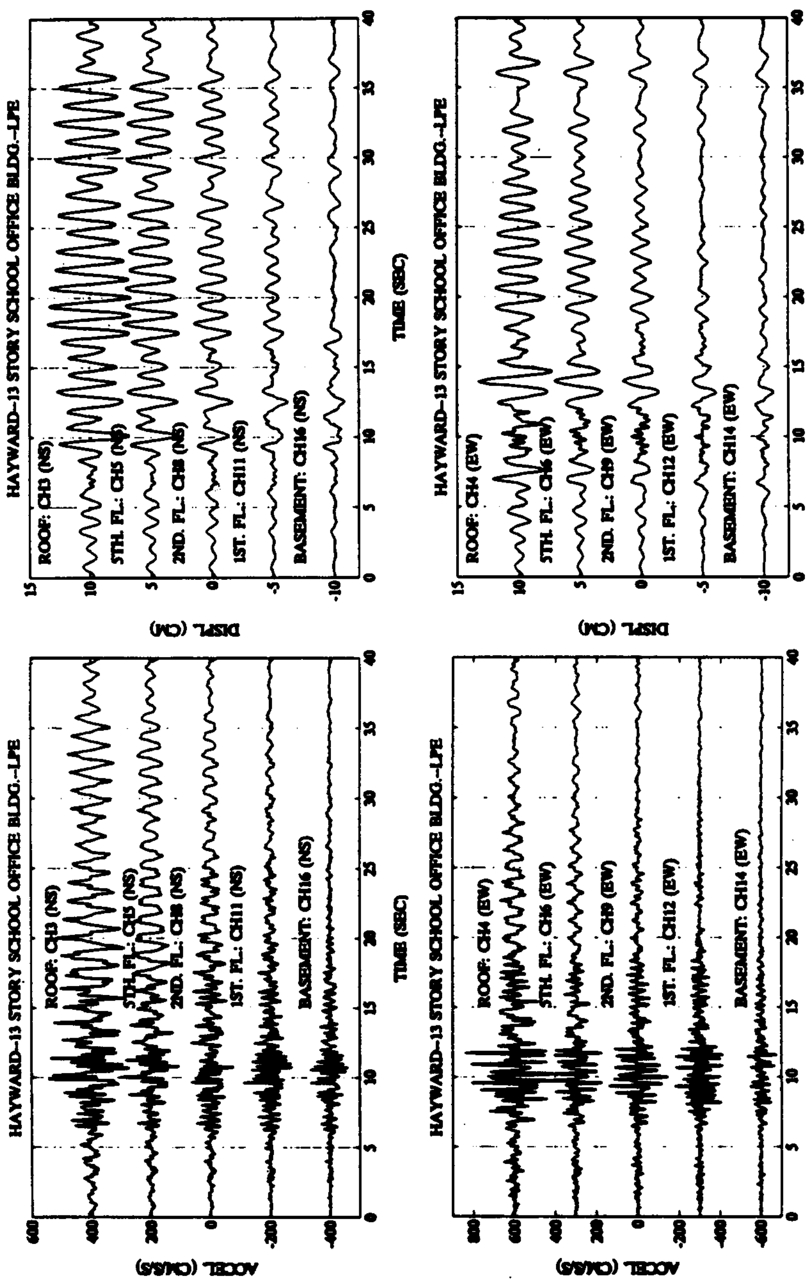

Figure 7. Processed acceleration and displacements at CSUH administration building

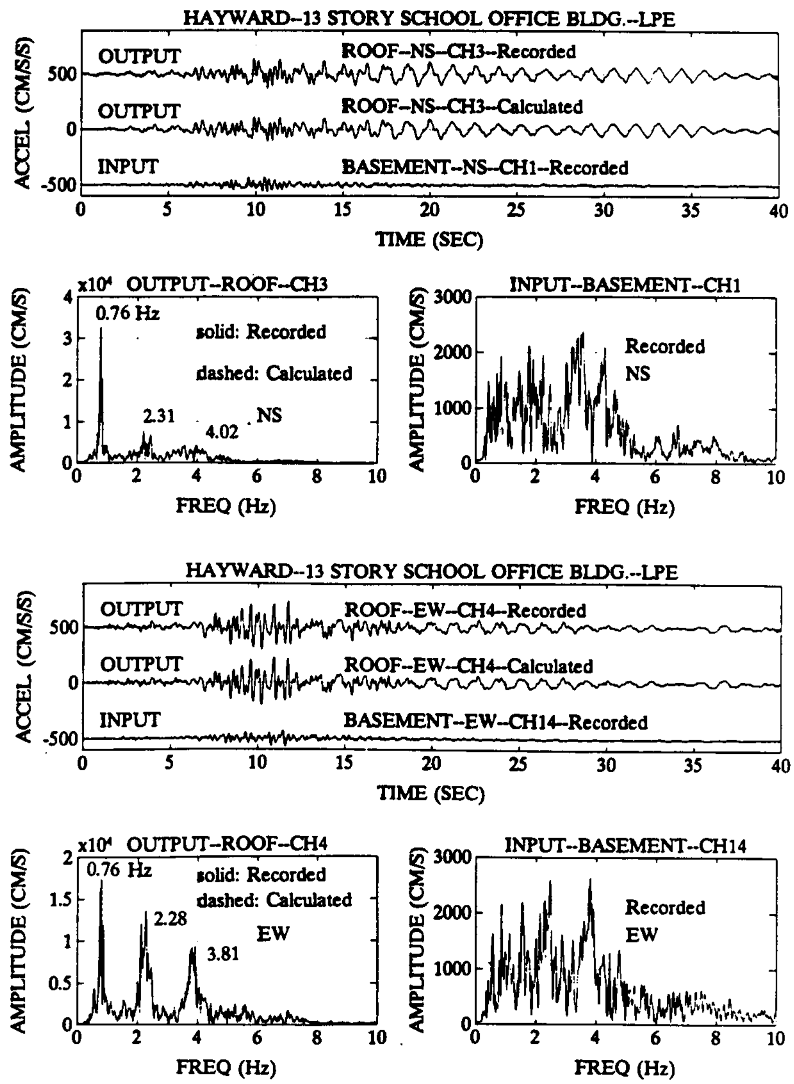

Figure 8. Recorded LPE and calculated (by system identification) roof level accelerations and Fourier amplitude spectra for CSUH administration building with basement motions as input

System identification results from application to the basement–roof pair of records in each direction (input–output) are shown in Figure 8. For the NS direction, Channel 1 (at the basement level) was used as the input and Channel 3 was used as the output. For the EW direction, Channel 14 and Channel 4 (roof) were used as input and output, respectively. Of particular interest is the excellent match of the recorded and calculated output motions and also the clear identification of the three significant modes in each direction. The estimated first-mode damping values are 3·4% and 2·3% of critical for the NS and EW directions, respectively.

Channels 2, 7 and 10 of the recorded LPE acceleration records were not digitizable (Shakal *et al.*[11]). This is unfortunate because it does not allow study of the torsional behavior or the identification of torsional contributions, if any. The fundamental mode frequency (period) is

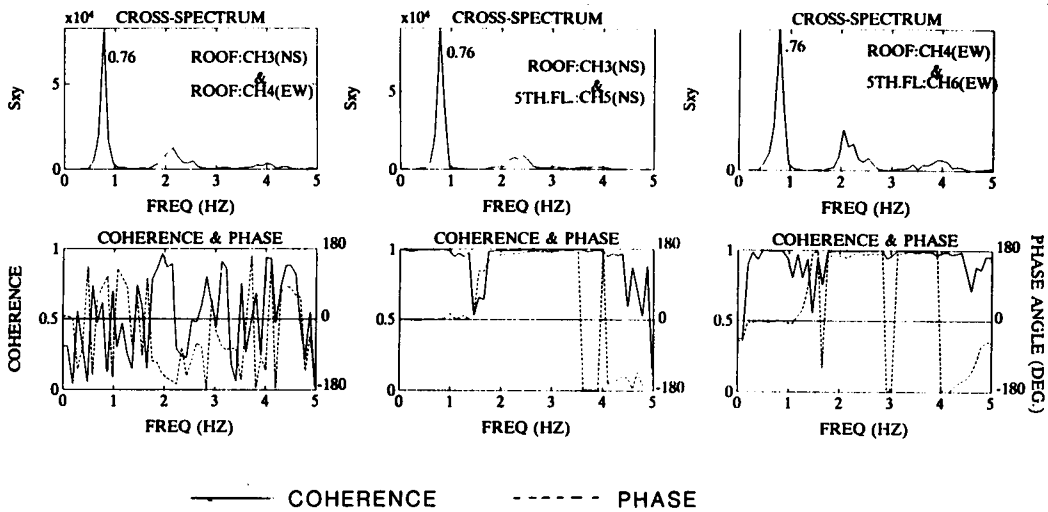

Figure 9. Cross-spectra and coherence function and phase angle plots

0·76 Hz (1·32 s) for both NS and EW directions. This similarity in translational frequency raises the possibility of a torsional–translational model at this frequency; however, a coherency plot of the two orthogonal motions (Channels 3 and 4) at the roof does not give credibility to torsional response at this frequency. As can be seen in Figure 9, the coherence at 0·76 Hz is low and the phase angle is not 0° or 180°. On the other hand, coherency between the two parallel motions at the roof and 5th floor (for both NS and EW directions) is unity and the phase angles are 0° for 0·76 Hz, implying a translational fundamental mode at that frequency. The changes in phase angles for the second and third modal frequencies are also noted in Figure 9.

Figure 10 shows time-histories and amplitude spectra of ambient vibration response at roof level recorded after the LPE. The identified frequencies (periods) are 0·92 Hz (1·09 s) in the NS direction and 0·86 Hz (1·16 s) in the EW direction. Note again that there is a difference in system sensitivity for the two NS data channels at roof level and that the ambient vibration data obtained in this study are expressed in microvolts rather than as a percentage of g. Damping percentages derived by low-pass filtering and auto-correlation techniques were 0·6% of critical for both directions. This process is illustrated in Figure 11.

3.2. Other data and analyses results

3.2.1. Prior test results for TRA and PPP. As indicated previously, the pre-LPE low-amplitude test results for both TRA and PPP are summarized in Table II. For TRA, the frequencies from the pre- and post-LPE low-amplitude tests are in good agreement (0·34 versus 0·34 and 0·32 Hz), and are larger than the LPE frequency (0·28 Hz). For PPP, the post-LPE frequency (0·48 Hz) is smaller than the pre-LPE frequency (0·59 Hz), but both are larger than the LPE frequency (0·38 Hz).

3.2.2. Other earthquakes recorded at SCCOB. In addition to the LPE response data of SCCOB (Figure 3), response data from the Morgan Hill,[12] California (1984) and the Mt. Lewis, California

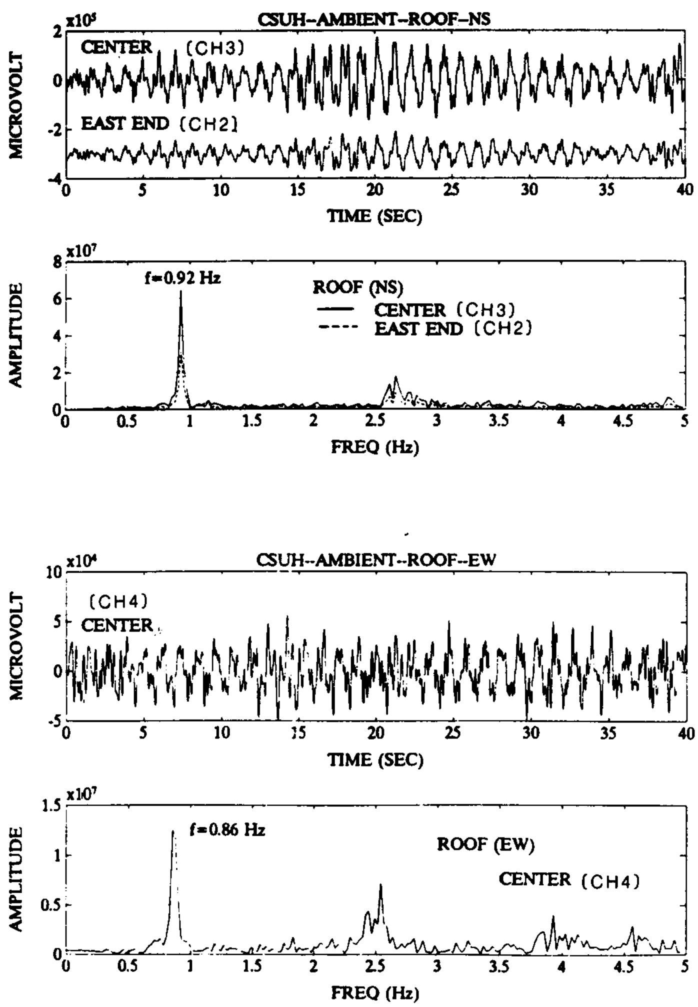

Figure 10. Ambient vibration response of roof (NS and EW directions) for CSUH administration building and corresponding Fourier amplitude spectra

earthquakes (1986) are also available (Darragh[4]). The dynamic characteristics of the building determined from each of the three earthquakes are different. Summarized in Table III are the dynamic characteristics as well as the peak accelerations at the roof and lower level of the Santa Clara county office building recorded during the three earthquakes. The dynamic characteristics were determined using the system identification process described above. It should be emphasized that the fundamental mode of this building is a translational–torsional mode. This was also noted by Boroschek *et al.*[15] It is noted that the period of the building during the Mount Lewis earthquake (1986) was smaller than that of the Morgan Hill earthquake (1984). However, the recorded peak accelerations at the roof of the building were larger for the Mount Lewis earthquake. The data sets from the three earthquakes are currently being studied in detail by the authors.

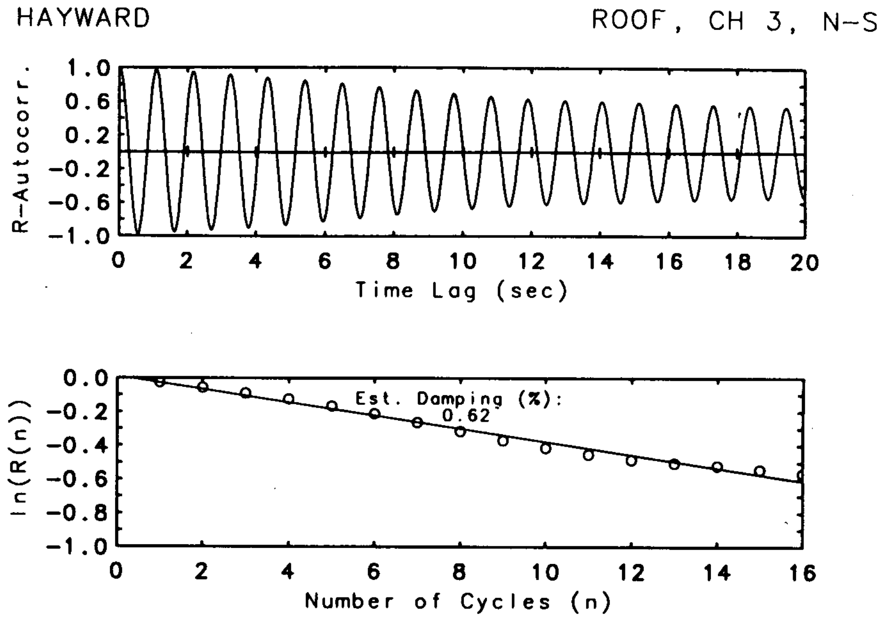

Figure 11. Auto-correlation curve and least-squares fit to amplitude decay, roof level, NS component, CSUH administration building

4. DISCUSSION AND CONCLUSIONS

Ambient testing of permanently-instrumented structures using a digital data acquisition system has been described. The results of the analyses of the data for the fundamental modes in terms of frequency (or period) and the corresponding percentages of critical damping for the five buildings are summarized in Table II. For TRA and PPP, results of low-amplitude tests performed prior to LPE are also included in Table II. The following discussions and conclusion are made:

- Use of permanently-installed accelerometers allows rapid and low-cost ambient testing of structures.
- In each of the five buildings tested, the first-mode periods associated with the strong-motion records are longer than those associated with the ambient vibration records. The magnitude of the difference depends on the specific building. The highest and lowest first-mode period ratios (LPE/ambient) are 1·47 and 1·14, respectively. These differences in period may be caused by several factors including: (1) possible soil–structure interaction that is more pronounced during strong-motion events than during ambient excitations (and similarly, in buildings with pile-foundations, possible pile–foundation interaction that may not occur during ambient excitation); (2) non-linear behaviour of the structure (such as micro-cracking of the concrete at the foundation or superstructure); (3) slip of steel connections; and (4) interaction of structural and non-structural elements.
- In each case, the percentage of critical damping for the first mode is smaller (by a significant margin) for the ambient data as compared to that from the strong-motion data. This is consistent with the factors cited above.
- The recorded strong-motion and ambient vibration data obtained from of the five buildings

Table II. Summary of identified first mode characteristic frequencies (f in hertz), periods (T in seconds) and damping (ζ)

Building	Nominal direction	Pre-LPE test and analyses $f/(T)$	Pre-LPE test and analyses ζ (%)	LPE data $f/(T)$†	LPE data ζ (%)	Post-LPE ambient $f/(T)$	Post-LPE ambient ζ (%)	Ratio (LPE/ambient) Freq.	Ratio (LPE/ambient) Period
(1) Administration building (CSUH)	NS			0·76 (1·32)	3·4	0·92 (1·09)	0·6	0·83	1·21
	EW			0·76 (1·32)	2·3	0·86 (1·16)	0·6	0·88	1·14
(2) Santa Clara county office-building, San Jose, California	NS			0·45 (2·22)	2·7	0·52 (1·92)	‡	0·87	1·16
	EW			0·45 (2·22)	2·7	0·52 (1·92)	‡	0·87	1·16
(3) Commercial office building, San Bruno, California	NS			1·17 (0·85)	7·2	1·72 (0·58)	2·2	0·68	1·47
	EW			0·98 (1·02)	4·1	1·41 (0·71)	2·3	0·70	1·44
(4) Transamerica building, San Francisco, California[13]	NS	0·34 (2·94)	0·9	0·28 (3·57)§	4·9	0·34 (2·94)	0·8	0·82	1·21
	EW	0·34 (2·94)	1·4	0·28 (3·57)	2·2	0·32 (3·12)	1·4	0·88	1.14
(5) Pacific Park Plaza, Emeryville, California[14]	NS	0·59 (1·70)‖	2·6	0·38 (2·63)	11·6	0·48 (2·08)	0·6	0·79	1·26
	EW	0·59 (1·70)	2·6	0·38 (2·63)	15·5	0·48 (2·08)	3·4	0·79	1·26
	Torsion	0·59 1·70	3·8	0·38 (2·63)					

† Identified by spectral analyses.
‡ Unidentifiable due to non-stationary signal.
§ A significant rocking mode is identified at 0·5 seconds.
‖ This is a torsional–translational mode.

Table III. Peak accelerations, periods and damping at Santa Clara county office building

		Loma Prieta NS	Loma Prieta EW	Morgan Hill NS	Morgan Hill EW	Mount Lewis NS	Mount Lewis EW	Ambient NS	Ambient EW
Accelerations (g)	Roof	0·34	0·34	0·17	0·17	0·32	0·37		
	Lower Lv.	0·10	0·09	0·04	0·04	0·04	0·04		
Period, T (s)		2·22	2·22	2·17	2·17	2·08	2·08	1·92	1·92
Damping, ζ (%)		2·7		1·95		2·12		—	—

provide a unique opportunity to study the dynamic characteristics of a variety of building structures and to assess the validity of low-amplitude non-destructive testing procedures.

In conclusion, we find from the current study, which dwells upon using ambient testing techniques, that the signals vary from building to building, from site to site and, naturally, at different elevations of each building. However, the data set is very useful in identifying dynamic characteristics from low-amplitude excitations. It is clear from this study that there are significant differences between the dynamic characteristics determined from low-amplitude tests and those determined from strong-motion records. Low-amplitude test results should be used with caution, if used to predict dynamic characteristics of building structures during strong-motion events which are the basis for earthquake resistant design procedures. We do not attempt to explain in detail the reasons for these differences, which are subject matter for future papers.

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REFERENCES

1. R. M. Stephen, J. P. Hollings and J. G. Bouwkamp, 'Dynamic behavior of a multi-story pyramid shaped building', EERC Report 73-17, University Engineeering Research Center, University of California, Berkeley, California, September 1974.
2. Kinemetrics, Inc., Application Note No. 5: Transamerica Building Ambient Vibration Survey, September 1979.
3. R. M. Stephen, E. L. Wilson and N. Stander, 'Dynamic properties of a thirty-story condominium tower building', EERC Report 85-03, University Engineering Research Center, University of California, Berkeley, California, April 1985.
4. R. Darragh, State of California, Division of Mines and Geology, Strong-Motion Instrumentation Program, personal communication.
5. M. Çelebi and E. Şafak, 'Recorded seismic response of Transamerica building. Part I: Data and preliminary analysis', *ASCE J. Struct. Engng* (August 1991).
6. M. Çelebi and E. Şafak, 'Recorded seismic response of Pacific Park Plaza. Part I: Data and preliminary analysis', *ASCE J. Struct. Engng* (June 1992).
7. J. C. Anderson, V. V. Bertero and E. Miranda, 'Seismic design criteria and measured response', *Proc. ASCE Structures Congress*, San Antonio, Texas, April 1992, pp. 575–578.
8. R. D. Marshall, L. T. Phan and M. Çelebi, *Measurement of Structural Response Characteristics of Full-Scale Buildings: Comparison of Results from Strong-Motion and Ambient Vibration Records*, NISTIR, Gaithersburg, Maryland, in preparation.
9. MathWorks, Inc., *User's Guide: System Identification Toolbox for Use with Mathlab*, South Natick, Massachusetts, 1988.
10. L. Ljung, *System Identification: Theory for the User*, Prentice-Hall, 1987.
11. A. F. Shakal, M. J. Huang, C. E. Ventura, M. Reichle, C. Ventura, T. Cao, R. W. Sherburne, M. Savage, R. Darragh and C. Peterson, 'CSMIP strong-motion records from the Santa Cruz mountains (Loma Prieta), California earthquake of October 17, 1989', Report No. OSM 89-06, California Department of Conservation, Division of Mines and Geology, Office of Strong Motion Studies, November 1989.
12. CDMG, 'Processed data from the strong-motion records of the Morgan Hill earthquake of 24 April, 1984', *Report OSMS 85-05*, California Department of Conservation, Division of Mines and Geology, Office of Strong Motion Studies, December 1985.

13. E. Şafak and M. Çelebi, 'Recorded seismic response of Transamerica building. Part II: System identification', *ASCE J. Struct. Engng* (August 1991).
14. E. Şafak and M. Çelebi, 'Recorded seismic response of Pacific Park Plaza. Part II: System identification', *ASCE J. Struct. Engng* (June 1992).
15. R. L. Boroschek, S. A. Mahin and C. A. Zeris, 'Seismic response and analytical modeling of three instrumented buildings', *Proc. 4th U.S. National Conf. on Earthquake Engineering*, Palm Springs, California, May 20–24, 1990, Vol. 22, pp. 219–228.