Proceedings - Fifth U.S. National Conference on Earthquake Engineering, Earthquake Awareness and Mitigation Across the Nation, Vol. 11, 1994

FULL-SCALE MEASUREMENT OF BUILDING RESPONSE TO AMBIENT VIBRATION AND THE LOMA PRIETA EARTHQUAKE

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ABSTRACT

This paper describes the collection and analysis of ambient vibration data from five buildings in the San Francisco Bay area that experienced strong shaking during the Loma Prieta earthquake of October 17, 1989. Results of data analyses show that, while the lower modes of vibration can be reliably identified from ambient vibration records, the frequencies of these modes are in each case higher than the frequencies derived from strong-motion response records. When soil-structure interaction is involved, the strong-motion modal frequencies may range from 70 to 80 percent of the corresponding values extracted from ambient vibration records. Estimates of structural damping derived from ambient vibration data are substantially smaller than those derived from strong-motion data and are consistent with predictions of a damping model based on forced vibration tests. Where soil-structure interaction is a significant factor, the overall damping for strong-motion response may be 3 to 4 times the indicated lower bound.

Introduction

Reliable estimates of modal frequencies, stiffness and damping of structures are essential to the prediction of dynamic response under loading conditions associated with serviceability or structural safety. Analytical models for predicting dynamic response usually involve substantial simplification of the real structure and, for various reasons, physical models for laboratory testing often prove impractical. Consequently, each of these approaches must depend on reliable full-scale field measurements for validation and/or improvement of the modeling technique. Recently, it has been possible to obtain detailed response records from heavily instrumented

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buildings and other structures that experienced extreme events such as earthquakes or wind storms. Generally, these measurements suggest a strong dependence of dynamic characteristics on displacement amplitude, thus raising questions as to the utility and proper interpretation of response measurements obtained under low levels of excitation. The Loma Prieta earthquake (LPE) of October 17, 1989, provided a unique opportunity to carry out a program of field measurements and data analysis for certain existing structures to better understand the significance of factors such as displacement amplitude in full-scale response measurements and the proper interpretation of such measurements.

The study described herein involved the selection of a number of buildings that were subjected to strong ground shaking during the LPE and for which reliable response records were available. Ambient vibration data were then obtained from the selected buildings and the dynamic characteristics derived from the two sets of data were compared. Damping estimates were compared with model predictions for low levels of excitation and for strong-motion response. The extent to which reliance can be placed on low-amplitude response measurements and their utility in predicting strong-motion response characteristics were examined.

Selection of Buildings

A total of five buildings were selected for the study from a large number of candidate structures affected by the LPE (see Marshall et al, 1992 for building locations, building details and instrumentation schemes). Brief descriptions and pictures of each building are given below.

The 13-story California State University Administration Building at Hayward (CSUH) was instrumented by the California Division of Mines and Geology (CDMG). The structural system consists of a perimeter reinforced concrete (RC) moment-frame, concrete shear walls around the elevator shafts up to the 2nd floor, and a steel moment-frame core above the 2nd-floor level. The foundation consists of a 0.45 m slab on grade and bearing piles.

The Transamerica building is a pyramid-shaped steel frame building with 60 floors above ground and 3 floors below, instrumented by

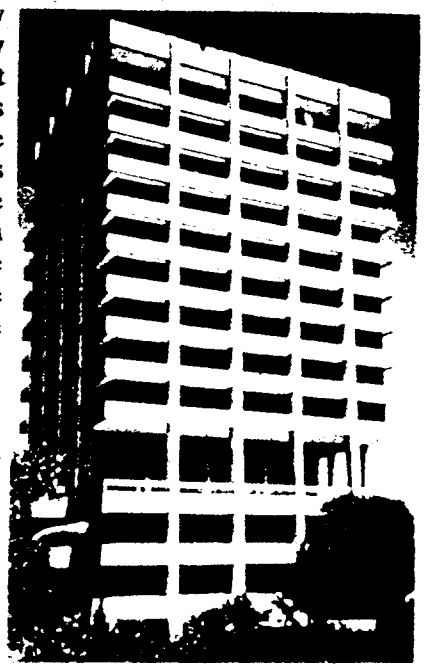

Figure 1. CSUH Building

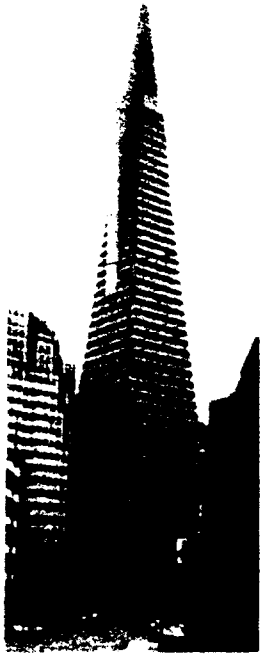

Figure 2. Transamerica Bldg.

Figure 3. San Bruno Commercial Office Building

Figure 4. Santa Clara Building

USGS. The building dimensions are 257.3 m height and 53 m by 53 m at the base. The foundation is a 2.74 m thick concrete mat.

The 6-story San Bruno Commercial Office Building was instrumented by CDMG and contains precast, post-tensioned floor beams acting integrally with the floor slabs. The perimeter columns are cast in cavities formed by the precast wall panels. A heavily reinforced E-W interior frame is located 4.88 m south of the geometric center of the building. This eccentricity introduces a twisting component to the E-W response. The foundation consists of individual spread footings located just below the ground floor which is a slab on grade.

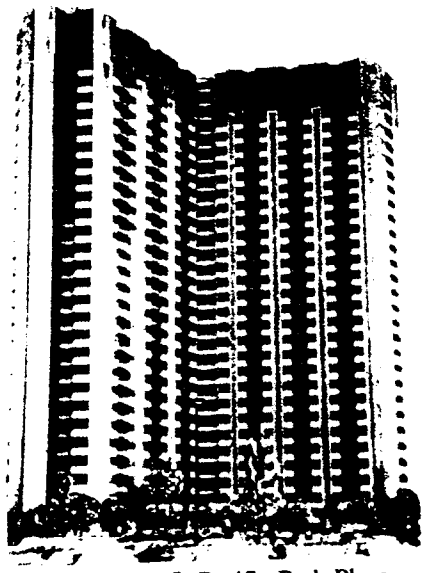

Figure 5. Pacific Park Plaza

The Santa Clara County Office Building is a 12-story moment-resisting steel frame structure with a concrete mat foundation, instrumented by CDMG. The building has a basic square planform with elevator and stair towers on the south and west faces.

Pacific Park Plaza is a 30-story RC moment-frame/shear-wall structure consisting of a central core and three wings with angular spacing of 120 degrees, instrumented by USGS. The foundation consists of a 1.52 m RC mat on friction piles driven along the column lines.

Building Vibration Recordings and Analyses of Data

Both the recorded strong-motion and the ambient vibration responses were analyzed to identify relevant dynamic characteristics and to provide a basis for comparison of these characteristics. Throughout this paper, unless otherwise stated, response records have been analyzed by system identification techniques [MathWorks, 1988] or by conventional spectral

analysis methods [Brook and Wynne, 1988] using commercially-available software.

Strong Motion Records

The instrumentation of each building consists of force balance accelerometers (FBA) having a nominal sensitivity of 2.5 volts/g. Recording was accomplished by means of strip-film recorders triggered by vertically-oriented accelerometers located on the base slab of the building. Peak accelerations, displacements, and estimated mean peak-to-peak displacements (MPPD) for the five buildings can be found in Marshall et al. [1992].

Examples of the analysis of strong motion data for the CSUH building are shown in Figure 6. Shown in this figure are roof-level accelerations calculated by system identification techniques with N-S and E-W basement-level accelerations as input, along with the Fourier amplitude spectra. The fundamental N-S translational mode is clearly identified at 0.76 Hz and higher modes are apparent at 2.31 and 4.02 Hz. Analyses of the records from the lower floors showed the spectral peak at 2.31 Hz to be associated with the 2nd translational mode.

The 1st and 2nd E-W translational modes are centered at 0.76 and 2.28 Hz, respectively, and a higher mode occurs at 3.81 Hz. Identical frequencies for the N-S and E-W 1st translational modes suggest the possibility of a torsional component, although this could not be confirmed from the records available for analysis. The pronounced peak at 3.81 Hz is apparent at each instrumented floor level and is the predominant frequency at the first floor level.

Ambient Vibration Measurements

The ambient vibration measurements were carried out using the existing FBA array. The digital data acquisition system was equipped with 16 sample-and-hold amplifiers and sampling was carried out at a net rate of 50 samples per second for each data channel. The recorded data and all subsequent analyses retained the units of microvolts, referred to transducer output. For those buildings having more than 16 accelerometers, it was necessary to repeat recordings using different accelerometer combinations. Typically, record lengths were 200 seconds.

Examples of the analysis of ambient vibration data for the CSUH building are shown in Figure 7, which includes ambient vibration response records and Fourier amplitude spectra at roof level for the N-S and E-W directions. The 1st and 2nd N-S translational modes are centered at 0.92 and 2.71 Hz, respectively. In the E-W direction spectral peaks occur at 0.86, 2.44 and 2.54 Hz with a lesser peak at 3.95 Hz. The first two peaks are believed to represent the 1st and 2nd translational modes, based on spectra obtained from lower floors.

Estimates of structural damping were obtained from the ambient vibration records using selective filtering and auto-correlation techniques. A typical auto-correlation curve and least-squares fit to the amplitude decay are shown in Figure 8.

Discussion of First-Mode Responses of Selected Buildings

Results of the response analyses are summarized in Table 1. Also included are the

observed 1st-mode frequency ratios, f_{LPE}/f_{Amb}, damping ratios computed using the ESDU (1983) model for small displacements and the upper limits of damping ratios according to ESDU model.

Frequency Ratios

From Table 1 it is seen that the CSUH Administration Building, Santa Clara County Office Building, and the Transamerica Building all have similar frequency ratios, averaging about 0.86. The first building has a steel moment-frame core and the others are purely steel frame structures. The average frequency ratios for Pacific Park Plaza and the San Bruno Office Building are 0.79 and 0.69, respectively. If the reductions in resonance frequency with displacement amplitude are attributed entirely to changes in structural stiffness, these stiffness changes are then approximately equal to the square of the frequency ratio. This "stiffness" ratio ranges from a low of 0.48 for the 6-story San Bruno Office Building (N-S) to a high of 0.77 for the CSUH Administration Building and the Transamerica Building.

The mean frequency ratio of 0.69 for the San Bruno Office Building can in large part be attributed to vertical motions of the individual spread footings [Phan et.al, 1992]. The frequency ratio of 0.79 for Pacific Park Plaza can also be attributed, at least in part, to soil-structure interaction [Çelebi et al, 1992, and Şafak et al, 1992]. Other factors that could have contributed to the relatively large changes in 1st-mode frequencies of these two concrete buildings include micro-cracking of the concrete, although no visible damage was experienced in either structure, and possibly joint slip in the precast wall panels (at perimeter columns of San Bruno building).

Damping Estimates

Estimates of structural damping (percent of critical) for the first translational modes (Table 1) are compared with the ESDU damping model for small amplitude displacements. Also included for comparison are the forced vibration test results for the precast concrete panel buildings tested by Ellis and Littler (1988). The damping estimates based on ambient vibration data are plotted against the corresponding 1st-mode translational frequencies in Figure 8. It can be seen from Figure 9 that, with the exception of the Transamerica Building and the anomalous estimate for Pacific Park Plaza, the estimates of structural damping obtained from ambient vibration records are reasonably consistent with those values covered by the ESDU small amplitude range. Estimates derived from the Transamerica ambient vibration records are consistently higher than the recommended range and this may be due to the gusty wind conditions prevailing at the time of the ambient vibration survey. As expected, the damping estimates derived from the LPE response records for the five buildings in this study exceed the ESDU upper-limit damping ratio in every case.

For large amplitude displacements, a summary of damping estimates and corresponding amplitudes of vibration for 165 buildings has been prepared by Davenport and Hill-Carroll (1986). These data are represented by the envelope shown in Figure 10 with the displacements plotted in terms of the rms amplitude divided by the height of the structure. The upper region of the envelope represents buildings of up to 10 stories in height while the lower region of the envelope represents data obtained from buildings of 20 stories or more in height. Damping estimates obtained from the strong-motion records for the five buildings in the current study are

TABLE 1. SUMMARY OF RESULTS OF ANALYSIS FOR 1ST-MODE RESPONSE

Building	Nominal Direction	Height H (m)	Loma Prieta Earthquake f(Hz)	Loma Prieta Earthquake ζ(%)	Ambient Vibration f(Hz)	Ambient Vibration ζ(%)*	Frequency Ratio (f_{LPE}/f_{Amb})	ESDU Small Amplitude Range ζ=f/K(%)	ESDU Upper Limit ζ=60/(100 x H)(%)
(1) CSUH Admin. Building	N-S	61	0.76	3.4	0.92	0.6	0.83	0.37 - 1.53	2.28
	E-W		0.76	2.3	0.86	0.6	0.88	0.34 - 1.43	2.28
(2) Santa Clara County Office Building	N-S	57	0.45	2.7	0.52	**	0.87	0.21 - 0.87	2.35
	E-W		0.45	2.7	0.52	**	0.87	0.21 - 0.87	2.35
(3) San Bruno Office Building	N-S	24	1.17	7.2	1.72	2.2	0.68	0.69 - 2.87	3.80
	E-W		0.98	4.1	1.41	2.3	0.70	0.56 - 2.35	3.80
(4) Transamerica Building	N-S	257	0.28	4.9	0.34	0.8	0.82	0.14 - 0.57	1.53
	E-W		0.28	2.2	0.32	1.4	0.88	0.13 - 0.53	1.53
(5) Pacific Park Plaza	N-S	94	0.38	11.6	0.48	0.6	0.79	0.19 - 0.80	1.94
	E-W		0.38	15.5	0.48	3.4	0.79	0.19 - 0.80	1.94
(6) Panelized Concrete Building [Ellis and Littler, 1988]	N-S	64				1.05		0.46 - 1.90	2.24
	E-W					0.76		0.37 - 1.55	2.24

* Determined by auto-correlation technique

** Unidentifiable due to combined modes

The range of K between 60 and 250 includes 90 percent of the data used to formulate the ESDU model.

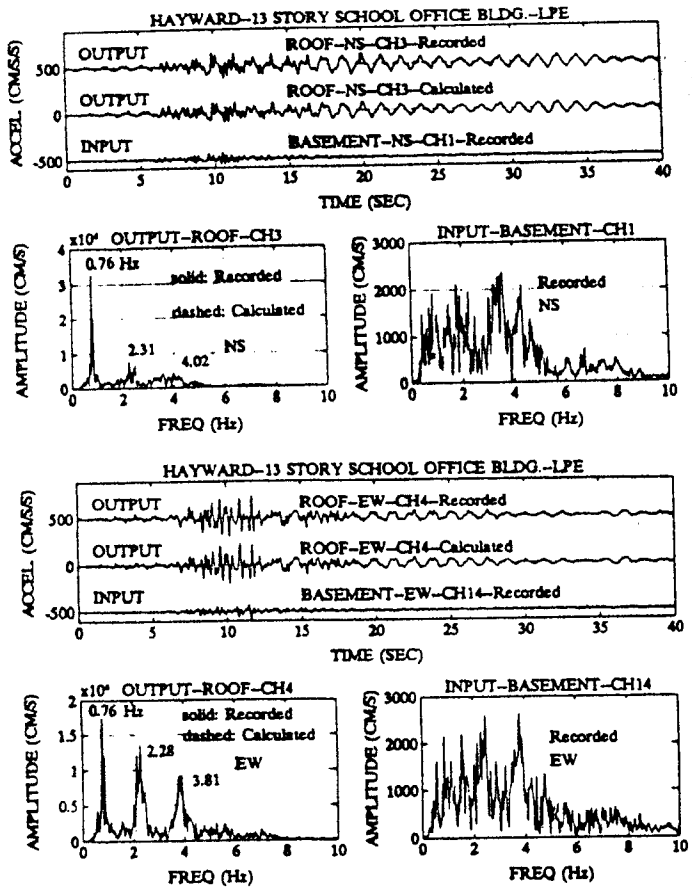

Figure 6. Recorded and Calculated Roof-Level Acceleration and Fourier Amplitude Spectra, CSUH Building.

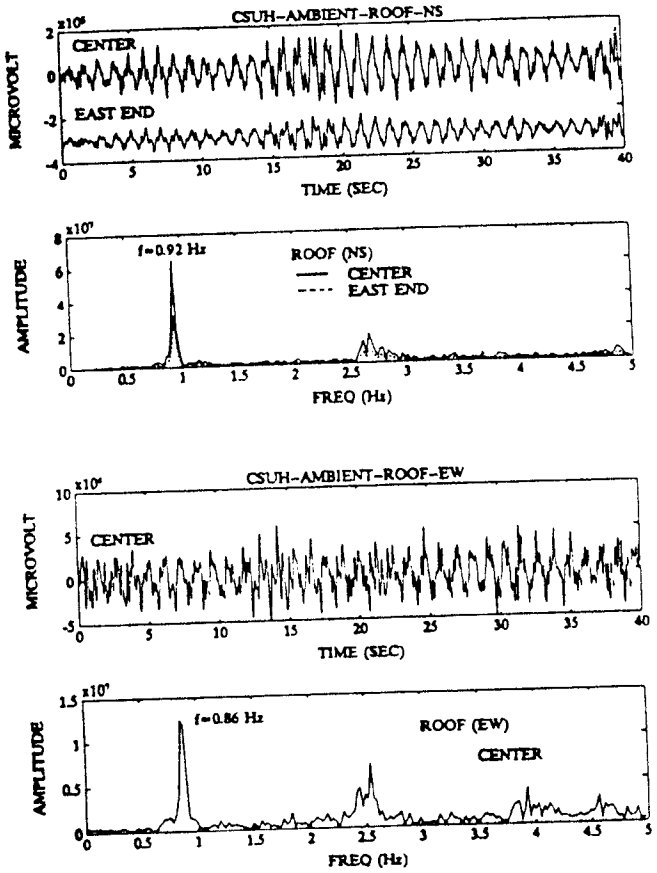

Figure 7. Ambient Vibration Response at Roof-Level Acceleration and Fourier Amplitude Spectra, CSUH Building

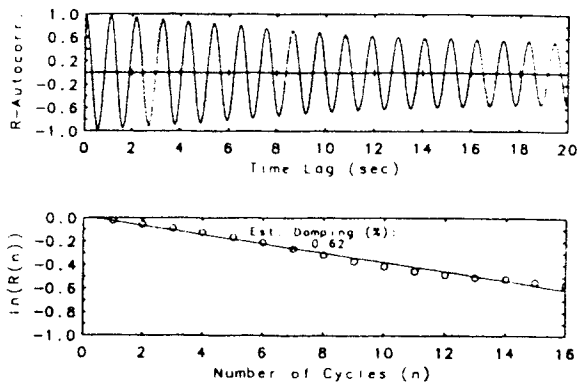

Figure 8. Auto-correlation Curve and Least -Squares Fit to Amplitude Decay, Roof Level, N-S

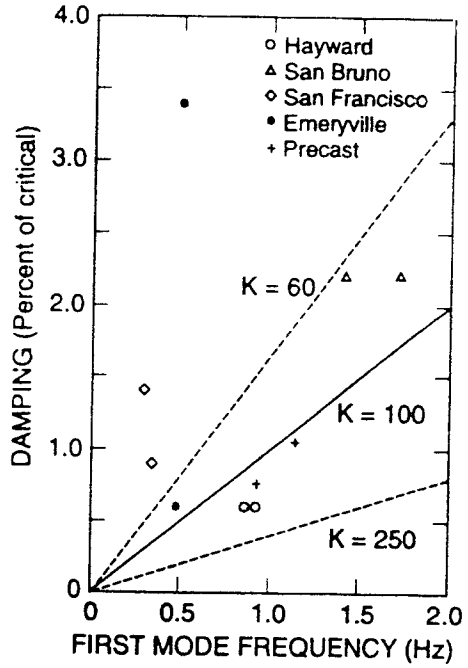

Figure 9. Ambient Vibration Damping Estimates vs. 1st-Mode Frequency

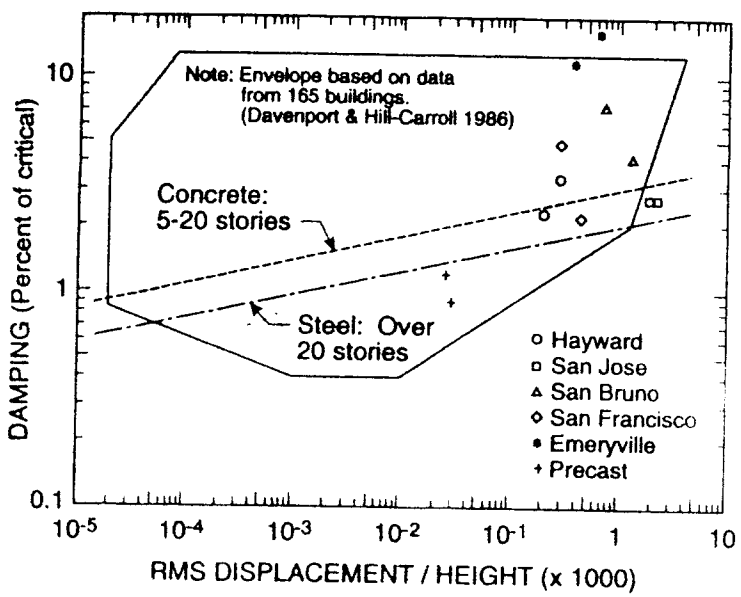

Figure 10. Strong-Motion Damping Estimates vs. rms Displacement Ratio

plotted in Figure 10 using estimates of the mean peak-to-peak amplitudes, averaged over several cycles and converted to rms amplitude by multiplying by 0.707/2. Also plotted in Figure 10 are the largest damping ratios for the forced vibration data by Ellis and Littler (1988). It is seen from Figure 10 that the regression lines in the above analysis represent a reasonable lower bound to the strong-motion damping estimates obtained for the five selected buildings.

Summary and Conclusions

Ambient vibration records were obtained from five buildings in the San Francisco Bay area following the Loma Prieta earthquake of October 17, 1989. Digital signal processing was performed on both ambient vibration and LPE response records with the objective of determining to what degree dynamic characteristics derived from ambient vibration data represent those characteristics associated with strong-motion response. Both conventional spectral analysis and system identification techniques were employed in the processing of response records. The following conclusions are drawn from this study:

- With proper signal conditioning, the sensitivity and signal-to-noise ratio of conventional FBA are sufficient to obtain reliable ambient vibration measurements.

- Ambient vibration data can be used to identify the first two or three modes of vibration without difficulty. However, there is a need for the development of comprehensive requirements for the assessment of dynamic characteristics of buildings and other structures by means of ambient and forced vibration tests.

- First-mode frequency ratios, f_{LPE}/f_{Amb}, for the five buildings included in this study range from a high of 0.88 to a low of 0.68.

- Strong-motion records for the two buildings exhibiting the lowest 1st-mode frequency ratios contain identifiable soil resonance frequencies; 0.76 Hz in the case of the San Bruno Commercial Office Building and 0.7 Hz in the case of Pacific Park Plaza, suggesting some effect from soil-structure interaction.

- Results of this study suggest that the frequencies of the 1st translational modes obtained from ambient vibration studies should be multiplied by a factor of from 0.8 to 0.9 to estimate the corresponding strong-motion frequencies. For those cases where soil-structure interaction plays a significant role, this factor may range from 0.7 to 0.8.

- For all five buildings, the damping ratios estimated from the LPE response records, either by system identification techniques or by auto-correlation techniques, are always higher than those ratios estimated from ambient vibration records.

- In general, estimates of the structural damping ratio (percent of critical) obtained in this study of ambient vibration records are consistent with published results of forced vibration tests (ESDU 1983) which can be described by the expression

$$\zeta_{\infty} = f/K$$

where f is the 1st-mode translational frequency and K is a factor ranges from 60 to 250.

- The lower bound for estimates of structural damping ratio obtained from Loma Prieta response records for which $\delta_{rms}/H \times 1000 > 0.1$ can be described by the relation

$$\zeta_s = 0.025(\delta_{rms}/H \times 1000)^{0.11}$$

in which δ_{rms}/H is the rms displacement at roof level divided by the building height.

- For buildings in which soil-structure interaction is a significant factor, the overall damping for strong-motion response may be 3 to 4 times the indicated lower bound.

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