STRONG MOTION INSTRUMENTATION OF A 62-STORY CONCRETE CORE RESIDENTIAL BUILDING IN SAN FRANCISCO

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Abstract

The One Rincon Hill Tower in San Francisco is the tallest concrete core shear wall structure in California. After completion of the construction, the building was extensively instrumented in 2012 with 72 sensors in a joint effort by the California Strong Motion Instrumentation Program of the California Geological Survey and the National Strong Motion Program of the U.S. Geological Survey. This paper describes the sensor locations in the building and the instrumentation objectives. Data of the building ambient vibration obtained by the instrumentation system and results of preliminary analysis are also presented and discussed.

Introduction

The One Rincon Hill Tower (south tower of a complex including two towers and pavilion) is a 62-story concrete core shear wall structure located in downtown San Francisco. The tower with 376 condominium homes was designed in 2004 and the construction was completed in 2008 (Figure 1). The building height from the foundation to the roof is about 618 feet which exceeds the 240 feet limit specified in the code for a typical concrete shear wall structure. The structural and architectural systems of the building were designed according to the 2001 San Francisco Building Code and based on performance-based seismic design (Klemencic et al., 2006 and Klemencic, 2008). However, the design was also peer-reviewed because of its uniqueness.

A special feature in the structural design is the use of outrigger columns connected to core shear walls with steel buckling-restrained braces (BRBs). In addition, the building is equipped with two water tanks (about 5' tall) located between Level 62 and 63 (Post, 2008 and 2012). These water tanks are designed to act as liquid tuned mass damper in order to reduce the sway from strong winds. These are predominately used to enhance human comfort from frequent wind storms with return periods of 1 to 10 years. One Rincon Tower is the first building in California to have a liquid tuned mass damper.

Figure 1. Views of the One Rincon Hill Tower from the street and from a neighboring high-rise building in downtown San Francisco. (photos by M. Huang)

Building Structure System

Vertical Load Carrying System

The vertical load carrying system of the building consists of concrete flat slabs supported by concrete columns and core shear walls. Typical residential floors are 8" thick post-tensioned slabs spanning between the center core and perimeter concrete columns. Post-tensioned tendons used in the concrete slabs are 0.5" in diameter (7-wire strand) with an ultimate tensile strength of 270 ksi. The floor slab at the center core is typically 12" thick.

The floor plan is rectangular at the Base Level with a footprint of about 113' by 137'. A curved outer facade is located on the west side between the 7th Level and upper levels. Below the 7th Level, concrete shear walls surround the building.

The maximum size of the outrigger columns is 2'-8" by 7'-6" at the Base Level. All reinforcement used in seismic resisting elements is in conformity with the ASTM A-706, Grade 60 standards. The minimum ultimate compressive strength of the concrete at 28 days is 5000 psi for the basement walls and foundation walls. The concrete strength at 56 days is 5500 psi for post-tensioned floor slabs and varying between 6000 and 8000 psi for columns and shear walls.

Lateral Force Resisting System

The lateral force resisting system of the building is comprised of a concrete ductile core wall system with added concrete outrigger columns in the transverse direction. An isometric view of the lateral force resisting system is shown in Figure 2. The core wall system is arranged in the form of perforated structural tube. The outrigger columns are connected to the core with steel buckling-restrained braces at two locations and terminate at Level 55. Lateral forces are carried by the floor diaphragms to the shear walls. Moments and shear forces are delivered to the foundation by the shear walls.

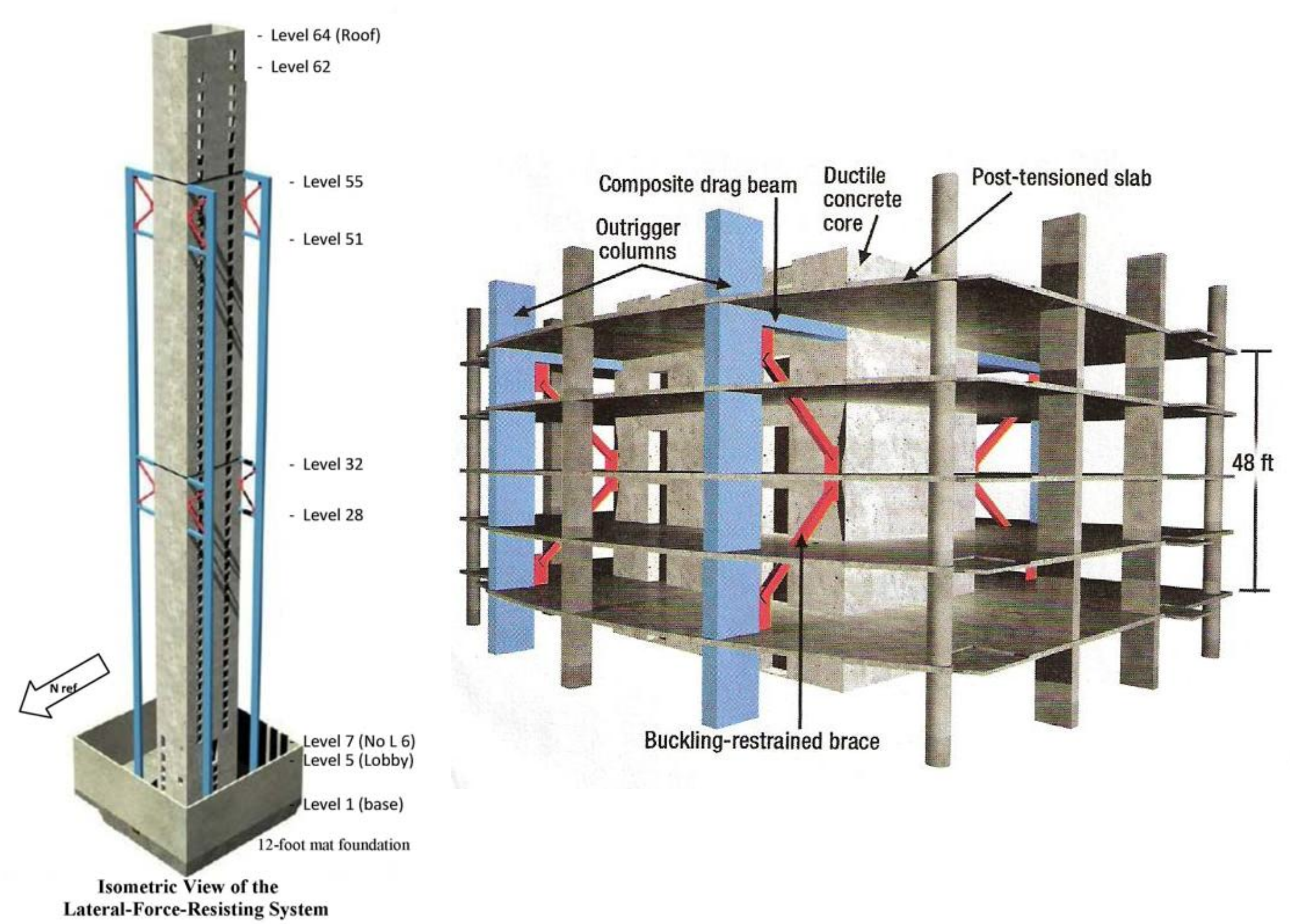

Figure 2. Lateral force resisting system of One Rincon Hill Tower and the outrigger systems. (from Klemencic et al., 2006)

In addition, the building has two water tanks located on the very top of the building. These tanks were designed to reduce sway from powerful Pacific winds by acting as tuned mass dampers. Conceptually, the presence of a tuned liquid damper allows the inertia of a great mass to be balanced by a comparatively lightweight tank of liquid in such a way that the liquid moves in one direction as the structure moves in the other, thus damping the structure's oscillation.

The seismic design methodologies for the One Rincon Hill Tower follow a path similar to previous performance-based design lateral systems in San Francisco. The goal of the seismic design is to ensure that the overall building behavior meets stated performance objectives at two different levels of anticipated seismic demand (DBE and MCE). The design of the lateral force resisting system follows a two-step process. First is the elastic analysis and design considering the wind loads and the DBE level earthquake forces. The second stage is comprised of nonlinear response analysis using strong-motion records scaled to the MCE ground shaking.

According to the structural plans, key design parameters of the building are as follows:

- Live loads for typical floors were taken as 40 psf and 25 psf for the roof, while partition dead load was assumed as 20 psf.
- Equivalent static force analysis was conducted based on Site Class B soil condition with the following lateral load coefficients: Zone 4; I = 1.0; Na = 1.0; Nv = 1.04. The response reduction factor was taken as 4.5 for the structural system composed of shear wall/bearing wall.
- Wind loads were computed based on wind tunnel testing conducted at the University of Western Ontario, Canada. Peak building wind acceleration was limited to 20 mg considering a 10-year return period for the input wind forcing function.
- Site specific response spectra were developed for both the DBE and MCE earthquake levels. The code-based elastic design was only performed for the DBE earthquake level.
- The time history records were selected and scaled to be consistent with the site-specific MCE response spectrum. Seven pairs of ground motions were used in the nonlinear response analysis.

The building meets the code-specified drift limits for the nonlinear analysis. The nonlinear seismic behavior of the structure is governed by coupling beam flexural behavior and flexural yielding of the wall near the Ground Level. Other potential mechanisms and actions are verified to remain elastic under the forces corresponding to the nonlinear time history analysis. These actions include wall shear, wall flexure outside of the intended hinge zone, foundation and diaphragms (Klemencic et al., 2006).

Foundation

The site of the One Rincon Hill Tower is underlain by Franciscan rock. According to the soil report (Treadwell & Rollo, 2004), the allowable bearing pressure is 30 ksf. The foundation of the building consists of a 12' thick massive mat foundation embedded into deep serpentine rock. Foundation design and analysis were carried out using a finite element method (Winkler-Foundation method). Demands on the mat foundation were determined through the nonlinear analysis.

Strong-Motion Instrumentation

The planning for the instrumentation of the One Rincon Hill Tower began in 2007. The permission of instrumentation was successfully obtained by CGS/CSMIP from the construction project manager and the developer in 2007. In general, instrumentation of a building involves the installation of accelerometers or other sensors at key locations throughout the structure. The number and location of sensors determines the amount of information that may be recovered about the response of the building after an earthquake. Sensors installed at key structural members allow the important modes of vibration to be recorded and specific measurement objectives to be achieved.

Target locations for 36 accelerometers in the One Rincon Hill Tower were initially developed by CSMIP engineering staff after studying the lateral force resisting systems from the structural plans. At the request of the Developer and the Project Manager, the sensors could not be installed inside any residential units. Therefore, the sensors could only be installed in the central core. The sensor locations developed were then reviewed by the structural engineer of record and representative members of the CSMIP Strong Motion Instrumentation Advisory Committee. CSMIP staff marked these sensor locations and started field installation in May 2008. However, the field installation was stalled due to electrical union requirements. Furthermore, the sensors in the stair wells of the center core had to be re-located by requirement of the City Fire Department.

In 2011, USGS/NSMP expressed interest in joining in the instrumentation of the building. Through the efforts and cooperation of upper management of CGS and USGS, the permission for joint instrumentation by CGS and USGS was secured from the Home Owner Association. The original 36 sensors and their locations were augmented with additional sensors from the USGS/NSMP. The instrumentation of the building was completed in May 2012.

The final instrumentation plan includes 72 accelerometers in the One Rincon Hill Tower. The locations of these 72 sensors are shown in Figure 3. Each of the 72 sensors is connected via cabling to one of three central recorders. The digital recorders coupled with a communication system allow the recording system to immediately send the data to the CSMIP office in Sacramento after the system is triggered by an earthquake. In addition, continuous, real-time data transmission to the USGS/NSMP office in Menlo Park is under development. Due to the congested built environment around the Tower, no instrument has been installed at a nearby site to measure the reference ground motion for the building.

The building description and the sensor layout for the building are included in the Center for Engineering Strong Motion Data (CESMD) at http://www.strongmotioncenter.org Strong-motion data from this building as well as other buildings will be available immediately after a significant earthquake. Data from previous earthquakes are also archived at the CESMD Data Center.

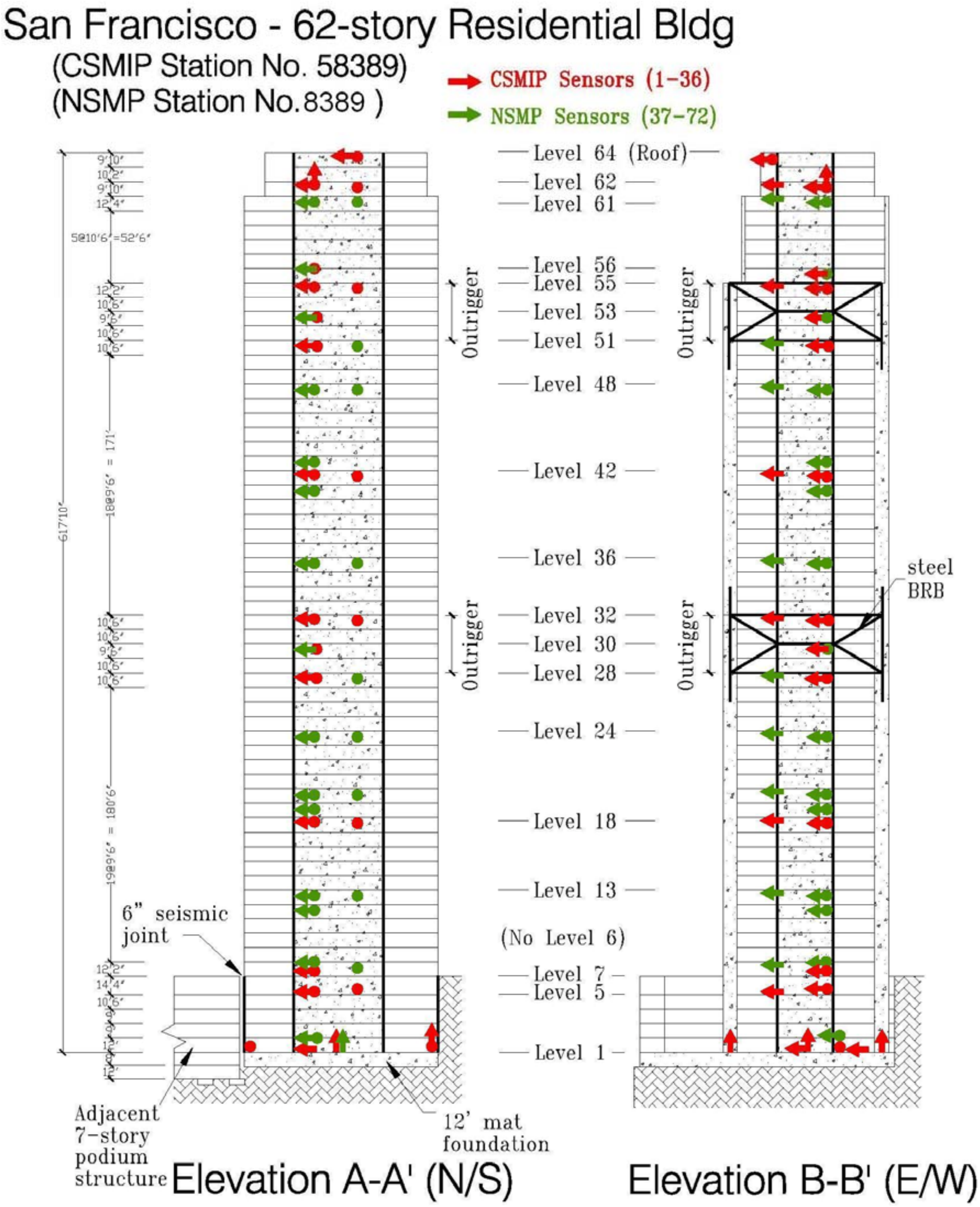

Figure 3. Elevation views showing the locations of the 72 sensors installed in One Rincon Hill Tower. (Arrows indicate sensing direction; solid circles indicated out of the page.

The primary objective of instrumentation for this building is to measure sufficient seismic data so that the response of the building to earthquake ground shaking can be studied. Although there are limitations on the locations for the sensors, in general, the more sensors that are installed, the more information that can be obtained.

The building foundation is a concrete mat with a thickness of 12 feet under the core shear walls. The motions of this rigid concrete mat are measured by six sensors including three horizontal and three vertical sensors. As shown in Figure 3, these six sensors were installed at strategic locations at Level 1 so the six components of rigid body motions can be determined or computed from these sensors. These six components include three translational motions and three rotational motions (i.e., two rocking and one torsional) of the building base.

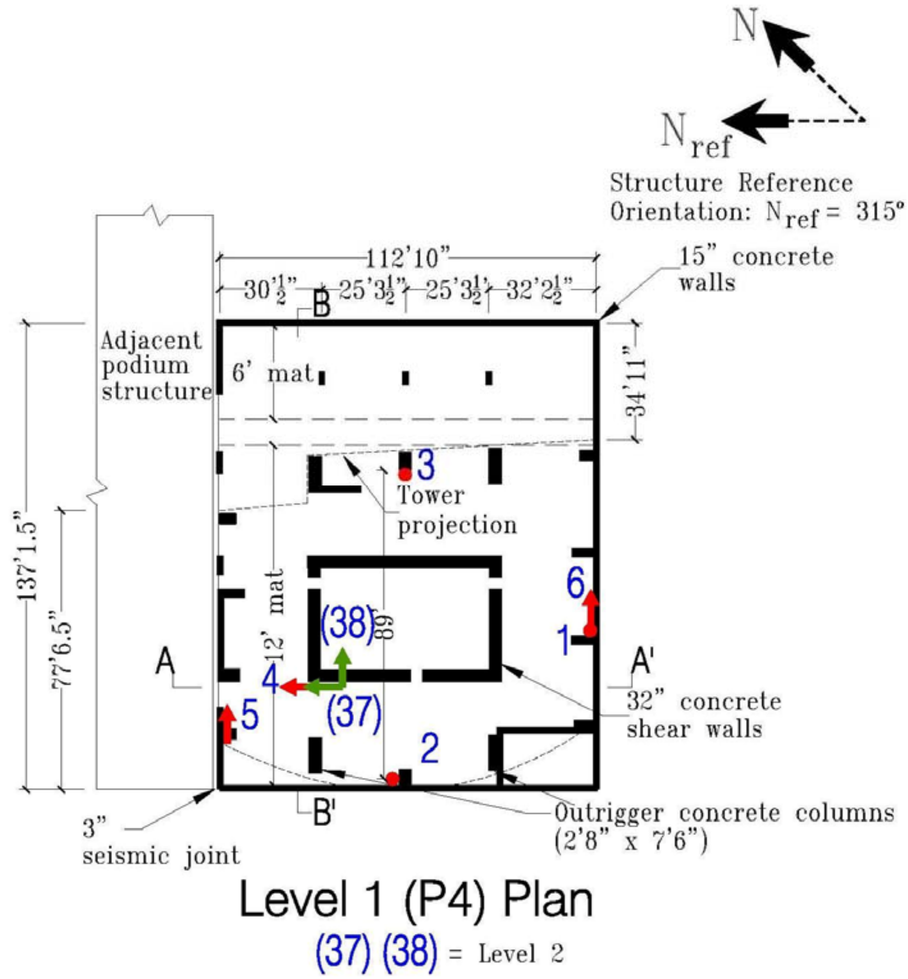

Figure 4. Sensor Locations at Level 1 to measure translational and rotational motions of the concrete mat foundation.

The remaining sixty-six sensors were installed in the upper stories of the superstructure. Sixty five sensors measure the lateral motions at 25 floor levels and one sensor measures the vertical motion at Level 62, which supports the water tanks. These sensors are located at the floors where seismic force resisting elements are changed or where the plan setbacks occur. Specifically, these floors are Level 5, 18, 28, 32, 42, 51, 55, 61, and 62 (Figure 3). These levels are instrumented with 3 sensors to measure the translational and torsional motions of the floor. Level 64 (roof) with only floor slab at the center core is instrumented with 2 sensors (Figure 5). Levels 8, 13, 20, 24, 36, and 48 are also instrumented with three sensors allowing better determination of the mode shapes. The remaining nine levels (Levels 2, 7, 12, 19, 30, 41, 43, 53, and 56) are instrumented with two sensors only. Consecutive floor instrumentation allows direct computation, without interpolation, of the inter-story drift from the data recorded at the two adjacent floors. Figure 6 shows the sensor locations at Levels 28, 30 and 32 at the lower outrigger beam connection. Similar sensor locations also occur at Levels 51, 53 and 55, at the upper outrigger beam connection.

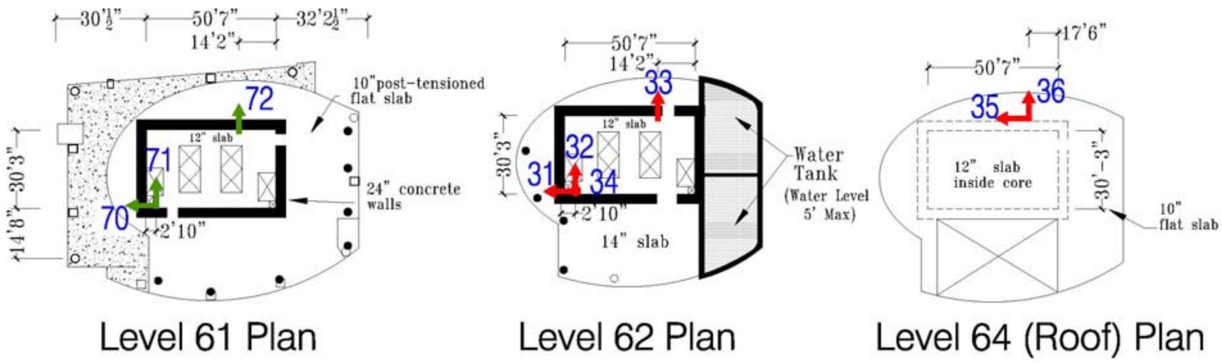

Figure 5. Sensor Locations at Levels 61, 62 (with water tank) and 64 (roof).

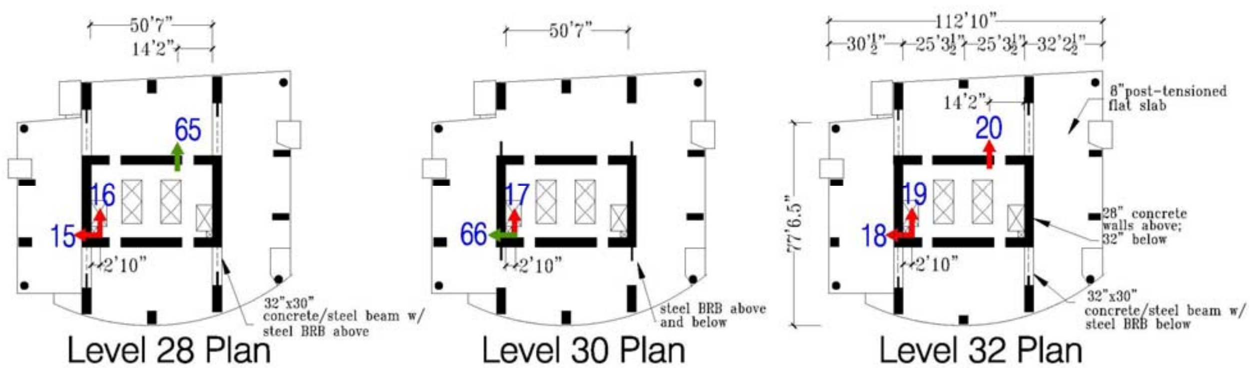

Figure 6. Sensor Locations at Lower Outrigger Frame connections at Levels 28, 30 and 32.

The records from this instrumentation will provide information on the input base motion and the response of the structure at different levels. Key parameters of the structural response, including modal periods and damping ratios for the first few modes, the base shear, inter-story drifts, and base rocking motion can be computed from the records.

Ambient Vibration Data

After the instrumentation in the building was completed, several sets of ambient data were taken by manually triggering the system. Each set of ambient data has duration of 2 to 5 minutes. The sampling rate is 200 samples per second. With all the data from 72 sensors, each set has a significant amount of data. More rigorous analyses of these sets of ambient data can be performed by using detailed system identification methods to obtain modal frequencies and mode shapes. The results of a collaborative study are presented in a separate paper (Celebi et al, 2012).

Simple analyses can be performed on the ambient data from any upper floors to obtain modal frequencies. For discussions in this paper, only one set of ambient data (about 2 minutes long), from three sensors (Channels 31, 32 and 33) at Level 62 are considered. The acceleration time history data from these three channels are shown in Figure 7. The accelerometers installed in the building can record motions with frequencies from zero to 100 Hz. The accelerations are dominated by extremely high frequencies and the building fundamental motions are embedded in the records.

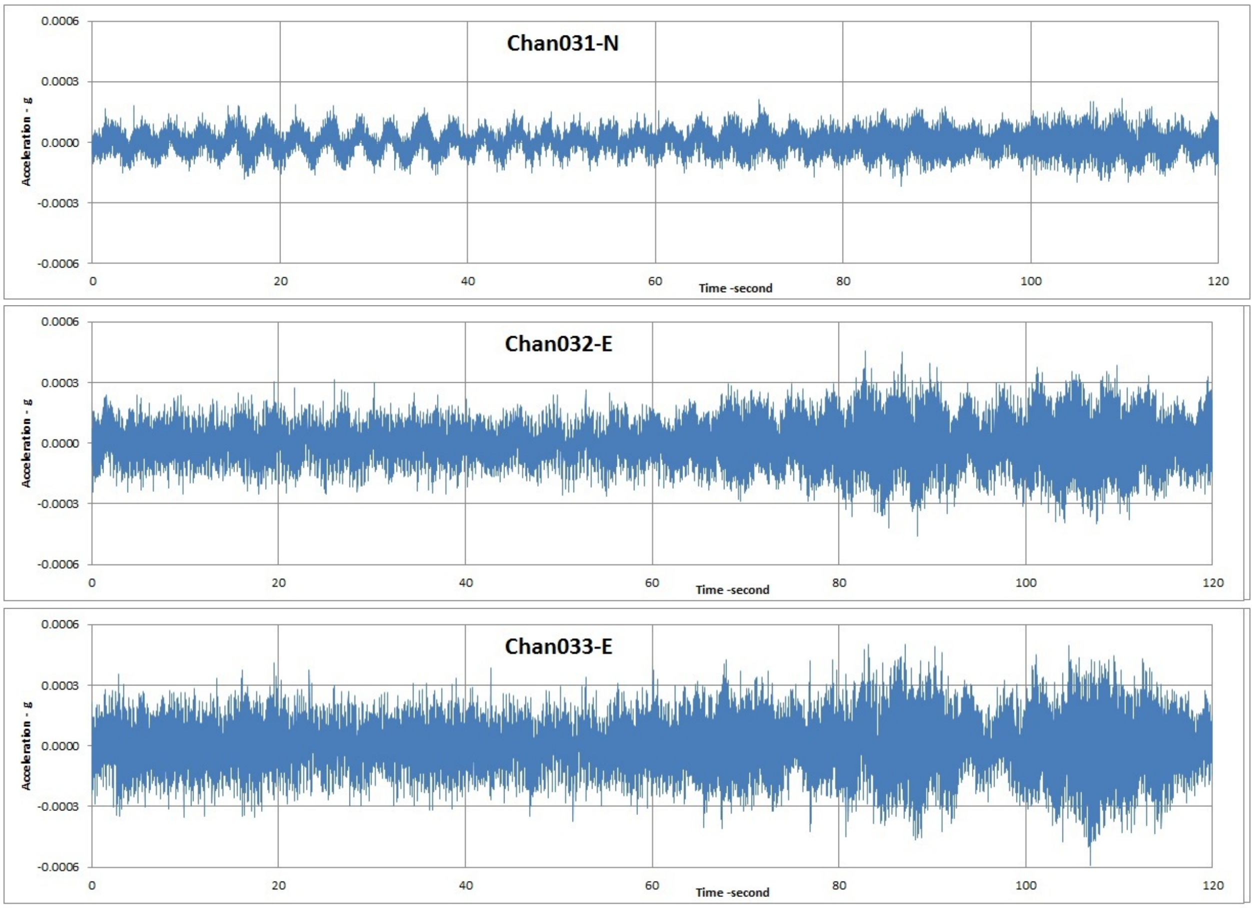

Figure 7. Ambient acceleration data from Sensors 31, 32 and 33 on Level 62 of the One Rincon Hill Tower.

To enhance the translational motion of the floor in the East direction and minimize the contribution of torsional motion, Channels 32 and 33 were averaged together. On the other hand, the difference of Channels 32 and 33 was obtained to enhance the torsional motion and minimize the translational motion in the East direction. The 120-second record was divided into 12 10-second windows. The Fourier transform of each window was then computed. The Fourier amplitudes of the 12 windows were summed and averaged. The results are shown in Figures 8, 9 and 10. The average spectra from Figures 7, 8 and 9 are re-plotted in Figure 11.

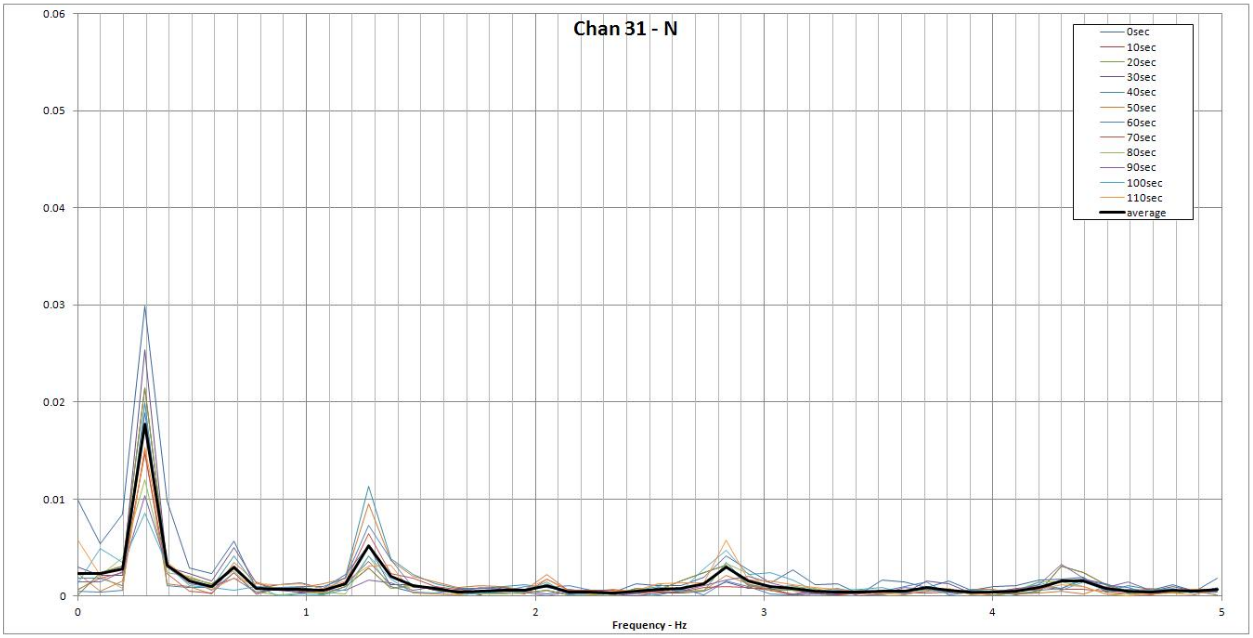

Figure 8. Fourier amplitude spectra of 12 10-second windows of the ambient data from Channel 31 in the north direction, and the average of the amplitudes. The translational modes are shown at near 0.3, 1.3 and 2.8 Hz, and the torsional modes at near 0.7 and 2.1 Hz.

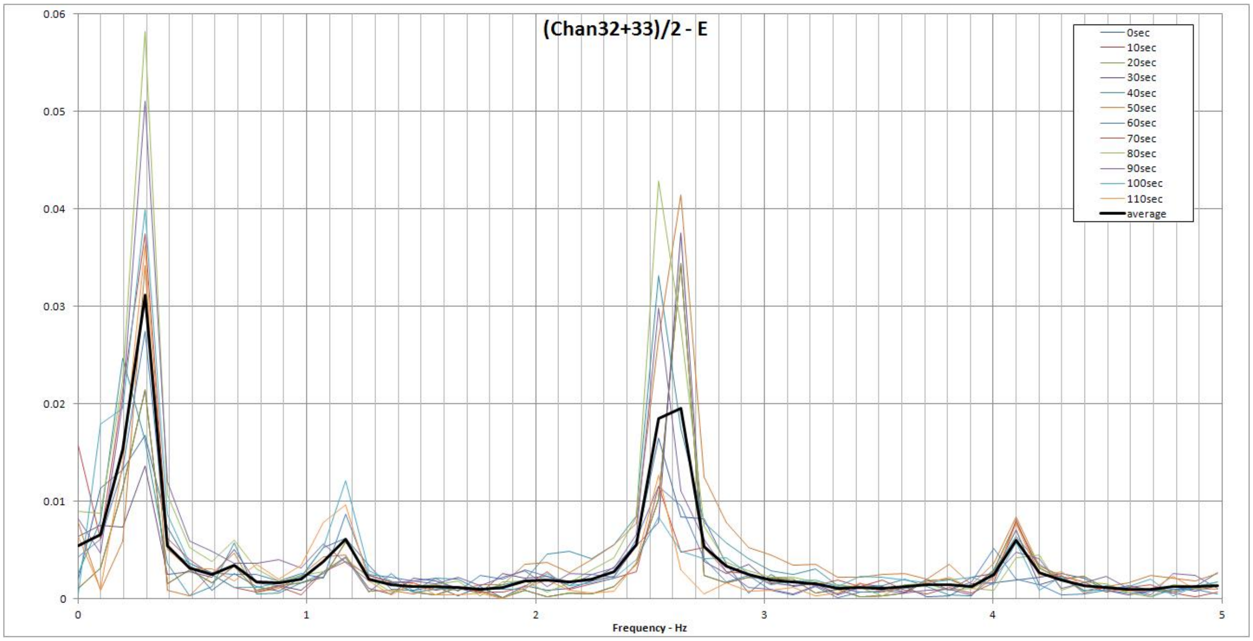

Figure 9. Fourier amplitude spectra of 12 10-second windows of the ambient translational motion from the average of Channels 32 and 33 in the east direction, and the average of the amplitudes. The translational modes are shown at near 0.3, 1.2, 2.6 and 4.1 Hz)

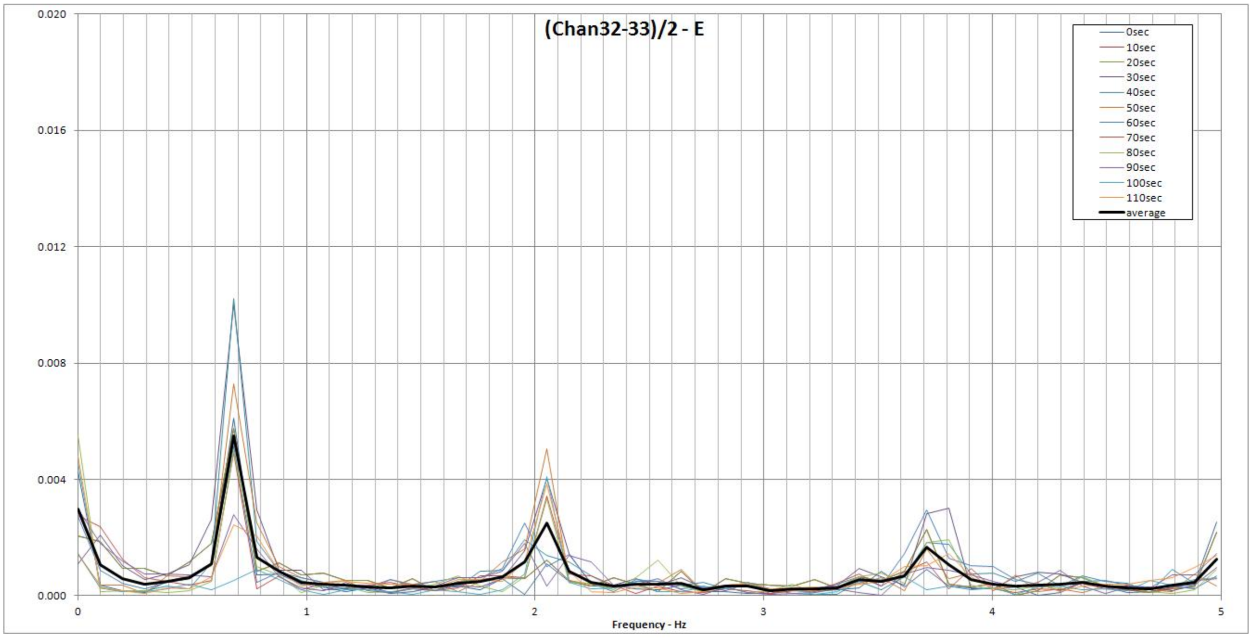

Figure 10. Fourier amplitude spectra of 12 10-second windows of the ambient torsional motion from the difference of Channels 32 and 33 in the east direction, and the average of the amplitudes. The torsional modes are shown at near 0.7, 2.1 and 3.7 Hz.

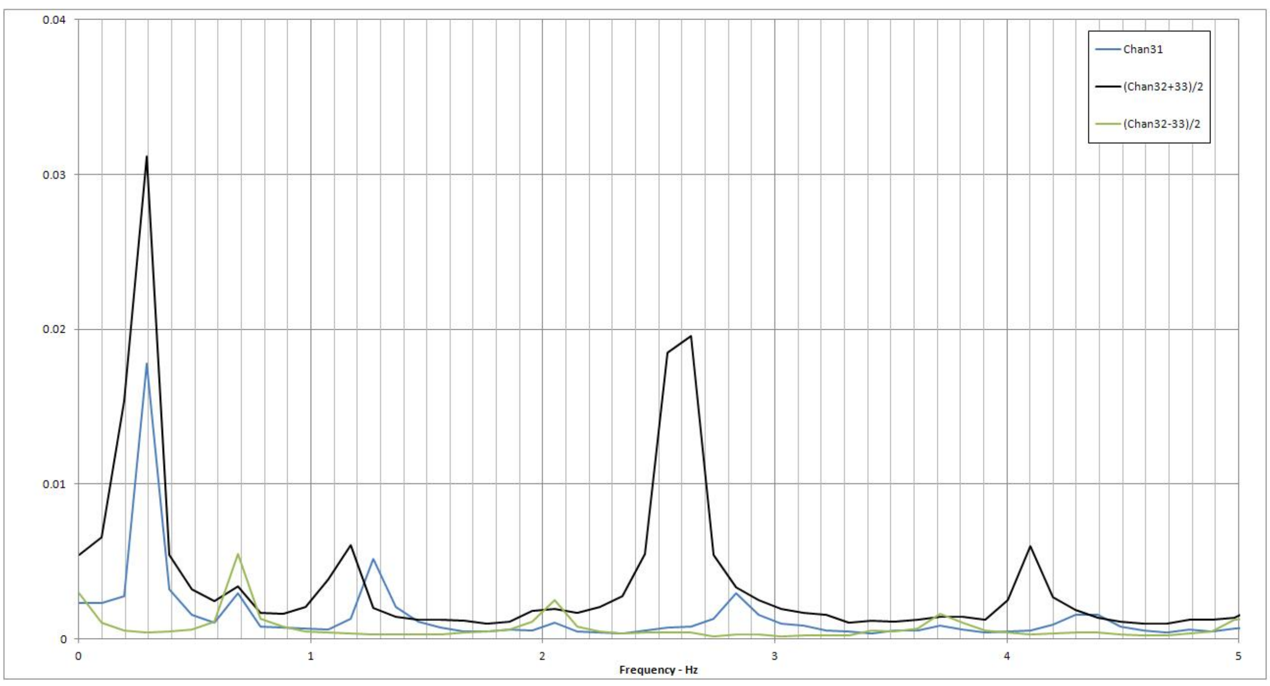

Figure 11. Average Fourier amplitude spectra of the ambient data from Channel 31 (N), and the average (translational motion) and difference (torsional motion) of Channels 32 (E) and 33 (E).

The simple analysis reflected in Figures 8 to 11 indicates that the frequencies of the first three fundamental modes are at about 0.3 Hz (N-S), 0.3 Hz (E-W) and 0.7 Hz (torsion), or 3.3 sec, 3.3 sec and 1.4 sec, respectively. The fundamental period of about 3.3 seconds can also be estimated from the velocity records shown in Figure 12, which were integrated and processed from the acceleration records shown in Figure 7. Furthermore, Figure 8 shows higher modes in the north-south direction at about 1.3 and 2.8 Hz. For the east-west direction, Figure 9 shows higher modes at about 1.2, 2.6 and 4.1 Hz. The mode of 2.6 Hz is predominant in the spectra shown in Figure 9 or 11. Higher torsional modes occur at about 2.1 and 3.7 Hz as shown in Figure 10. These modal parameters correspond to the linear response of the building to small ambient excitation and can serve as the baseline model for the building response to earthquakes. The fundamental period of 3.3 seconds is relatively short for a 62-story building, for which the building structure is subjected to very low level of excitation. This period is expected to be longer during earthquake shaking.

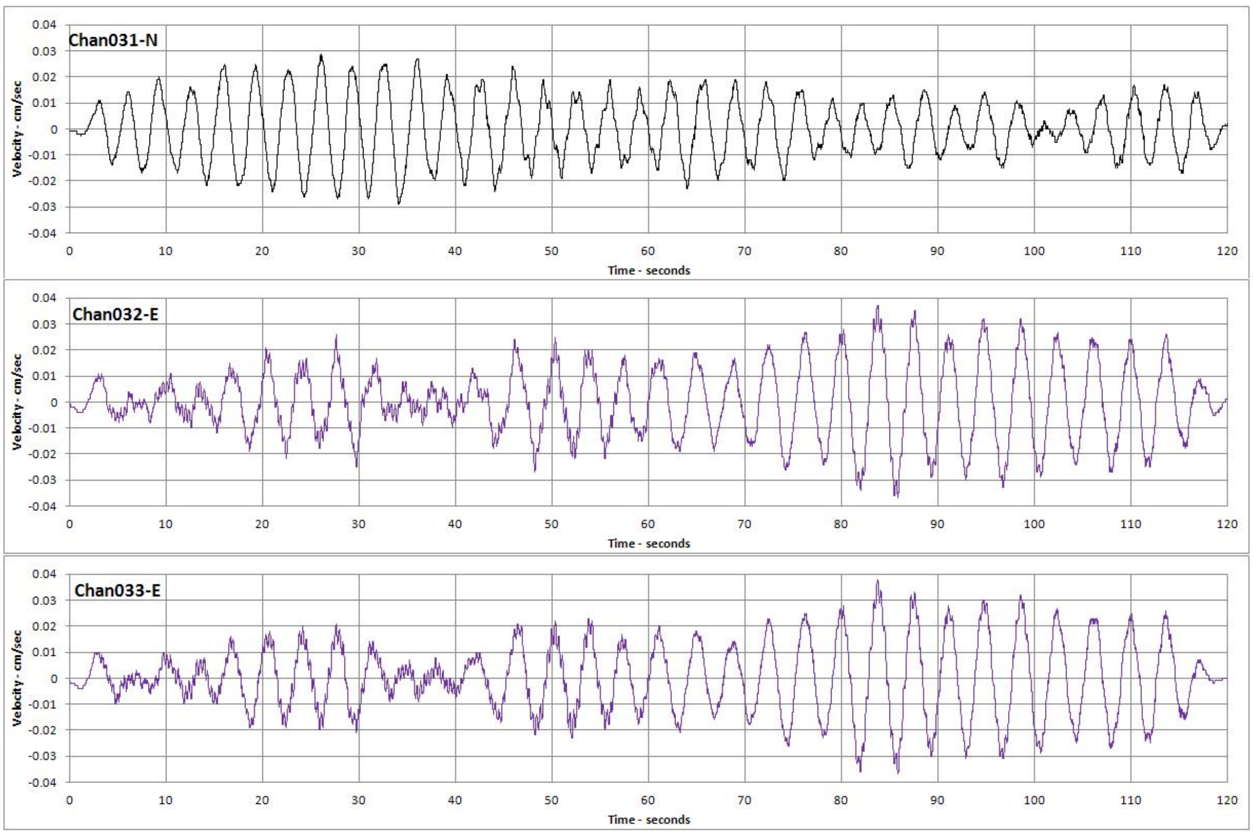

Figure 12. Velocity time histories integrated and processed from the acceleration data recorded by Sensors 31, 32 and 33 shown in Figure 7. A frequency band of 40 Hz to 6 seconds was used.

The velocity time history ambient records from selected sensors along the height of the building are plotted in Figure 13 for the east-west direction and in Figure 14 for the north-south direction. The beat phenomenon can be observed in the east-west direction, caused by the coupling between the building structure and the liquid damper system. The beat phenomenon has been observed in most combined structure-liquid damper systems (Yalla and Kareem, 2001).

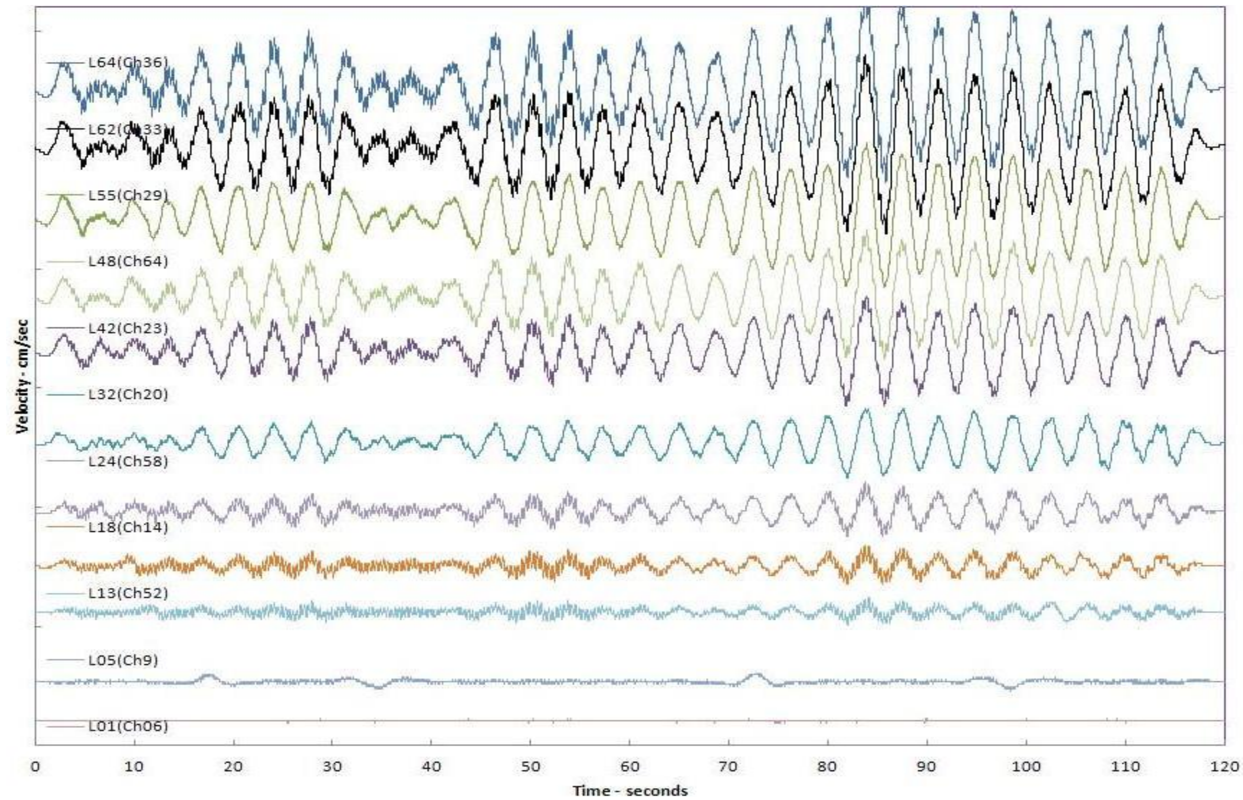

Figure 13. Velocity ambient records from selected sensors in the east-west direction, along the height of the building.

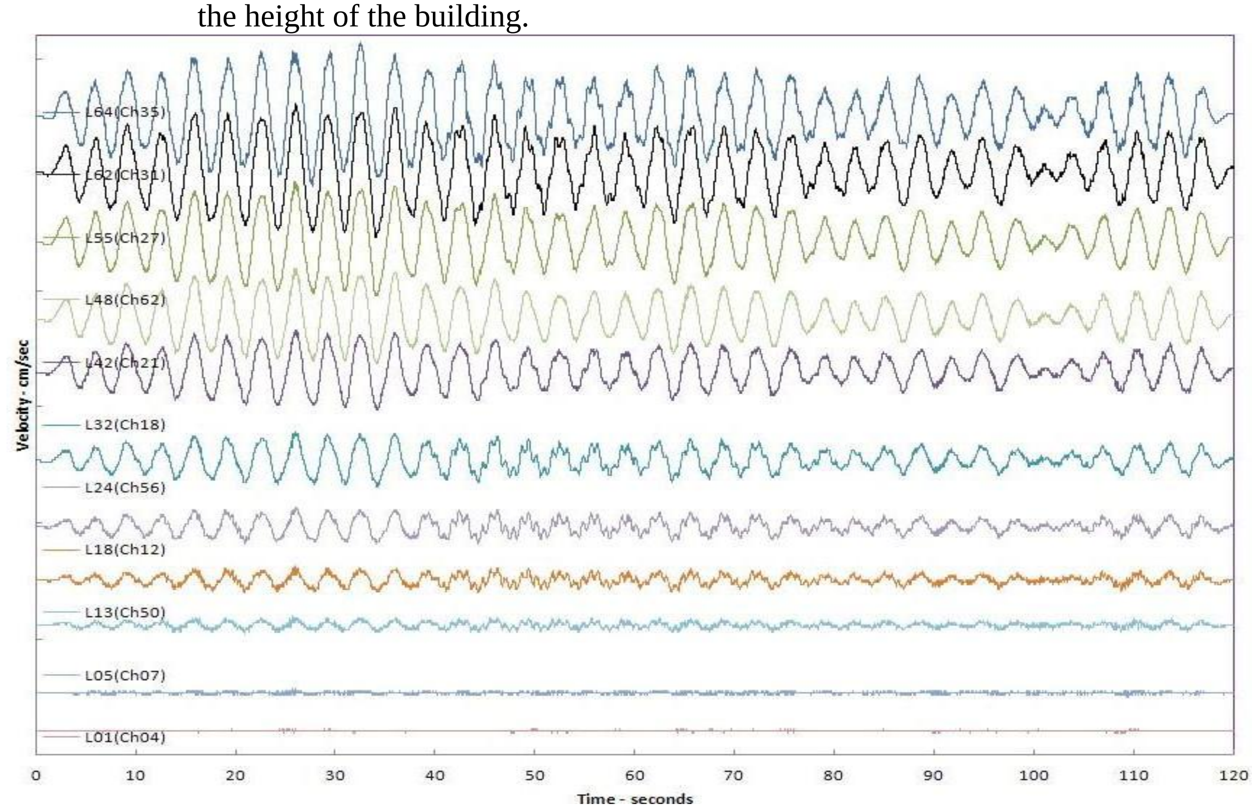

Figure 14. Velocity ambient records from selected sensors in the north-south direction, along the height of the building.

Summary

The One Rincon Hill Tower in San Francisco was jointly and extensively instrumented by the California Strong Motion Instrumentation Program of the California Geological Survey and the National Strong Motion Program of the U.S. Geological Survey in 2012. The instrumentation system can be manually triggered to record ambient vibration data. It will record building seismic response data from which the building performance can be understood and the effectiveness of the performance-based seismic design can be assessed after future significant earthquakes. The recorded data will be available so that the near-real-time data can be used for post-earthquake evaluation of the building performance.

Acknowledgement

The California Strong Motion Instrumentation Program of the CGS and the National Strong Motion Program of the USGS extend their appreciation to the Home Owners Association which permitted and cooperated in the installation of strong-motion equipment in the One Rincon Hill Tower. Beverly Wilson, general manager of One Rincon Hill Association, Ben Irving, building engineer and Jeff Sell, construction project manager, provided valuable assistance. Dr. John Parrish, State Geologist of the CGS and Dr. Tom Brocher, Director of the USGS Earthquake Science Center, coordinated the efforts of the two agencies. Drs. Joe Fletcher and Erol Kalkan of the USGS National Strong Motion Program developed the locations for 36 additional sensors. CSMIP also extends its appreciation to members of the Strong Motion Instrumentation Advisory Committee and its Buildings Subcommittee in recommending the building for instrumentation. Dr. Farzad Naeim of John A. Martin & Associates, Prof. Jack Moehle and Dr. Yousef Bozorgnia of the Pacific Earthquake Engineering Center reviewed and commented on the sensor locations proposed by CSMIP.

The instrumentation was made possible through the efforts of CSMIP engineers and technicians who planned and installed the instrumentation. The assistance of Deputy Director Hanson Tom of the City of San Francisco Department of Building Inspection was important in obtaining the City’s support. CSMIP staff D. Swensen and E. Kalkan (now with the USGS) assisted with engineering; the instrumentation was installed by R. Schoengarth, S. Fife, J. Filak, D. Leiser, and A. Bollinger.

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