STRONG MOTION INSTRUMENTATION OF TWO NEW SUPER TALL BUILDINGS IN CALIFORNIA AND RESULTS FROM AMBIENT AND EARTHQUAKE RESPONSE DATA

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Abstract

The Wilshire Grand Tower in Los Angeles and the Salesforce Tower in San Francisco are two new super tall buildings in California. Both buildings use concrete core shear walls to resist earthquake forces and were designed using a performance-based seismic design approach. During construction, the Wilshire Grand Tower and the Salesforce Tower were extensively instrumented with 36 and 32 sensors, respectively, in a joint effort by the owners and the California Strong Motion Instrumentation Program. This paper describes the sensor locations in the buildings and the instrumentation objectives. Data recorded at the Salesforce Tower during the M4.4 Berkeley earthquake of January 4, 2018, and the ambient vibration data obtained by the instrumentation systems in both buildings are presented. Results from some preliminary analyses of the data are also discussed.

Introduction

The Wilshire Grand Tower in downtown Los Angeles, shown in Figure 1, is a 73-story mixed-use office and hotel building with a surrounding podium. The main tower has 900 hotel rooms on the upper 40 floors, 400,000 square feet of office space, and various restaurants and retail spaces. The height of a typical story is 11.5 feet for hotels and 14 feet for offices. The top of the structure features restaurants, an architectural roof top sail and an architectural spire. The rooftop sail is a steel structure standing 97 feet above the main roof. A tubular steel cantilever spire is attached to the east side of the sail and extends 176 feet above the sail. With the spire, this is the tallest building west of the Mississippi River with a height of approximately 1,100 feet. The building was designed in accordance with the 2011 City of Los Angeles Building Code and performance-based seismic design procedures which were reviewed by a peer review panel (Joseph, et al., 2014; Joseph, et al., 2015). Construction began in 2014 and the building opened on June 23, 2017. The building was required by the City to be extensively instrumented by the owner. CSMIP reviewed the proposed sensor locations from the structural engineer of record, developed specifications and provided technical assistance in instrumentation. The instrumentation system with 36 sensors in the building was completed in June 2017.

The Salesforce Tower in downtown San Francisco, shown in Figure 1, is a 61-story office building. The tower is next to the new Transbay Transit Center. The top occupied floor is 901 feet above the street level. With the crown structure at the top, the building is 1,070 feet in height and is the tallest building in San Francisco. The height of a typical story is 14.75 feet. The crown structure comprises 152.5 feet tall steel concentrically braced steel frames, supported at the top of concrete walls at Level 64 and steel columns at Level 62. The building was designed according to the 2010 San Francisco Building Code and performance-based seismic design procedures which were reviewed by a peer review panel (Valley, et al., 2014; Klemencic, 2017). Construction began in 2013 and the building opened on May 22, 2018. The owner was required by the City to instrumented the building at three levels. However, more extensive instrumentation was suggested. CSMIP developed the sensor locations and instrumentation plans, and worked with the contractor to install the instrumentation system in the building. The instrumentation system with 32 sensors in the building was completed in February 2018.

Figure 1. Views of the Wilshire Grand Tower in Los Angeles (left) and the Salesforce Tower in San Francisco (right).

Wilshire Grand Tower in Los Angeles

Building Structural System

The Wilshire Grand Tower has a roughly rectangular floor plan with dimensions of up to 244 by 112 feet. The core wall is also roughly rectangular, with dimensions of up to 128 by 38 feet. The vertical load carrying system inside the concrete core wall consists of concrete beams and slabs. Outside the core wall, the system consists of lightweight concrete over metal decks supported by steel beams, steel box columns filled with concrete, and concrete core walls. The floor slabs comprise 3.25" concrete fill over 3" metal deck from Floors 2 to 30, and 4.25" concrete fill over 2" metal deck from Floors 31 to the Roof. Concrete flat slabs are the floor system used at the First Floor and below. As shown in Figures 2 and 3, the sail at the tower top is a glazed steel braced frame structure standing 97 feet about the main roof at Level 73. There are no floor slabs in the sail structure. A tubular steel cantilever spire is attached to the east side of the sail and extends to 176 feet above the sail. A large glass skylight separates the tower from the adjacent podium structure.

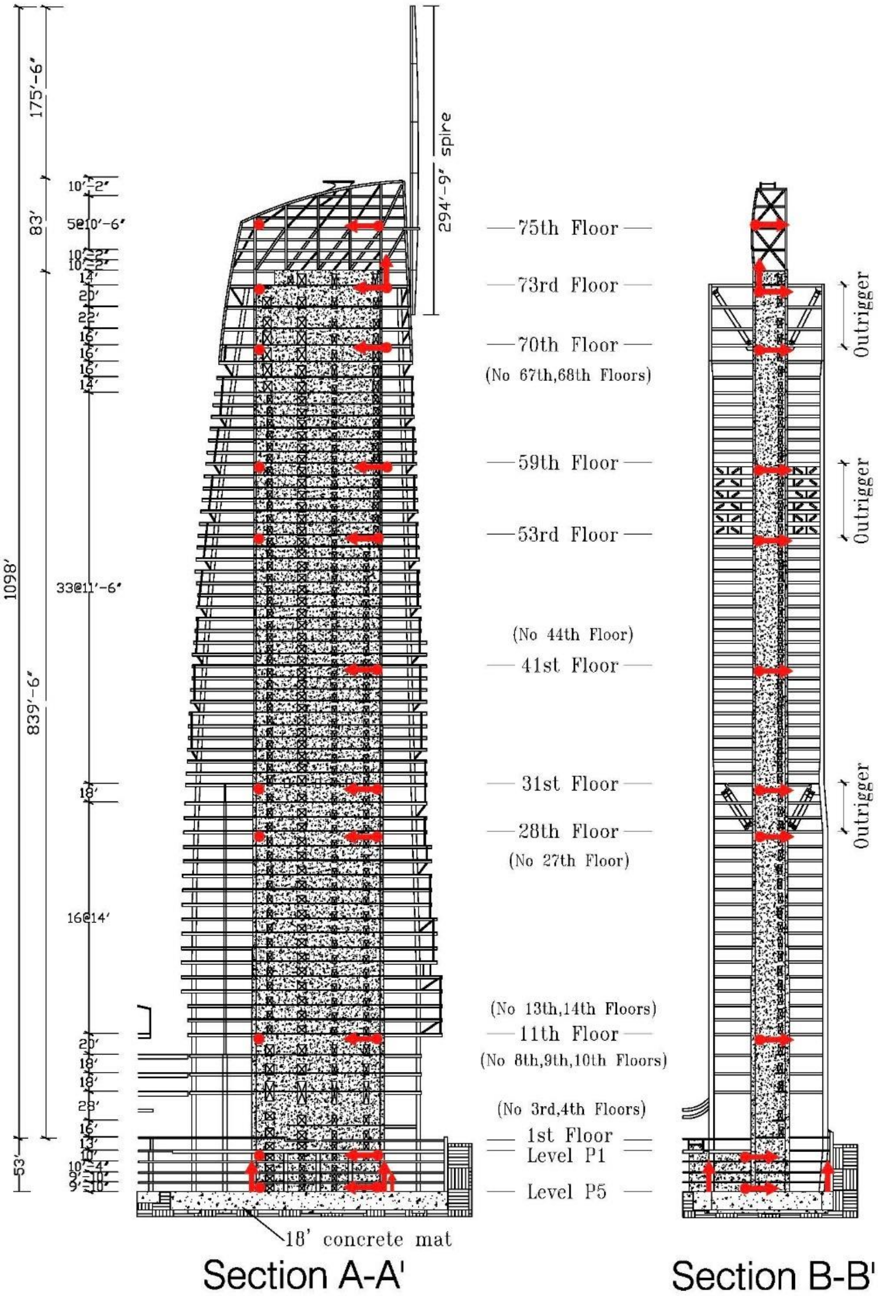


Figure 2. Section views showing the lateral force resisting system of Wilshire Grand Tower with concrete core walls and outriggers at three levels. The locations of the 36 sensors installed in the building are also shown. (Arrows indicate sensing direction; solid circles indicated out of the page.)

Figure 3. View of the concrete core wall and steel gravity system for Wilshire Grand Tower (left), and the rooftop sail structure and spire (right).

The lateral force resisting system of the building comprises concrete core shear walls with steel buckling restrained brace (BRB) outriggers and belt trusses. Concrete walls are 48" thick at the base of the structure and 24" thick near the top of the building. In the transverse direction, the core wall is about 38 feet wide and 895 feet tall, which results in a very large slenderness ratio of about 23.5. Three outriggers, as shown in Figure 2, consisting of steel BRBs extending between the core walls and concrete-filled steel box columns, are used to resist the overturning moments. A total of 170 braces are placed at three locations along the height of the structure: (1) lower outriggers between 28th and 31st Floor with ten double-double 2,200-kip BRBs (40 total); (2) middle outriggers between 53rd and 59th Floor with ten BRB frames, each frame having twelve 800-kips BRBs (120 total); and (3) upper outriggers between 70th and 73rd Floor with ten single 2,200-kip BRBs (Nieblas & Tran, 2015; Joseph et al, 2014; Joseph et al., 2016). Three-story tall steel belt trusses wrap the building at two levels to improve torsional behavior and minimize the effects of differential shortening, as shown in Figure 4.

The tower is supported on an 18 feet thick concrete mat foundation which bears on bedrock. The site is underlain by siltstone and sandstone of the Fernando Formation. The footprint of the mat foundation extends beyond the perimeter of the tower in order to reduce the bearing pressure beneath the mat and provide greater stability for the foundation. The foundation was poured continuously in mid-February of 2014; a total of 21,200 cubic yards of concrete were poured in 18.5 hours (Nieblas, 2014).

The seismic design for the podium and basement was based on the prescriptive procedures in the 2010 California Building Code and the ASCE7-05. However, the seismic design of the tower was based on performance-based procedures. In the performance-based seismic design, the building responses are checked to meet stated performance objectives at two different shaking levels: Maximum Considered Earthquake (MCE) with a 2,475-year return period, and Service Level Design Earthquake (SLDE) with a 43-year return period. First, the design was performed using a linear elastic building model subjected to the wind loads and the SLDE level earthquake forces. Response history analyses were then performed using a nonlinear building model subjected to 11 pairs of ground motion records at the MCE shaking level. Records from two main earthquake sources were used for the analyses: magnitude 7.8 from the distant San Andreas fault and magnitude 6.6 from the local Puente Hills blind thrust fault (Joseph et al. 2015).

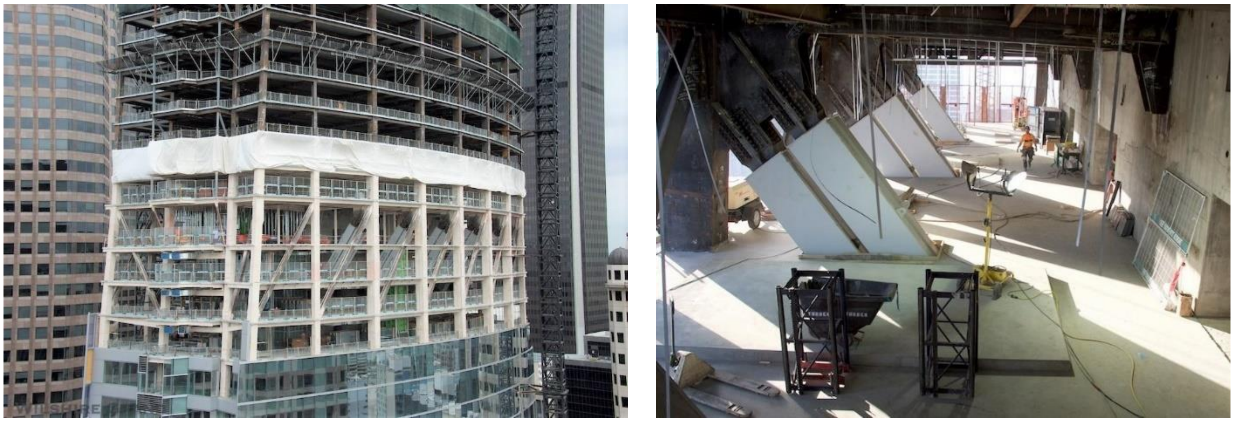


Figure 4. Steel belt trusses and BRBs between the 28th and 31st Floor of Wilshire Grand Tower.

Strong-Motion Instrumentation

The Wilshire Grand Tower was required by the City of Los Angeles to be extensively instrumented with a minimum of 32 sensors (LATBSDC, 2011). Starting in 2011, high-rise buildings with performance-based design were required to be instrumented with a minimum number of sensors dependent on the number of stories (Naeim, 2013). CSMIP contacted the owner’s representative in December 2014, and offered to provide technical assistance in instrumentation as well as maintain the instrumentation system after it was installed. An agreement was reached between CSMIP and the building owner in February 2015. The structural engineer of record and the peer review panel proposed the locations of 36 sensors in the building. CSMIP engineering staff reviewed the proposed sensor locations and recommended changes to optimize placements of these 36 sensors. The locations of these 36 sensors were finalized and approved by the peer review panel. CSMIP then developed the technical specifications for the instrumentation system in June 2015. During construction, CSMIP visited and marked the sensor locations in the building with the contractor and the equipment manufacturer. The sensor cables were run by the contractor, and the sensors and recorder were installed by the equipment manufacturer. CSMIP staff performed the acceptance test for the system on June 29, 2017.

The locations of the 36 accelerometers in the Wilshire Grand Tower are shown in Figure 2. Each of the 36 sensors is connected via cabling to the 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. Due to the congested built environment around the building, no instrument has been installed at a nearby site to measure the reference ground motion for the building.

The primary objective of instrumentation for this building was to install a sufficient number of sensors to measure the response of the building to earthquake ground shaking. 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 recorded data should be adequate to characterize the seismic response of the building.

The motions of the rigid concrete mat foundation are measured by six sensors including three horizontal and three vertical sensors. As shown in Figure 5, these six sensors were installed at strategic locations at Level P5 so the six components of rigid body motion could be determined from the records 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. Three horizontal sensors were repeated at Level P1, the highest level where the tower floor slab is still tied to the adjacent podium structure.

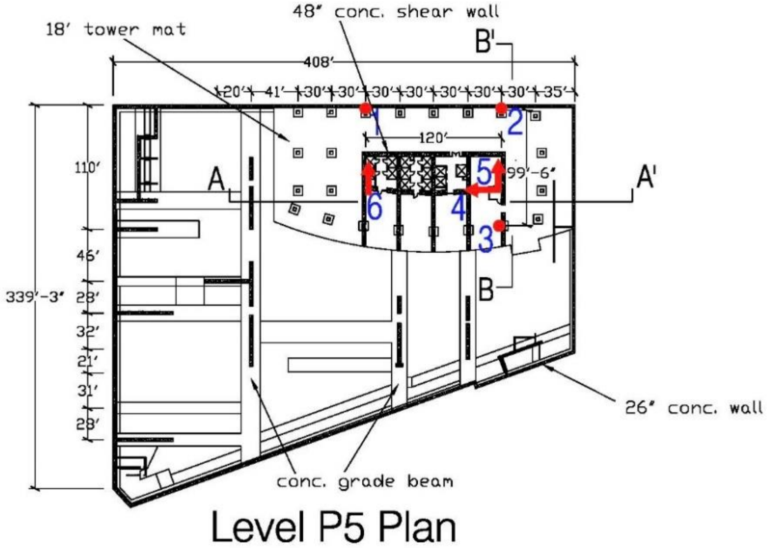


Figure 5. Locations of six sensors at Level P5, base of Wilshire Grand Tower, which measure translational and rotational motions of the concrete mat foundation.

The remaining 27 sensors were installed in the upper stories of the tower. The levels where the outrigger brace connections occur were selected to be installed with sensors. Specifically, these floors are 28th, 31st, 53rd, 59th, 70th and 73rd, as shown in Figure 2. Each of these levels was instrumented with three sensors (see Figure 6) to measure the translational and torsional motions of the floor. The 11th and 41st Floors, which are in between the outriggers, were instrumented with three and two sensors, respectively, to allow better determination of the vibration mode shapes. A vertical sensor was added at the top of the core shear wall at the 73rd Floor to measure how the building motion is amplified in the vertical direction. Finally, the sail structure on the tower top was instrumented with three sensors at the 75th Floor.

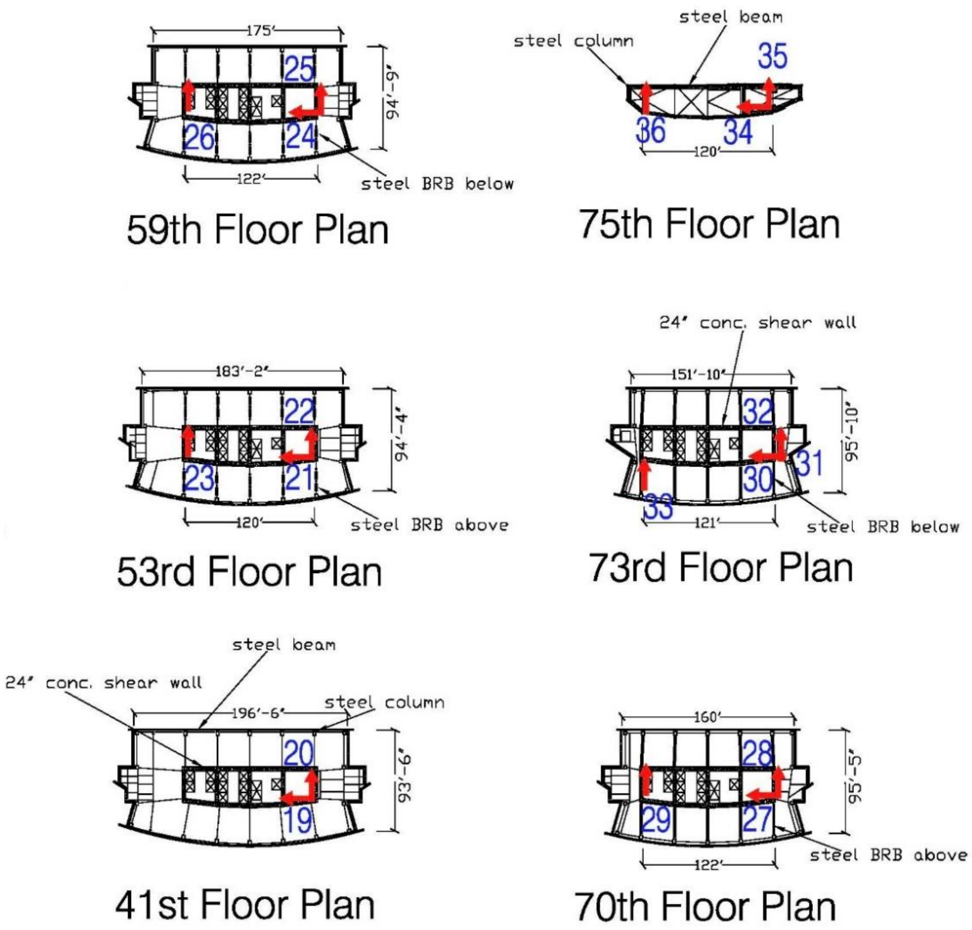


Figure 6. Sensor locations at the 41st Floor and above at Wilshire Grand Tower.

Ambient Vibration Data

After instrumentation of the building was completed, ambient vibration data were taken by manually triggering the system on September 21, 2017. The ambient data has a duration of 2.5 minutes. The sampling rate is 200 samples per second. More rigorous analyses of the ambient data can be performed by using detailed system identification methods to obtain modal frequencies and mode shapes (Celebi, et al. 2013). However, the building fundamental periods can be easily obtained from the ambient data. Figure 7 shows the ambient velocities integrated from the ambient acceleration records from sensors in the transverse (NS) direction at the eleven instrumented levels along the height of the building. A frequency band pass filter of 46 Hz to 10 seconds was applied in the data processing. Similarly, Figure 8 shows the ambient velocities from sensors in the longitudinal (EW) direction. It can be observed from Figures 7 and 8 that the ambient motions in the transverse direction were about six times larger than those in the longitudinal direction. This is due to the fact that the area exposed to wind loading is larger in the transverse direction and also that the building is stiffer in the longitudinal direction. The ambient data clearly show that the building fundamental period at the ambient shaking level is about 6.0 seconds in the transverse direction and about 3.4 seconds in the longitudinal direction. These periods can be obtained from either the time history plots in Figures 7 and 8 or the velocity response spectra shown in Figure 9.

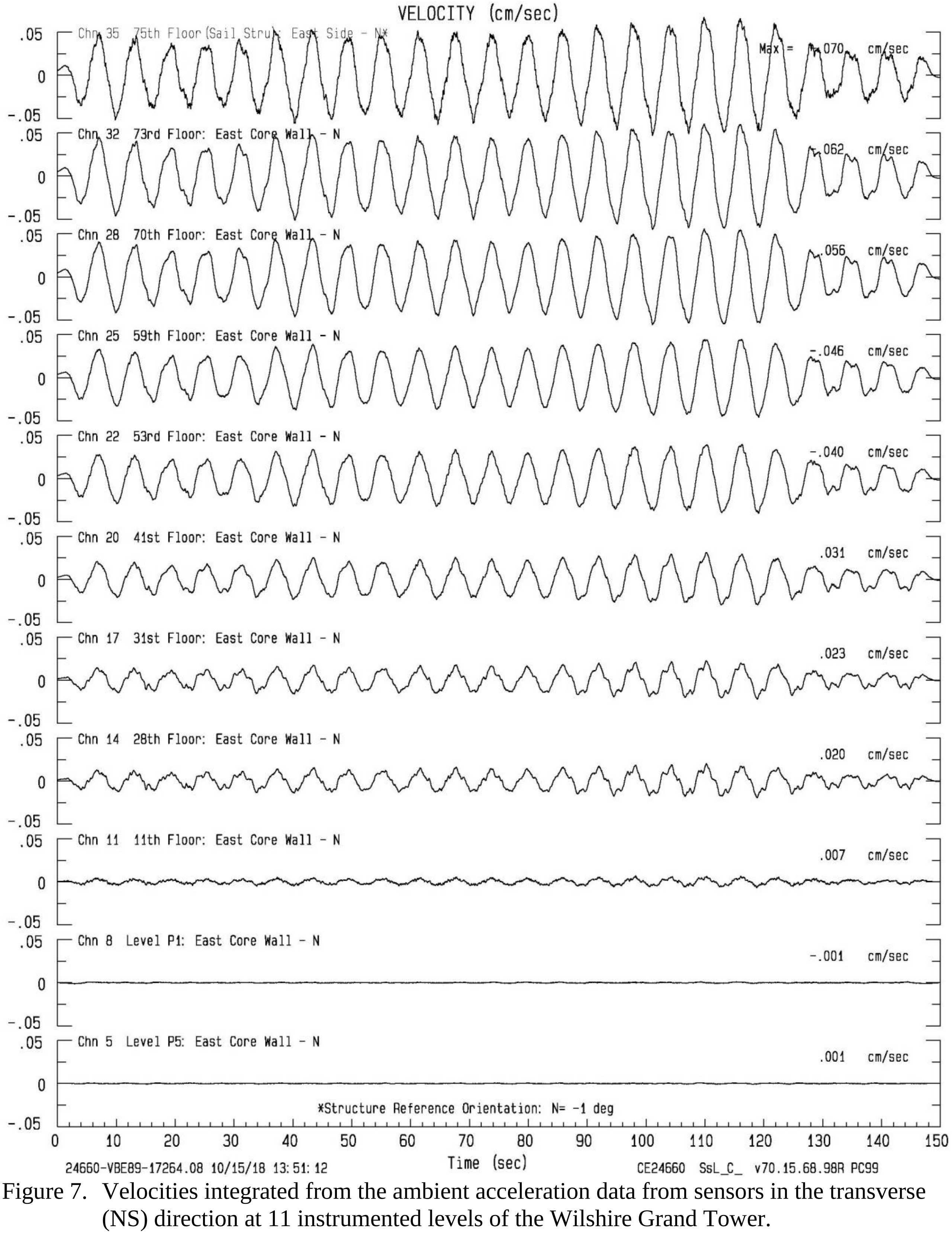


Figure 7. Velocities integrated from the ambient acceleration data from sensors in the transverse (NS) direction at 11 instrumented levels of the Wilshire Grand Tower.

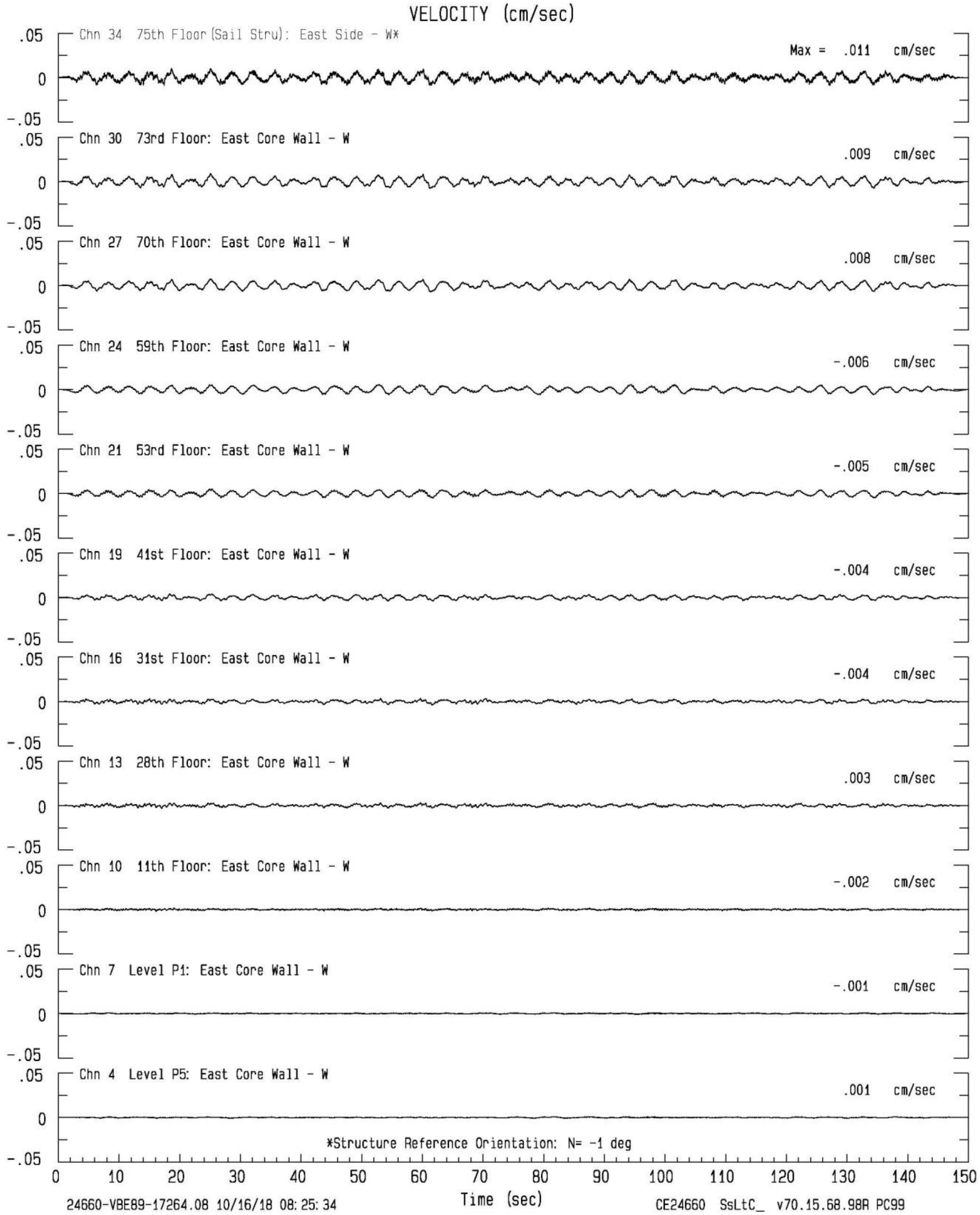


Figure 8. Velocities integrated from the ambient acceleration data from sensors in the longitudinal direction (EW) at 11 instrumented levels of the Wilshire Grand Tower.

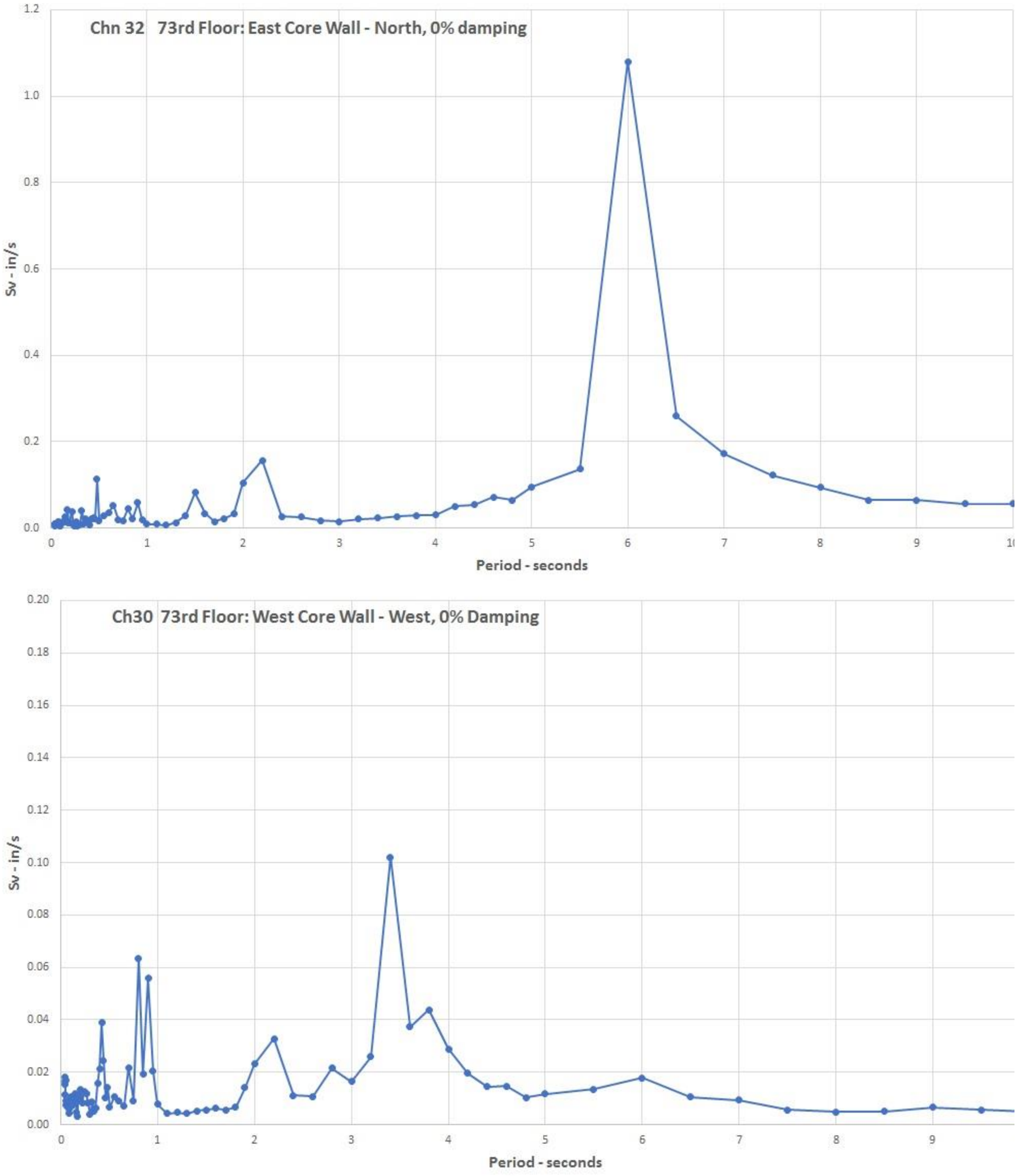


Figure 9. Zero percent damping velocity response spectra (Sv) of the ambient data from Sensor 32 (transverse direction) and Sensor 30 (longitudinal direction) on the 73rd Floor of the Wilshire Grand Tower.

Salesforce Tower in San Francisco

Building Structural System

The Salesforce Tower has a roughly square floor plan with dimensions of up to 167 by 167 feet and rounded corners. The core wall is roughly square, with dimensions of up to 89 by 83 feet. The building includes three stories below grade for parking and 61 stories above grade for offices. The basement footprint is slightly larger than the tower, with dimensions of 198 by 184 feet. The typical story height is 14′-9". The vertical load carrying system inside the concrete core wall consists of concrete beams and slabs. Outside the core wall, the system consists of lightweight concrete over metal decks supported by steel beams and columns, and concrete core walls. The exterior walls of the building are vertically straight between Levels 1 and 27. Beyond Level 27, the exterior walls gradually taper in. The top occupied floor (Level 61) is 901 feet above street level. With the steel crown structure, the top of the tower reaches a height of 1,070 feet, as shown in Figure 10. The Salesforce Tower is the tallest building in San Francisco.

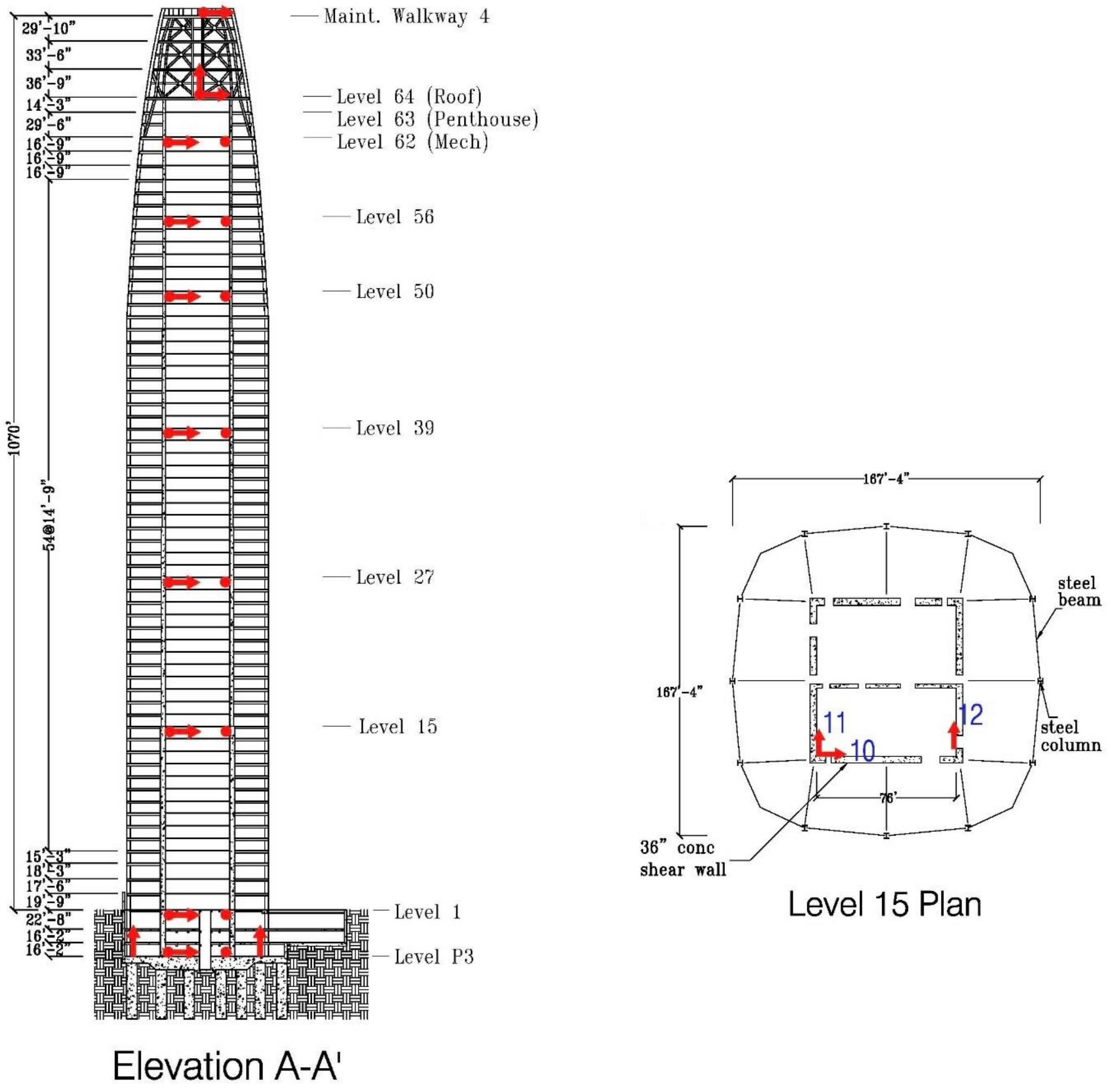
The lateral force resisting system of the building comprises special concrete shear walls at the central elevator and stair core. The northern cell of the core shear wall terminates at Level 50, as shown in Figure 11. The southern cell of the core shear wall tops out at Level 64 (961 feet above the street level). The concrete wall thickness varies from 48" at the base of the structure to 24" near the top. The slenderness ratio of the concrete core is about 12.9 in the east-west direction and 12.0 in the north-south direction. The tower is crowned with a 152.5 feet tall ordinary steel concentrically braced frame structure supported at the top of concrete walls (Level 64) and steel columns at Level 62, as shown in Figure 12. There are no floor slabs on the steel crown structure.

The tower foundation is a concrete mat supported by 42 rectangular deep foundation elements (barrettes). The concrete mat varies in thickness from 14 feet at the core to 5 feet at the perimeter. The barrettes are 5 by 10.5 feet in plan and 185 to 230 feet long and are socketed into the bedrock below. The site is underlain by fill, sand and old bay mud. The depth to the bedrock from the street level is about 250 feet.

The Salesforce Tower was designed in accordance with the 2010 San Francisco Building Code. A performance-based seismic design approach was used for the building (Klemencic, et al., 2017). Response history analyses were performed using a nonlinear building model subjected to two suites of 11 pairs of ground motion records at the MCE shaking level (Valley, et al., 2014). One suite represented long period ground motions, while the other suite represented shorter period ground motions. Nonlinear soil-structure-foundation interaction analyses were performed to assess the effects from the adjacent Transbay Transit Center. The crown structure was designed as a non-structural component (Valley, et al., 2014).

Strong-Motion Instrumentation

The Salesforce Tower was required by the City of San Francisco to be instrumented at three levels (code-type instrumentation). CSMIP contacted the structural engineer of record (SEOR) and suggested extensive instrumentation of the building. CSMIP obtained permission from the owner in February 2016 to extensively instrument the building as part of the CSMIP network. CSMIP staff developed and proposed the locations for 32 accelerometers in the building after studying the structural and architectural floor plans of the building. The sensor locations were then reviewed and commented on by the SEOR, the owner and a representative member of the Strong Motion Instrumentation Advisory Committee. During construction, CSMIP visited and marked the sensor locations in the building with the electrical contractor. The electrical contractor installed the sensor cables and received funding from the owner and CSMIP. CSMIP staff installed most of the sensors and the recorder in the building in December 2017 and completed the installation of the remaining sensors in the crown structure on February 21, 2018.



Elevation A-A'

Level 15 Plan

Figure 10. Elevation view showing the locations of the 32 sensors installed in the Salesforce Tower, and a typical framing plan for lower floors (Level 15 is shown).

The locations of the 32 accelerometers in the Salesforce Tower are shown in Figure 10. Each of the 32 sensors is connected via cabling to the central recorder. The digital recorder 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. Due to the congested built environment around the building, no instrument has been installed at a nearby site to measure the reference ground motion for the building.

Figure 11. Views of Salesforce Tower after (left) and during (right) construction. The reduction of the concrete shear wall core at Level 50 can be seen in the right photo.

Figure 12. Views of concrete core wall and steel gravity system of Salesforce Tower during construction (left) and the steel crown structure on the top of the building (right).

The building foundation is a concrete mat. The motions of this rigid concrete mat are measured by six sensors including three horizontal and three vertical sensors. As shown in Figure 13, these six sensors were installed at strategic locations at Level P3 so the six components of rigid body motion could be determined from records 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. Three horizontal sensors were repeated at Level 1 where the floor slab is tied to the 24" perimeter concrete walls at street level.

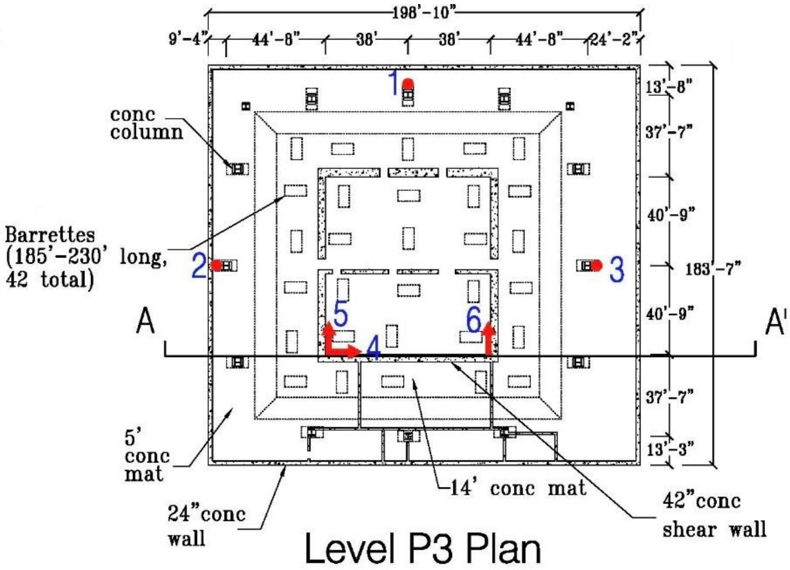
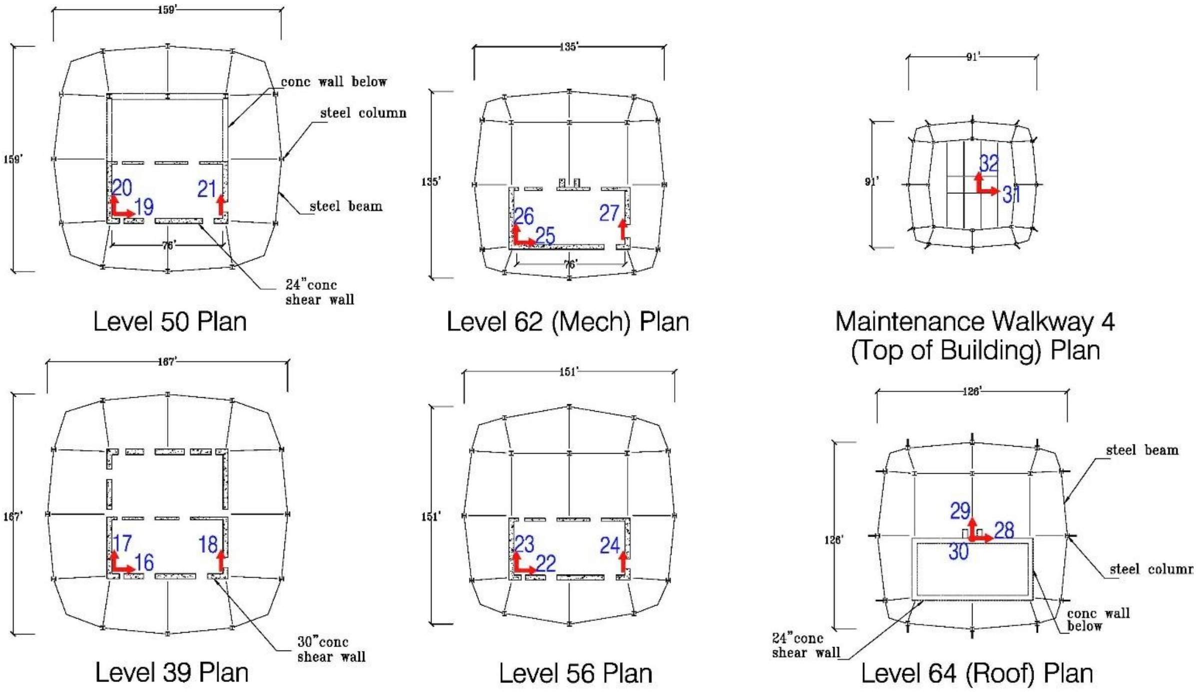


Figure 13. Locations of six sensors at Level P3, base of the Salesforce Tower, which measure translational and rotational motions of the concrete mat foundation.

The remaining 23 sensors were installed in the upper stories of the tower. The levels selected to be installed with sensors are spaced evenly along the height of the building. Specifically, these floors are Levels 15, 27, 39, 50, 56 and 62, as shown in Figure 10. In particular, Level 50 was selected because the core concrete shear walls are reduced at this level. Each of these levels was instrumented with three sensors to measure the translational and torsional motions of the floor. At the request of the owner, these sensors could not be installed in any office space. Therefore, they could only be installed inside the central core, as shown in Figure 14. The sensors were installed in the southern cell of the core wall because it goes all the way to Level 64. The sensor locations inside the core are repeated at each level except at Level 64. For the crown structure, three sensors including one vertical sensor and two horizontal sensors were installed at Level 64, which is the top of the core shear wall and the base of the steel crown structure. Finally, two horizontal sensors were installed at the top of the steel crown structure to measure its response.



Level 50 Plan

Level 62 (Mech) Plan

Maintenance Walkway 4 (Top of Building) Plan

Level 39 Plan

Level 56 Plan

Level 64 (Roof) Plan

Figure 14. Sensor locations at the 41st Floor and above at Wilshire Grand Tower.

Record from M4.4 Berkeley Earthquake of January 4, 2018

The M4.4 Berkeley earthquake occurred on January 4, 2018 at a distance of about 10 miles from the Salesforce Tower. At the time of the earthquake, most of the sensors in the building had been installed. The sensors at the crown structure were not installed because the area was not accessible yet. The instrumentation system with 26 installed sensors recorded the Berkeley earthquake even though the system was not fully installed. The recorded motions from the Berkeley earthquake were small amplitude responses of the building. Recorded peak accelerations were 1.3% g at Level P3 and 3.0% g at Level 62. The acceleration records are shown in Figure 15 for the north-south direction and in Figure 16 for the east-west direction. The first vibrational mode of the building in each direction was hardly excited by this small earthquake which did not generate any significant long period ground motions. Motions of higher modes dominated in the acceleration, velocity and displacement time histories. However, we could find the first mode in the tripartite response spectra plots, such as those from the sensors at Level 62 shown in Figure 17. The first mode period is about 5.0 seconds in each direction. In addition, the floor torsional motion could be seen in the records of a pair of sensors in the north-south direction at the upper levels, such as the records shown in Figure 15 from Sensors 26 and 27 at Level 62.

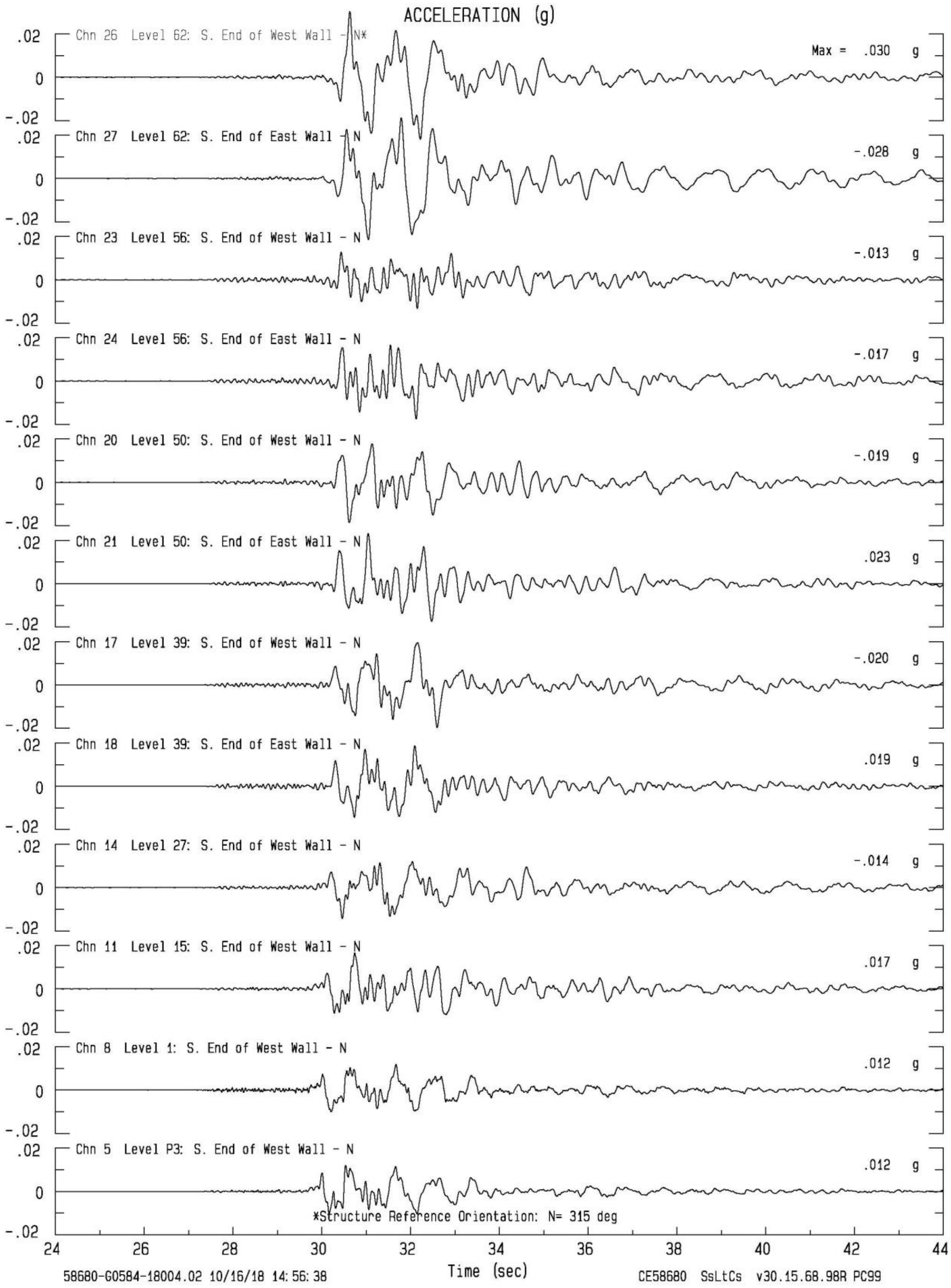


Figure 15. Acceleration records from selected sensors in the NS direction obtained from Salesforce Tower during the M4.4 Berkeley earthquake of January 4, 2018.

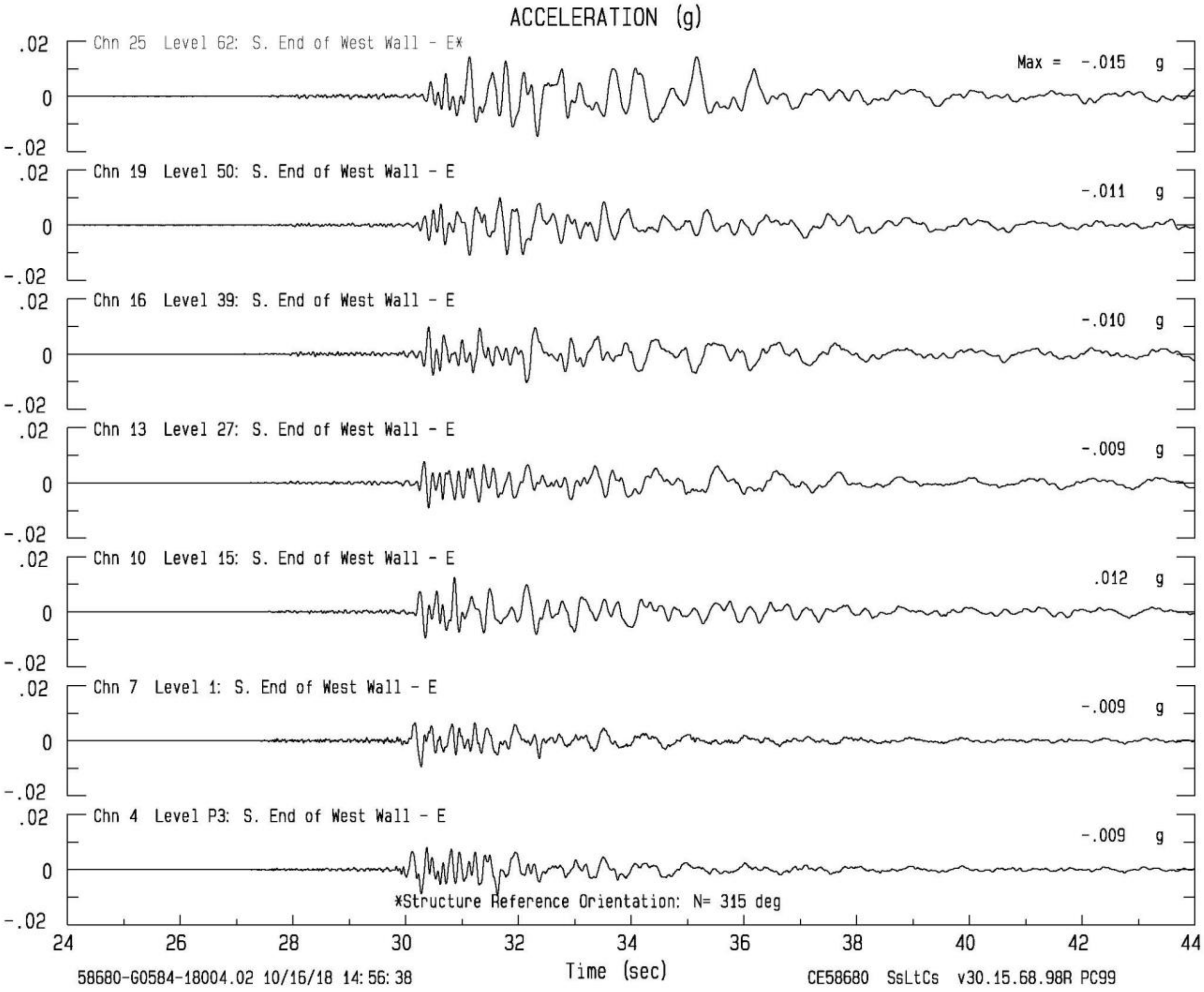


Figure 16. Acceleration records from selected sensors in the EW direction obtained from Salesforce Tower during the M4.4 Berkeley earthquake of January 4, 2018.

Ambient Vibration Data

After the instrumentation in the building was completed, ambient vibration data were taken by manually triggering the system on March 1, 2018. The ambient data has a duration of 2.5 minutes. The velocities integrated from the ambient acceleration records from selected sensors at the ten instrumented levels along the height of the building are shown in Figures 18 and 19 for the north-south and east-west directions, respectively. A frequency band pass filter of 46 Hz to 10 seconds was used in data processing. The record at the top of the crown structure contains some high-frequency motions which are probably associated with local vibration of the steel members. The zero damping velocity response spectra for the ambient motions measured at Level 64 are shown in Figure 20. The time history plots and the response spectra clearly show that the building fundamental period at the ambient shaking level is about 5.0 seconds in both directions.

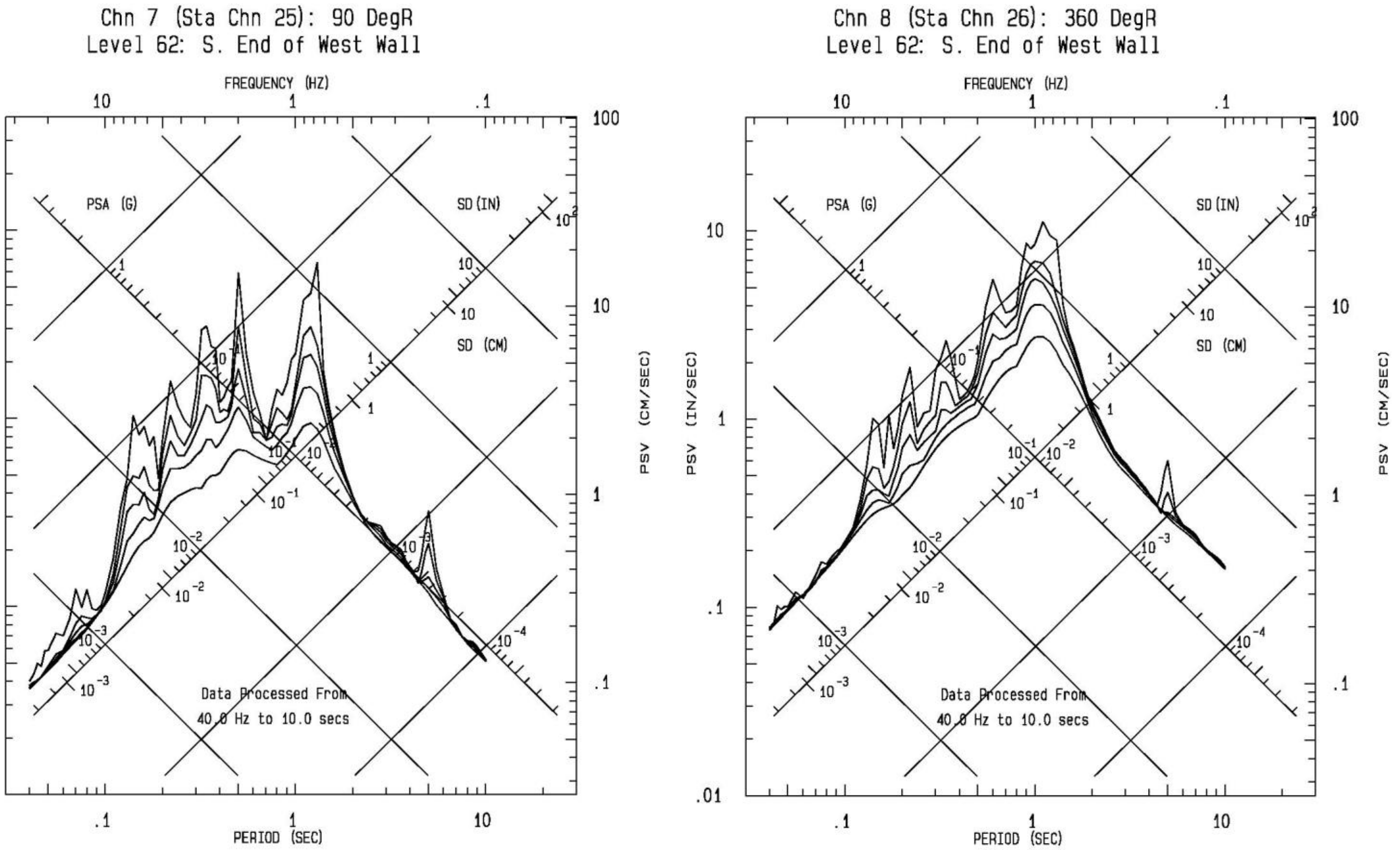


Figure 17. Tripartite response spectra plot of the M4.4 Berkeley earthquake records from the Sensors 25 and 26 at Level 62 of the Salesforce Tower. Building fundamental period of 5 seconds in each direction can be seen on the plots.

Summary

The Wilshire Grand Tower in Los Angeles and Salesforce Tower in San Francisco are two new super tall buildings in California. They have been extensively instrumented jointly by the owners and the California Strong Motion Instrumentation Program. The ambient data from the Wilshire Grand Tower show that the fundamental period is about 6.0 seconds in the transverse direction and 3.4 seconds in the longitudinal direction. The ambient data from the Salesforce Tower show that the fundamental period is about 5.0 seconds in both directions. The data recorded at Salesforce Tower show that the fundamental mode was hardly excited by the M4.4 Berkeley earthquake of January 4, 2018.

The building description and the sensor location diagrams for these two super tall buildings are included in the Center for Engineering Strong Motion Data (CESMD) at https://www.strongmotioncenter.org Ambient vibration data from these two building and the strong-motion data from the Salesforce Tower are available at the CESMD Data Center.

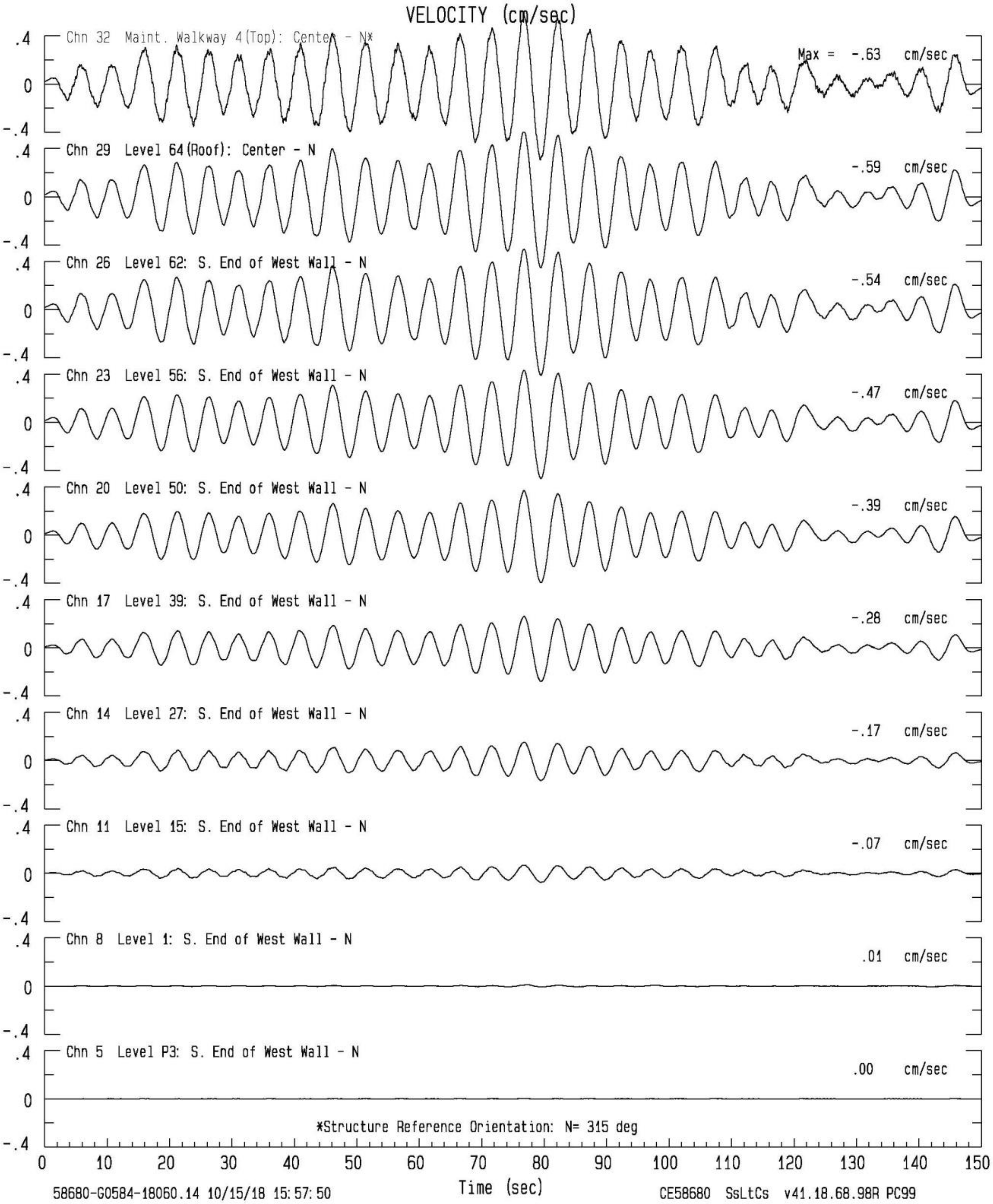


Figure 18. Velocities integrated from the ambient acceleration data from sensors in the north-south direction at ten instrumented levels of the Salesforce Tower.

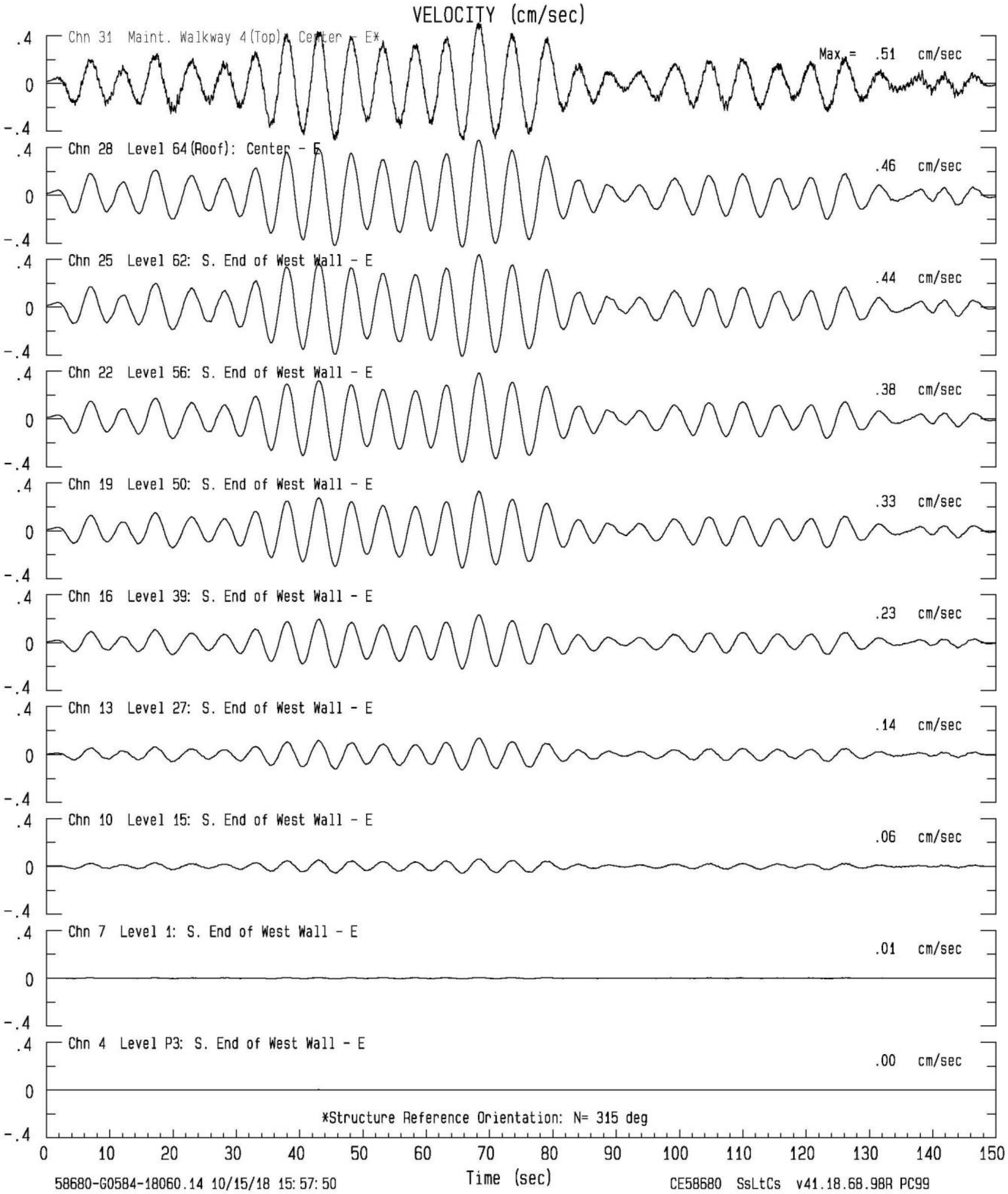


Figure 19. Velocities integrated from the ambient acceleration data from sensors in the east-west direction at ten instrumented levels of the Salesforce Tower.

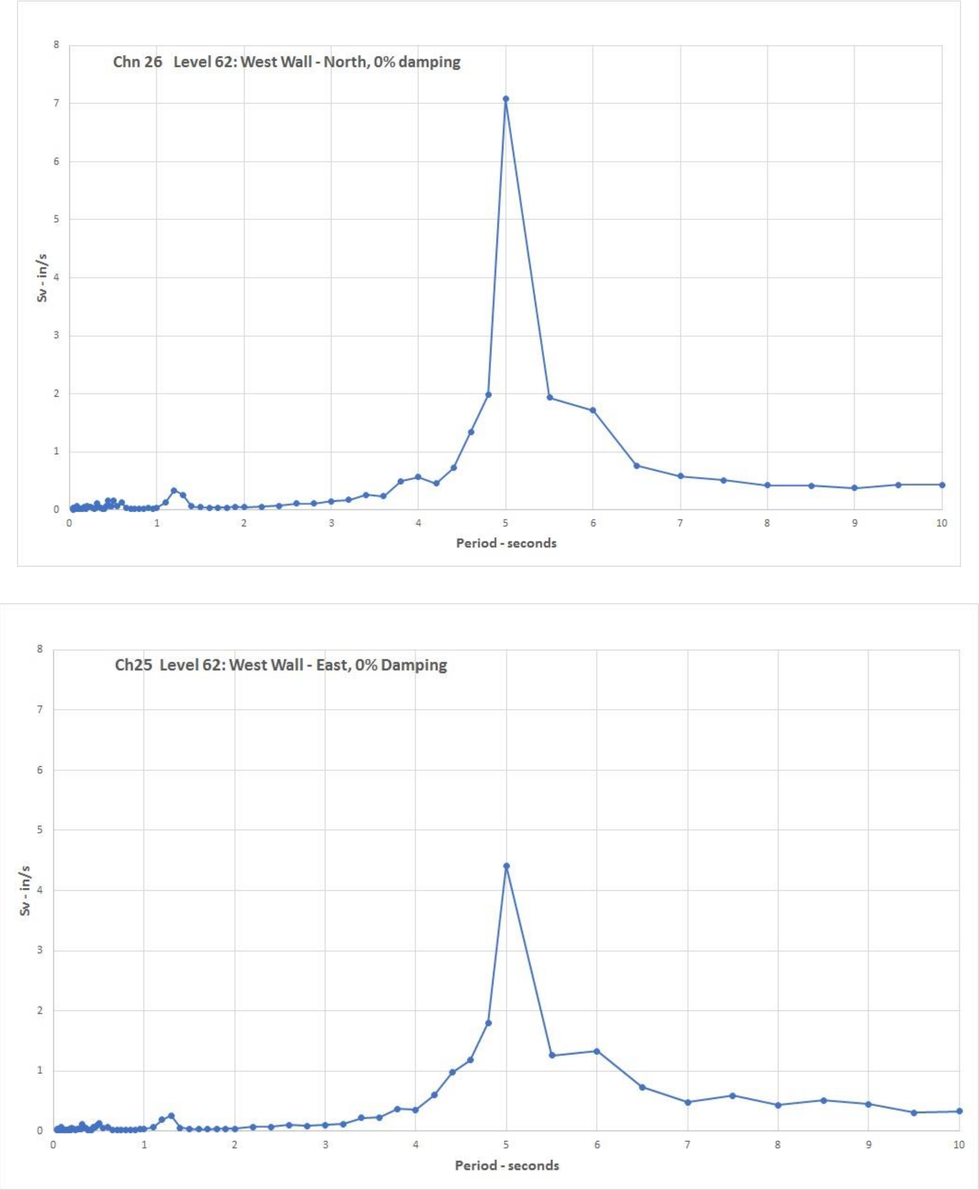


Figure 20. Zero percent damping velocity response spectra (Sv) of the ambient data from Sensor 26 (NS direction) and Sensor 25 (EW direction) on Level 62 of the Salesforce Tower.

Acknowledgements

The California Strong Motion Instrumentation Program of the California Geological Survey, Department of Conservation extends its appreciation to the owners who permitted and cooperated in the installation of strong-motion equipment in the Wilshire Grand Tower and the Salesforce Tower. The instrumentation efforts by CSMIP were directed by the Program Manager Dr. Tony Shakal and the Field Operations Manager Carl Petersen who retired at the end of 2017. CSMIP also extends its appreciation to members of the Strong Motion Instrumentation Advisory Committee and its Buildings Subcommittee for recommending the buildings for instrumentation. Dr. Farzad Naeim of Farzad Naeim Inc. reviewed and commented on the sensor locations proposed by CSMIP. Josh Gebelein of Brandow & Johnston and Michael Valley of Magnusson Klemencic Associates assisted CSMIP in obtaining permission from the owners and reviewed the sensor locations.

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