COLLABORATIVE RECORDED DATA BASED RESPONSE STUDIES OF FOUR TALL BUILDINGS IN CALIFORNIA

Daniel Swensen[(1)] and Mehmet Çelebi[(2)]

[(1)] California Geological Survey, Strong Motion Instrumentation Program
[(2)] U.S. Geological Survey, Earthquake Science Center

Abstract

Seismic instrumentation, recorded earthquake responses, and collaborative studies of the response records from four tall California buildings are summarized in this summary paper. These buildings include the tallest San Francisco building, the 61-story Salesforce Tower, and the tallest California building, the 73-story Wilshire Grand Tower, as well as a 51-story residential building in Los Angeles and a 24-story government building in San Diego. Various system identification methods are used to analyze the largest earthquake response records retrieved from seismic arrays installed in each of the four buildings. Significant structural dynamics characteristics (fundamental periods and critical damping percentages) are extracted. In general, critical damping percentages for the first mode are <2.5%, consistent with recent studies and recommendations.

Introduction

The California Strong Motion Instrumentation Program (CSMIP) has installed seismic monitoring arrays on numerous tall buildings in California over the past few decades. Response studies of four of these tall buildings have recently been completed. These buildings include the Salesforce Tower in San Francisco (CSMIP Station No. 58680), the Wilshire Grand Tower in Los Angeles (CSMIP Station No. 24660), a 51-story residential building in Los Angeles (CSMIP Station No. 24M07) and a 24-story government building in San Diego (CSMIP Station No. 03631). Table 1 summarizes selected features of these four buildings. Data recorded in these buildings from recent earthquakes were analyzed using various methods to determine dynamic response characteristics and drift ratios. The analysis methods employed in these studies and selected results are summarized in this paper. Additional details of the response studies of these four tall buildings are separately provided in Çelebi et al. (2019), Çelebi et al. (2020), Çelebi et al. (2021), and Çelebi and Swensen (2021).

Summary of Building Structural Systems

Salesforce Tower

The Salesforce Tower is the tallest building in San Francisco, reaching a height of 1,070 feet. The building includes three stories below grade for parking and 61 stories above grade for offices. It has a roughly square floor plan with dimensions of up to 167 by 167 feet and rounded corners (Figure 1). 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 consists of concrete over metal deck 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 inward. The lateral force resisting system of the building comprises special concrete shear walls at the central core. The northern cell of the core shear wall terminates at Level 50, whereas the southern cell tops out at Level 64. The concrete wall thickness varies from 48" at the base of the structure to 24" near the top. The tower is crowned with a ~150 feet tall steel braced frame structure. The tower foundation is a concrete mat supported by 42 rectangular deep foundation elements called 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. See Çelebi et al. (2019) and Huang et al. (2018) for additional details.

Wilshire Grand Tower

The Wilshire Grand Tower in downtown Los Angeles is a 73-story mixed-use office and hotel building with a surrounding podium. The top of the structure features an architectural roof top sail and spire. The sail is a steel structure standing 97 feet above the main roof, and the tubular steel spire extends 176 feet above the sail (Figure 2). With the spire, this is the tallest building west of the Mississippi River with a height of approximately 1,100 feet. The tower has a roughly rectangular floor plan with dimensions of up to 244 by 112 feet. The typical story height varies from 11.5 feet to 14 feet. The vertical load carrying system consists of concrete over metal deck supported by steel beams, steel box columns filled with concrete, and concrete core walls. The lateral force resisting system of the building consists of 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. A total of 170 braces are placed at three locations along the height of the structure as part of the outrigger system and three-story tall steel belt trusses wrap the building at two levels. The tower is supported on an 18-foot thick concrete mat foundation which bears on bedrock. See Çelebi et al. (2020) and Huang et al. (2018) for additional details.

51-Story Residential Building

The 51-story residential building located in downtown Los Angeles comprises 51-stories above grade with an additional three levels below. Levels 1 to 6 comprise the podium of the building, whereas the tower of the building extends from Level 6 to the roof. The plan areas of the podium and tower have approximate dimensions of 321 by 118 feet and 156 by 95 feet, respectively. There is no seismic joint or separation between the tower and podium levels of the structure. The vertical and lateral load-carrying system consists of a dual-core concrete shear wall and perimeter concrete column system. The two load-carrying systems are interconnected with concrete flat slabs. The tower is supported on a concrete mat foundation that varies in thickness from 5 to 13 feet. The podium rests on a combination of continuous and spread footings and a few smaller mat footings. See Çelebi et al. (2021) for additional details.

24-Story Government Building

The 24-story government building in San Diego is 24 stories above and 2 stories below ground level. In-plan shape of the building is best described as irregular-rectangular and asymmetric.

The base dimensions of the building are approximately 296 by 199 feet, whereas typical floor dimensions are 253 by 100 feet. The vertical load carrying system consists of concrete over metal deck supported by steel beams and columns. The lateral load resisting system consists of special steel moment frames in each direction. In addition, viscous dampers are located along the height of the structure from Level 6 to the roof, in the transverse direction only. The building is supported on a concrete mat foundation that varies in thickness from 3 to 18 feet. See Çelebi and Swensen (2021) for additional details.

Table 1. Summary of selected features of four instrumented tall buildings involved in recent response studies

Building	Salesforce Tower	Wilshire Grand Tower	51-story Resid Bldg	24-story Govt Bldg
No. of Stories (Above/Below Ground Level)	61/3	73/5	51/3	24/2
Construction Material	Mixed	Mixed	Reinforced Concrete	Steel
Structural System	Concrete core shear walls with steel gravity framing	Concrete core shear walls with steel beams and concrete-filled steel box columns, three BRB outriggers, and two truss-belt systems	Concrete core shear walls and concrete columns	Steel moment frames with viscous dampers
Shear Wall to Floor Area Ratio (%)	1.24-3.95	4.0-5.8	~2.9	N/A
No. of Channels	32 accelerometers	36 accelerometers	30 accelerometers	24 accelerometers
Recorded Events	M4.4 Berkeley Earthquake of January 4, 2018	M4.5 S. El Monte Earthquake of Sept. 18, 2020 **M7.1 Ridgecrest Earthquake of July 5, 2019** M6.4 Ridgecrest Earthquake of July 4, 2019	M7.1 Ridgecrest Earthquake of July 5, 2019	M7.1 Ridgecrest Earthquake of July 5, 2019

Summary of Seismic Monitoring Arrays

Salesforce Tower

The Salesforce Tower instrumentation was completed by CSMIP in February of 2018. Thirty-two accelerometers were installed on 10 levels of the building. The vertical distribution of sensors in the building can be seen in the building section shown in Figure 1, which also includes plan views of selected instrumented floors of the building. Figure 1 was modified from the sensor layout of the building developed by CSMIP, which can be found on its website (www.strongmotioncenter.org) and includes plan views of all instrumented levels. To date, the Salesforce Tower has recorded motions from one significant earthquake, the M4.4 Berkeley Earthquake of January 4, 2018. Unfortunately, at the time of the Berkeley earthquake, only 27 of the 32 accelerometers had been installed (channels 1 to 27). However, shortly thereafter, a set of ambient data for all 32 channels was recorded.

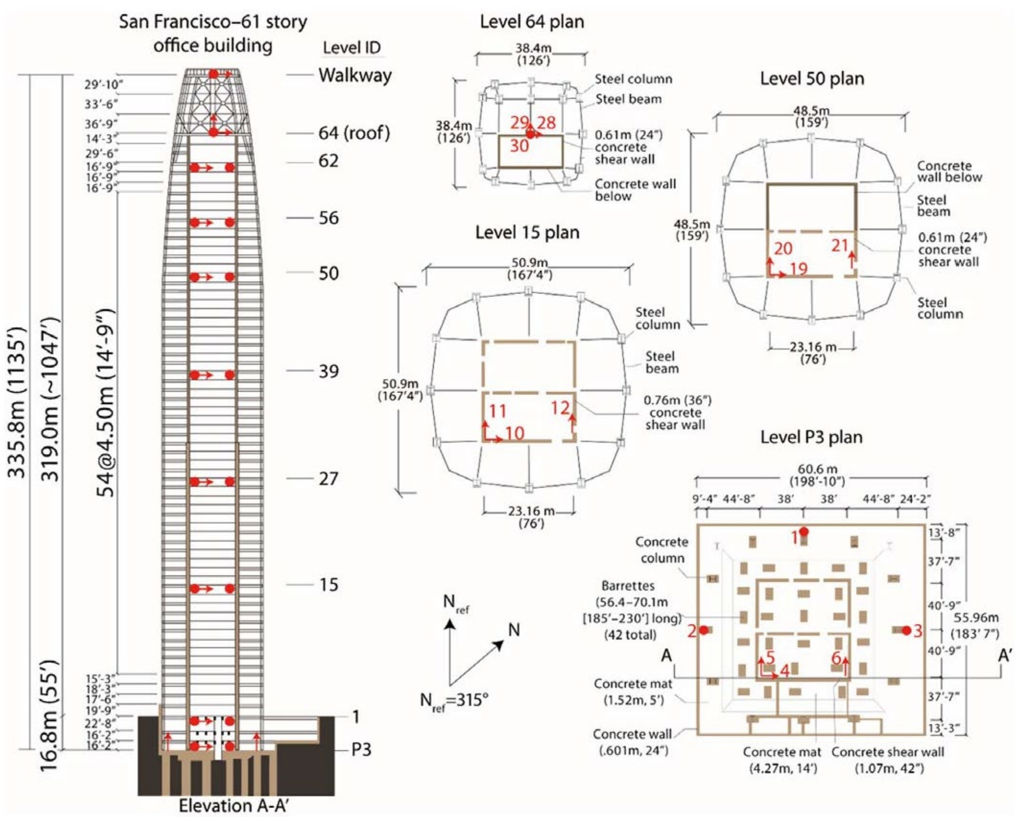

Figure 1. Vertical section, in-plan orientations, and dimensions at Levels P3, 15, 50, and 64 and shear wall distributions and thickness of the Salesforce Tower. Location and orientation of accelerometers are shown by red dots and arrows. Figure from Çelebi et al., (2019) which was modified from a figure at www.strongmotioncenter.org which includes plan views of all instrumented levels.

Wilshire Grand Tower

The instrumentation of the Wilshire Grand Tower by CSMIP was completed in June of 2017 by installing thirty-six accelerometers on 11 levels of the building. The vertical distribution of sensors in the building can be seen in the two building sections shown in Figure 2, which also includes a photograph of the building. The plan views of all instrumented levels can be seen in Figure 3. Figures 2 and 3 were modified from information for the building provided by CSMIP on (www.strongmotioncenter.org). To date, the Wilshire Grand Tower has recorded earthquake motions from three different significant events, which are listed in Table 1. The records from the M7.1 Ridgecrest Earthquake of July 5, 2019 were used for the analyses in Çelebi et al. (2020) and are summarized in this paper.

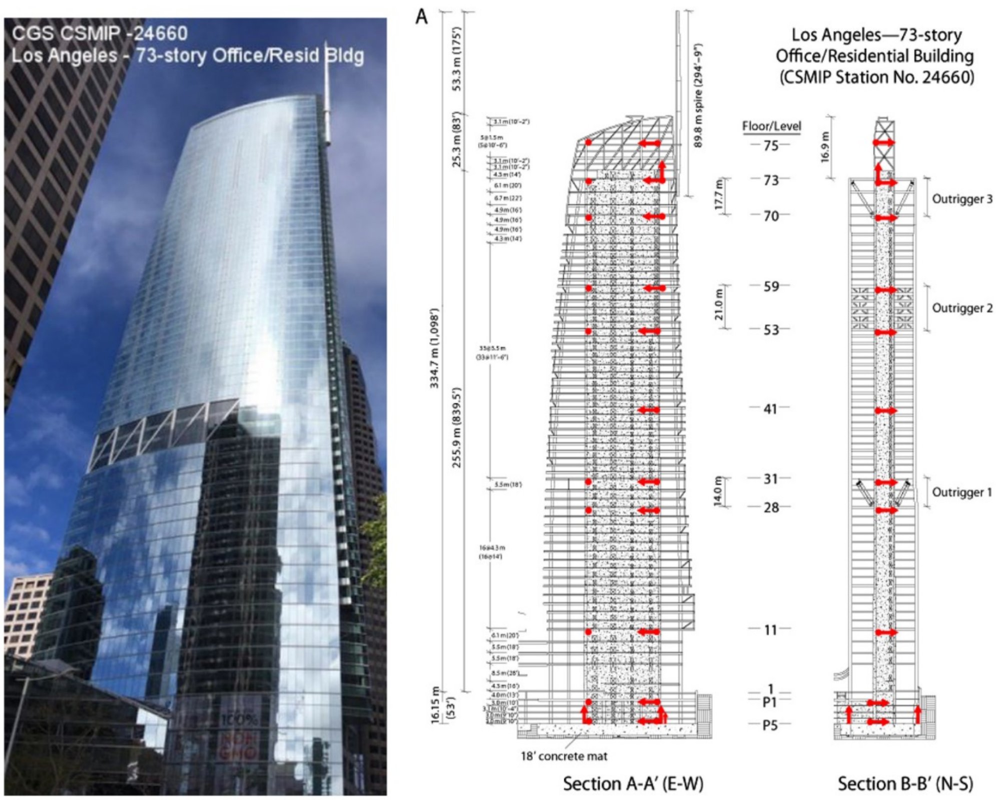

Figure 2. Photograph of the Wilshire Grand Tower and NS and EW vertical sections (www.strongmotioncenter.org). Vertical sections of the building depict vertical dimensions, the locations of outriggers and belt trusses, as well as the levels at which accelerometers are deployed (arrows indicate orientations). Figure from Çelebi et al. (2020), which was modified from www.strongmotioncenter.org.

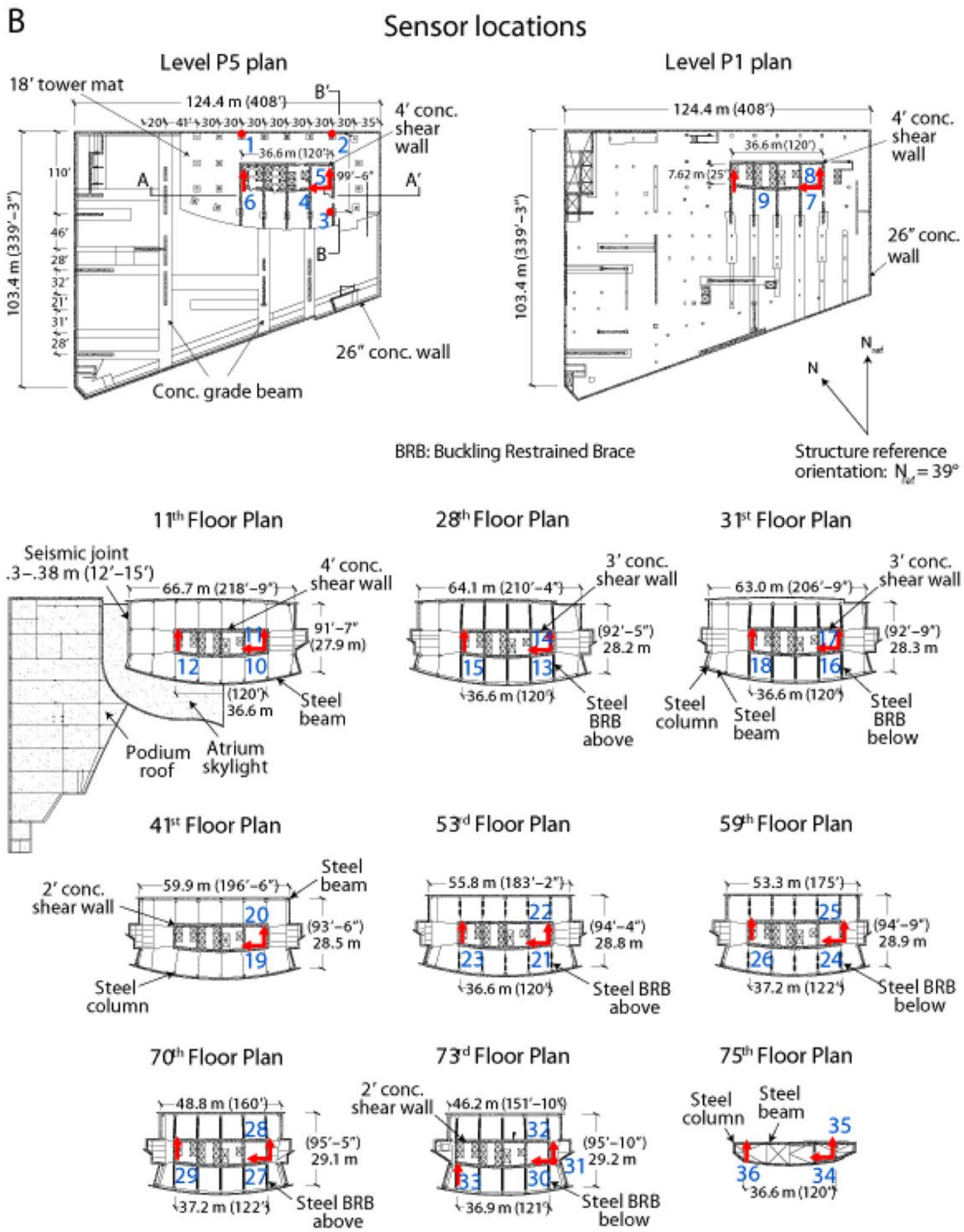

Figure 3. Plan views of floors of the Wilshire Grand Tower showing the core–shear walls and deployed accelerometers with locations and orientations. Figure from Çelebi et al. (2020), which was modified from www.strongmotioncenter.org.

51-Story Residential Building

The 51-story residential building was instrumented by CSMIP in April of 2019 with the installation of thirty accelerometers on eight levels of the building (Figure 4). The vertical distribution of sensors in the building can be seen in the building section shown in Figure 4, which also includes plan views of all instrumented floors of the building. Figure 4 was modified from the sensor layout of the building developed by CSMIP, which can be found on their website (www.strongmotioncenter.org). Note that Levels 13, 14, and 44 are not included in the floor numbering scheme utilized for the building (i.e. there is no Level called 13, 14 or 44 in the building). This means, for example, that the floor level identified in Figure 4 as Level 52, is actually the 49th level of the building. To date, the 51-story residential building has recorded motions from one significant earthquake, the M7.1 Ridgecrest Earthquake of July 5, 2019.

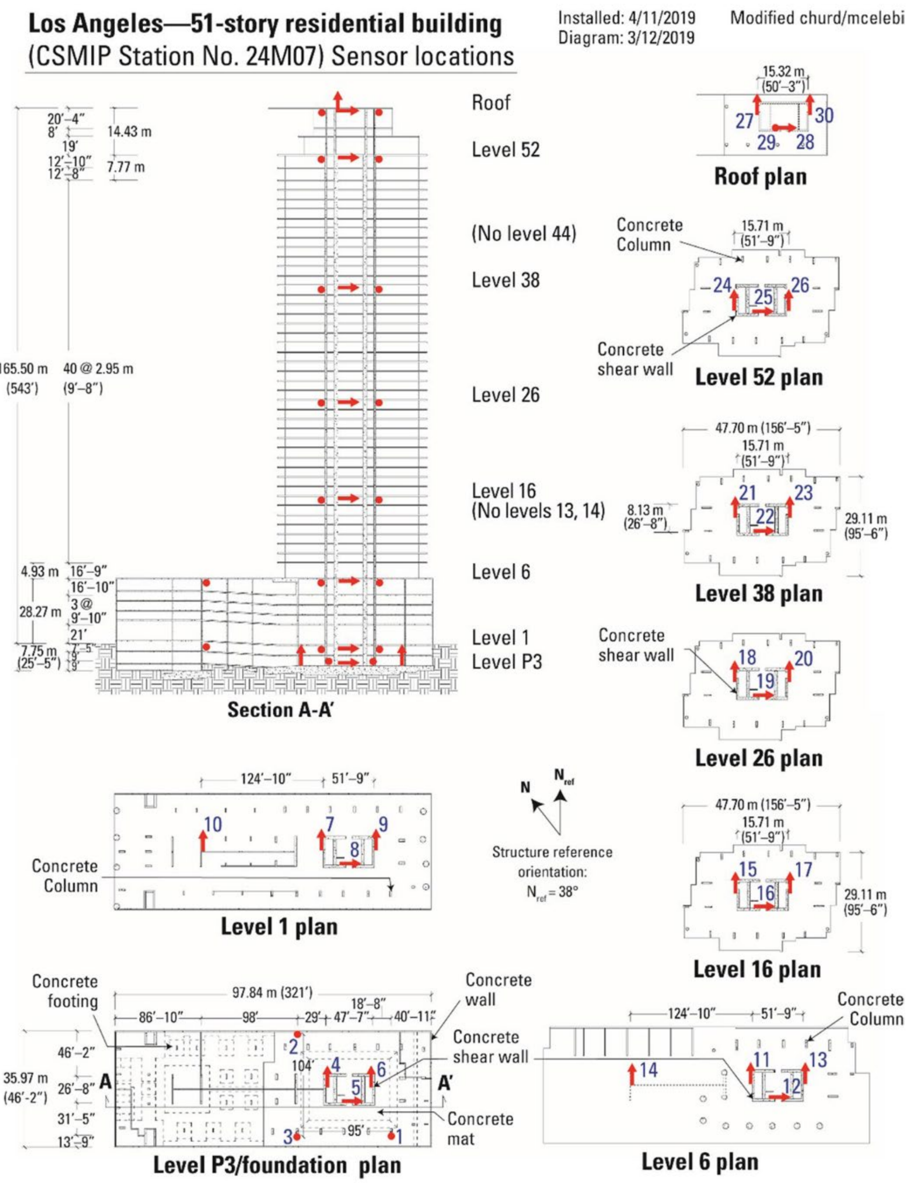

Figure 4. Eight plan views of different levels at the 51-story Residential Building show dimensions and deployed accelerometers in the N-S, E-W, and vertical orientations, according to the reference north as shown. Plan views of floors also show the core shear walls. A vertical section of the building depicts vertical dimensions and distribution of accelerometers. Figure from Çelebi et al. (2021).

24-Story Government Building

The instrumentation of the 24-story government building by CSMIP was completed in June of 2017. Twenty-eight accelerometers were installed on nine levels of the building. The vertical distribution of sensors in the building can be seen in the building section shown in Figure 5, which also includes plan views of all instrumented floors of the building. Figure 5 was modified from the sensor layout of the building developed by CSMIP, which can be found on their website (www.strongmotioncenter.org). Note that sensors 25 to 28 were installed on a pedestrian bridge, which is separated from the building by a seismic joint. To date, the 24-story Government Building has recorded motions from one significant earthquake, the M7.1 Ridgecrest Earthquake of July 5, 2019.

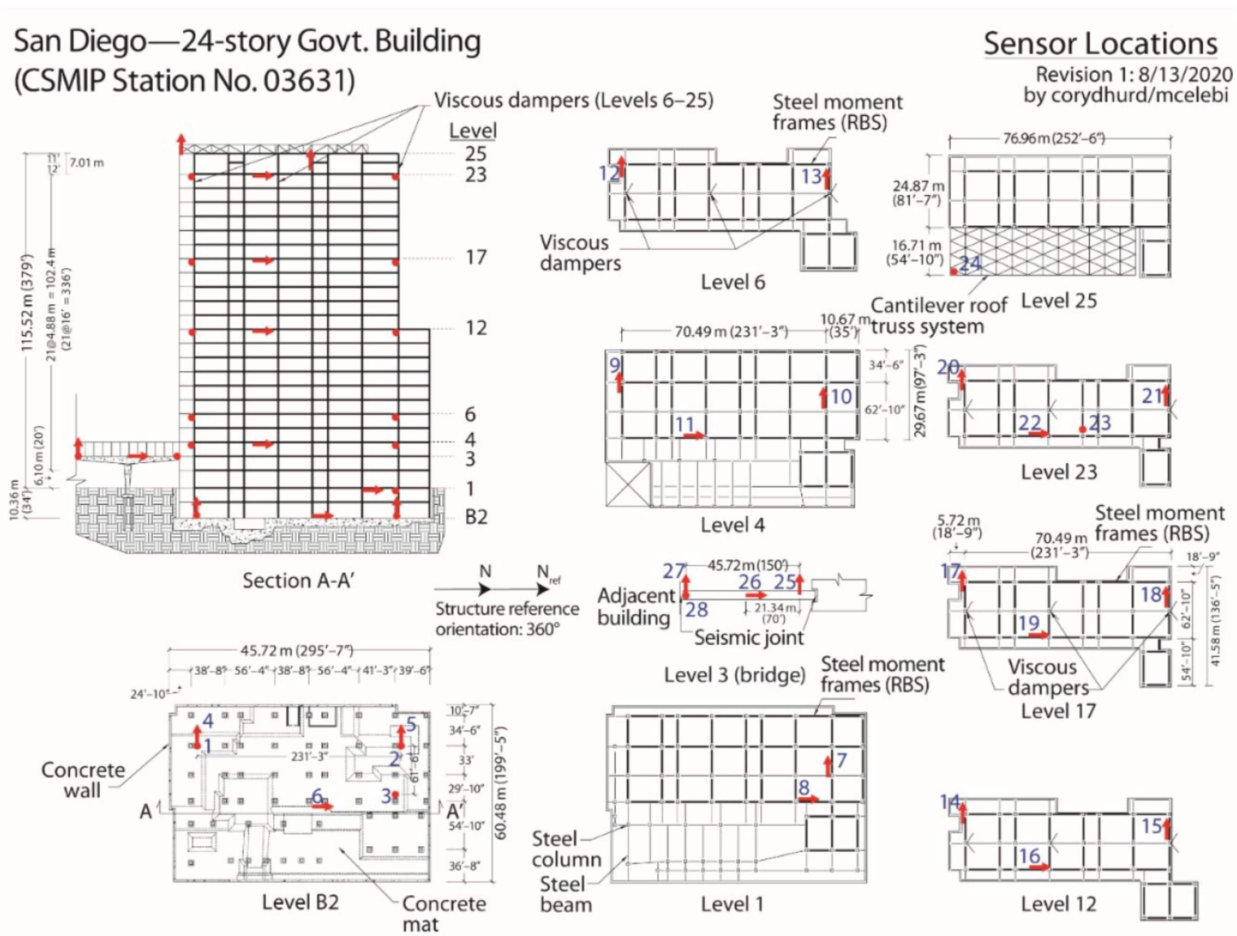

Figure 5. Instrumented vertical section and plan views that show dimensions, as well as arrows and dots depicting locations and orientations of accelerometers deployed throughout the 24-story Govt. Building. Figure from Çelebi and Swensen (2021).

Summary of Analysis Methods and Results

Data recorded in these four tall buildings from recent significant earthquakes were analyzed using several methods to determine their dynamic response characteristics. Through various spectral analysis techniques, including spectral ratios, time-frequency distribution plots, and cross-spectra, with associated coherency and phase angle plots, the first three modal periods and modal damping percentages were determined for each building. These modal periods and modal damping percentages were validated for each building using the N4SID system identification process. Also, through application of the N4SID process, the first three mode shapes were identified for the north-south, east-west, and torsional directions of each building.

In addition to dynamic response characteristics, average drift ratios were also computed from the response data of these four tall buildings to recent earthquakes. Data from pairs of consecutive instrumented levels were used for these analyses. Because adjacent floor levels were not instrumented in these buildings, pairs of consecutive instrumented levels are typically several floor levels apart. As a result, the calculated drift is an average drift which occurs over several levels.

The modal periods, modal damping percentages, and maximum drift ratios determined from the recent response studies of these four tall buildings are summarized in Table 2. Additional details of the analyses performed, as well as the results obtained from these studies, can be found in the references previously mentioned in this paper.

Table 2. Summary of modal periods, modal damping percentages and maximum drift ratios determined from recent response studies of four instrumented tall buildings

		Salesforce Tower			**Wilshire Grand Tower**			**51-story Residential Bldg**			**24-story Govt Bldg**		
		NS	**EW**	**TOR**	**NS**	**EW**	**TOR**	**NS**	**EW**	**TOR**	**NS**	**EW**	**TOR**
Modal Period (sec)	**1**	5.00	5.00	1.30	6.25	3.70	2.38	4.76	3.57	2.22	3.45	3.33	3.33
	2	1.20	1.11	0.57	1.56	0.83	0.93	1.06	0.83	0.82	1.11	1.09	1.05
	3	0.52	0.50	0.33	0.64	0.38	0.48	0.46	0.38	0.29	0.67	0.64	0.63
Modal Damping (%)	**1**	1.30	0.60	1.50	3.55	1.48	2.25	2.40	2.10	2.20	4.40	1.30	1.10
	2	1.80	1.00	1.20	2.06	2.37	2.62	1.60	2.00	1.70	4.50	4.00	2.40
	3	1.00	1.20	2.10	2.60	1.00	0.49	2.60	1.20	1.70	5.40	2.90	1.70
Max Drift Ratio (%)		0.015	-	-	0.11	0.06	-	0.145	0.145	-	-	0.065	-

Discussion of Results and Conclusions

This paper summarizes the response studies of four tall buildings in California which have recently been completed. These buildings were instrumented by CSMIP and include the Salesforce Tower in San Francisco, the Wilshire Grand Tower in Los Angeles, the 51-story Residential Building in Los Angeles and the 24-story Government Building in San Diego. Data recorded by these buildings from recent earthquakes were analyzed using various methods to determine dynamic response characteristics and drift ratios. Selected results are summarized in Table 2.

The results summarized in Table 2 reflect the dynamic response characteristics due to the largest shaking experienced by these buildings to date; however, in each case this shaking was relatively light. As a result, the structural responses did not exhibit significant nonlinearity or shifts in vibrational periods. Given the seismic hazard associated with the locations of these buildings it is anticipated that stronger shaking may be experienced in the future. With higher shaking intensities in the future, the buildings may exhibit different behaviors and performances, and the vibrational periods may lengthen beyond those identified in these studies.

In general, critical damping percentages for the first mode of these buildings were determined to be <2.5%. This is consistent with other studies of earthquake response data from instrumented buildings in the United States, Japan, Turkey, and other countries. It is also consistent with design recommendations published by the Los Angeles Tall Buildings Structural Design Council and the Pacific Earthquake Engineering Research Center, both of which recommend 2.5% damping based on analyses such as these.

Drift ratios are important to quantify because they can be assessed as an indicator of damage. In the case of these four buildings the measured motions, and therefore the computed drift ratios, were determined to be too small to have caused damage.

References

Çelebi, M., Haddadi, H., Huang, M., Valley, M., Hooper, J. and Klemencic, R. (2019). The Behavior of the Salesforce Tower, the Tallest Building in San Francisco, California Inferred from Earthquake and Ambient Shaking, Earthquake Spectra, Volume 35, No. 4, pages 1711–1737, November 2019 (https://doi.org/10.1193/112918EQS273M).

Çelebi, M., Ghahari, S. F., Haddadi, H. and Taciroglu, E. (2020). Response study of the tallest California building inferred from the Mw7.1 Ridgecrest, California earthquake of 5 July 2019 and ambient motions, Earthquake Spectra, Vol. 36(3) 1096–1118, (https://doi.org/10.1177/8755293020906836).

Çelebi, M., Swensen, D. and Haddadi,H. (2021). Response study of a 51-story-tall Los Angeles, California building inferred from motions of the Mw7.1 July 5, 2019 Ridgecrest, California earthquake, Bulletin of Earthquake Engineering, online version February 19, 2021. (https://doi.org/10.1007/s10518-021-01053-9).

Çelebi, M. and Swensen, D. (2021). Response study of a tall San Diego, California building inferred from the M7.1 July 5, 2019 Ridgecrest, California earthquake motions*, in print,* The Open Construction & Building Technology Journal, Volume 15, 2021.

Huang, M., Swensen, D., Haddadi, H. and Reitz, T. (2018). Strong motion instrumentation of two new super tall buildings in California and results from ambient and earthquake response data, SMIP18 Seminar Proceedings, 117-138.