The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

ANALYSIS OF RECORDED RESPONSES OF SUPER TALL BUILDINGS IN CALIFORNIA DURING LARGE DISTANT AND MODERATE CLOSE EARTHQUAKES

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ABSTRACT:

Super tall buildings are sensitive to large distant earthquakes because these large earthquakes can generate significant long-period ground motions. The response of a super tall building during a large distant earthquake can be as significant as the response to a close moderate earthquake. In California, several super tall buildings have been extensively instrumented with strong-motion accelerometers and their responses to large distant and close moderate earthquakes have been recorded. In this paper, the recorded data from two super tall buildings, a 52-story and a 54-story building in downtown Los Angeles, 30 km from the M6.7 1994 Northridge, 170 km from the M7.3 1992 Landers, and 190 km from the M7.1 1999 Hector Mine earthquake, are analyzed. Key building response parameters including the inter-story drift ratios and the total roof drift, which are also important engineering demand parameters in seismic designs of buildings, are computed. The response parameters for these two super tall buildings during the distant Landers and Hector Mine earthquakes, and the close Northridge earthquake are compared. The results show that the roof movements and inter-story drift ratios were larger during the distant Landers and Hector Mine earthquakes, although the floor accelerations were larger in the Northridge. It reiterates the importance of considering large distant earthquakes in the structural design of super tall buildings.

KEYWORDS: Super Tall Building, Large Earthquake, Long-Period Ground Motion, Engineering Demand Parameter, Inter-Story Drift Ratio

1. INTRODUCTION

It is well known that designs of super tall buildings with fundamental periods longer than 3 or 4 seconds need to also consider the response to large distant earthquakes because large earthquakes generate long-period ground motions that can travel a long distance (e.g., Mwafy et al., 2006). The California Strong Motion Instrumentation Program (CSMIP) has instrumented about 200 buildings in California. Significant records have been obtained from two super tall buildings in downtown Los Angeles during the 1991 Sierra Madre (M5.6, 33 km away), the 1992 Landers (M7.3, 169 km), the 1992 Big Bear (M6.5, 133 km), the 1994 Northridge (M6.7, 31 km), and the 1999 Hector Mine (M7.1, 193 km) earthquakes (Shakal et al., 1992 and 1994). Information on the instrumented buildings and the processed data are available at the Center for Engineering Strong Motion Data at http://www.strongmotioncenter.org web site. The records from large distant Landers and Hector Mine earthquakes and the moderate close Northridge earthquake are selected for analyses in this paper. The responses of these two tall buildings to the Sierra Madre and Big Bear earthquakes were relatively smaller and will not be discussed herein. Locations of the two instrumented tall buildings in downtown Los Angeles, and epicenters of the Northridge, the Landers and Hector Mine earthquakes are shown in Figure 1. It is noted that a magnitude 8.3 earthquake that is expected to occur on the segment of San Andreas Fault, only 30 miles away from downtown Los Angeles, was considered during the design of these two super tall buildings.

The 52-story building is a concentrically-braced steel frame structure at the core with outrigger steel moment frames, while the 54-story building is a perimeter steel moment frame structure (tube) with vertical setbacks at the 36th and 46th floors. The buildings were designed in 1988 and were each instrumented with 20 accelerometers by CSMIP in 1990. The structural system and sensor locations for these two buildings are shown in Figure 2. The records from sensors in only one of the horizontal directions are presented herein, i.e., the north-south direction for the 52-story building and the east-west direction for the 54-story building.

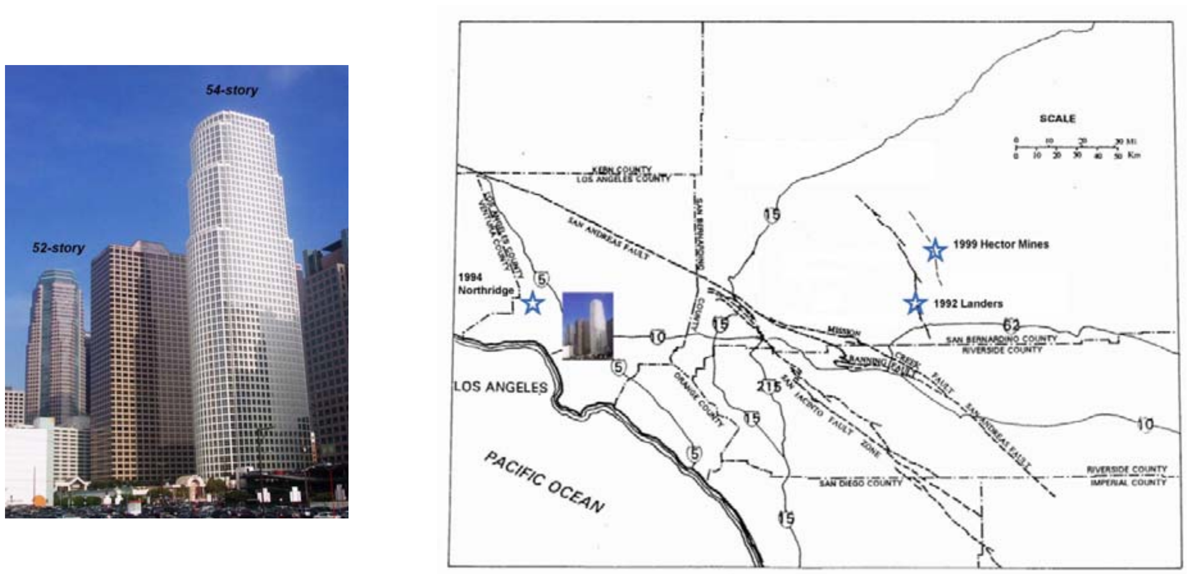


Figure 1. Photo of the 52-story and 54-story buildings in downtown Los Angeles (left), and map of the locations of these buildings and epicenters of the 1994 Northridge, the 1992 Landers and 1999 Hector Mine earthquakes(right).

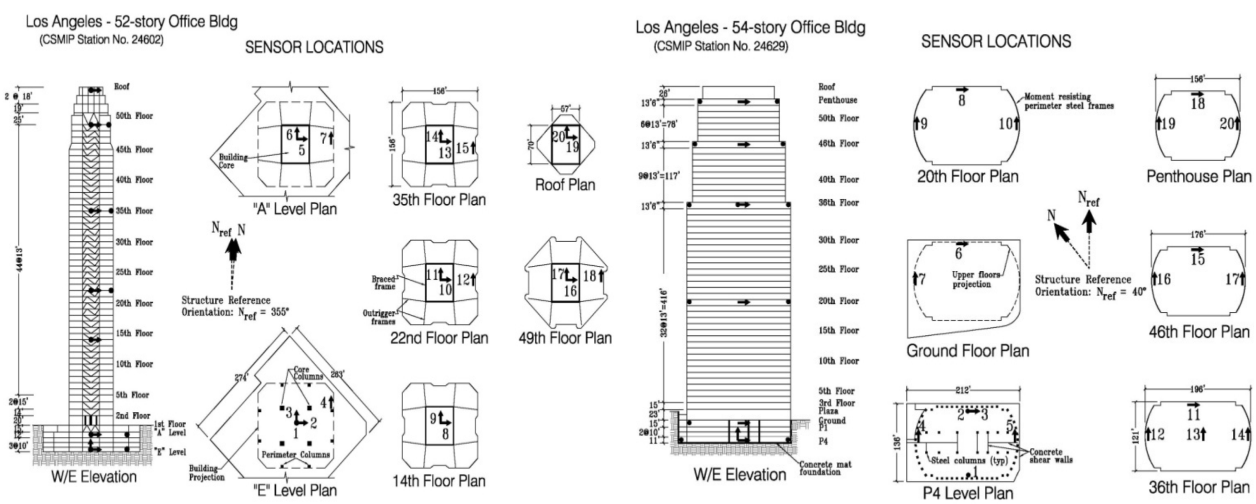


Figure 2. Instrumentation configuration of the 52-story and 54-story buildings in downtown Los Angeles.

Recently, the inter-story drift ratio (IDR) has been used as the key building response parameter for damage assessment of an instrumented building after a significant earthquake (Naeim et al., 2005). The IDR is also the key engineering demand parameter for performance-based design and analysis. For a building with every floor instrumented, the inter-story drift of any story can be calculated by differencing the displacements of the two successive instrumented floors if rocking of the building base is negligible. If the building base experiences significant rocking, then the contribution of base rocking has to be subtracted from the inter-story drift. The inter-story drift ratio is then equal to the inter-story drift divided by the story height. The computation is pretty straightforward. However, for a building with only limited number of floors instrumented, the piecewise cubic polynomial interpolation procedure can be used to compute the displacements at non-instrumented floors from the instrumented floors that are well located along the height of the building (Goel and Chadwell, 2007a&b).

2. 52-STORY BUILDING

The recorded accelerations by the sensors at the building center in the north-south direction during the 1994 Northridge earthquake are shown in Figure 3. The corresponding computed displacements are plotted in Figure 4. These records show that the building has a fundamental period of about 6 seconds and a second modal period of about 1.8 seconds in the NS direction. The maximum roof displacement relative to the base (roof drift) is 14.2 cm. For a vibration with a period of 6 seconds, the acceleration corresponding to a 14 cm displacement is 1.5%g, which can hardly be seen in the acceleration record with a peak of 41%g in Figure 3. However, the building motion in the latter part of the displacement record was mainly in the fundamental mode as shown in Figure 4.

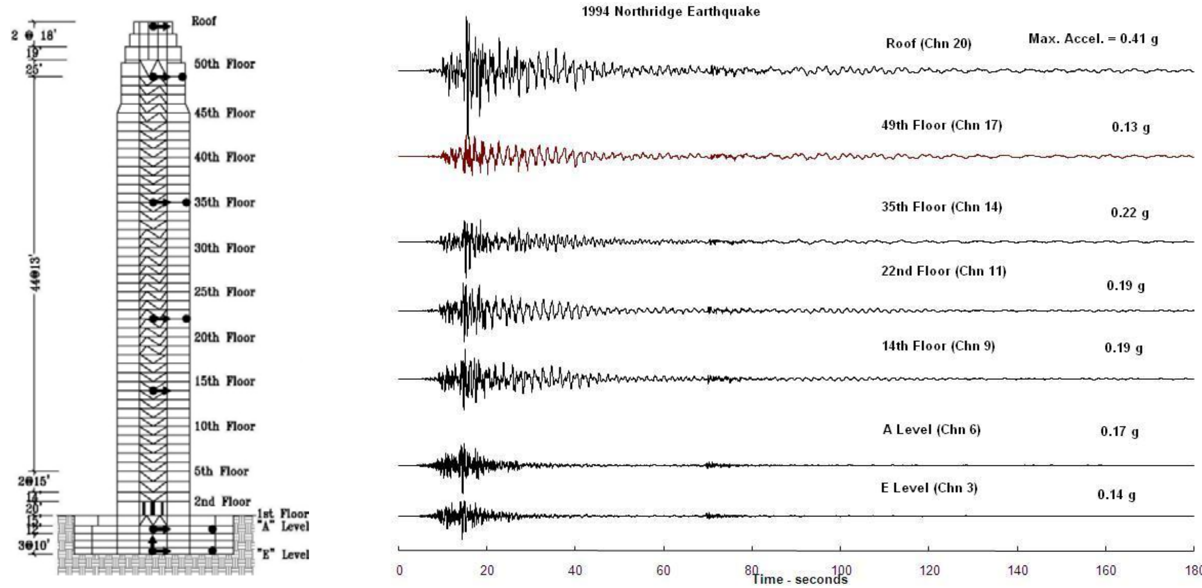


Figure 3. Recorded accelerations in the north-south direction from the 52-story Building in Los Angeles during the 1994 Northridge earthquake.

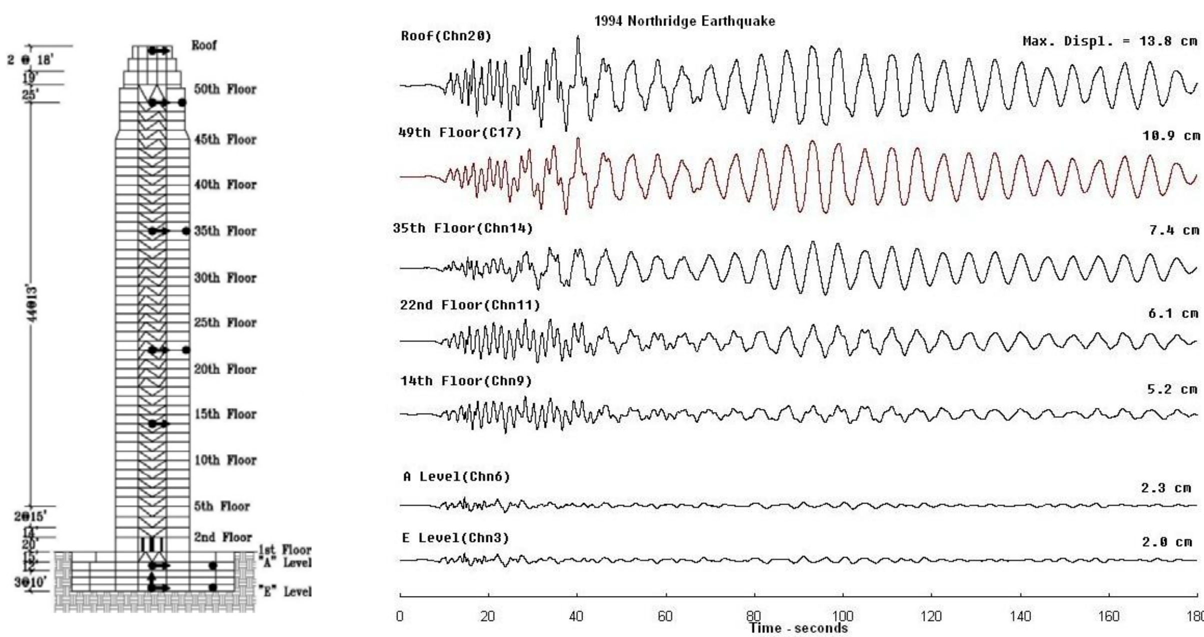


Figure 4. Displacements in the north-south direction corresponding to the recorded accelerations in Figure 3.

To compute the inter-story drift for each story, it is necessary to estimate the displacements at the 51 non-instrumented floors. The piecewise cubic polynomial interpolation procedure is used to compute the absolute displacements at the 51 non-instrumented levels from the displacements determined from the measurements at the seven levels shown in Figure 4. Figure 5(a) shows the interpolated absolute displacements along the height at time 20 seconds, for example. The displacement curve is smoothly interpolated from the measurements at seven instrumented floors. The curve is similar to the second mode shape. The drift of any level, i.e., displacement of each level relative to the building base (Level E), is computed from the absolute displacements. The inter-story drift ratio for any story is obtained by differencing the absolute or relative displacements at two adjacent levels and then dividing it by the story height.

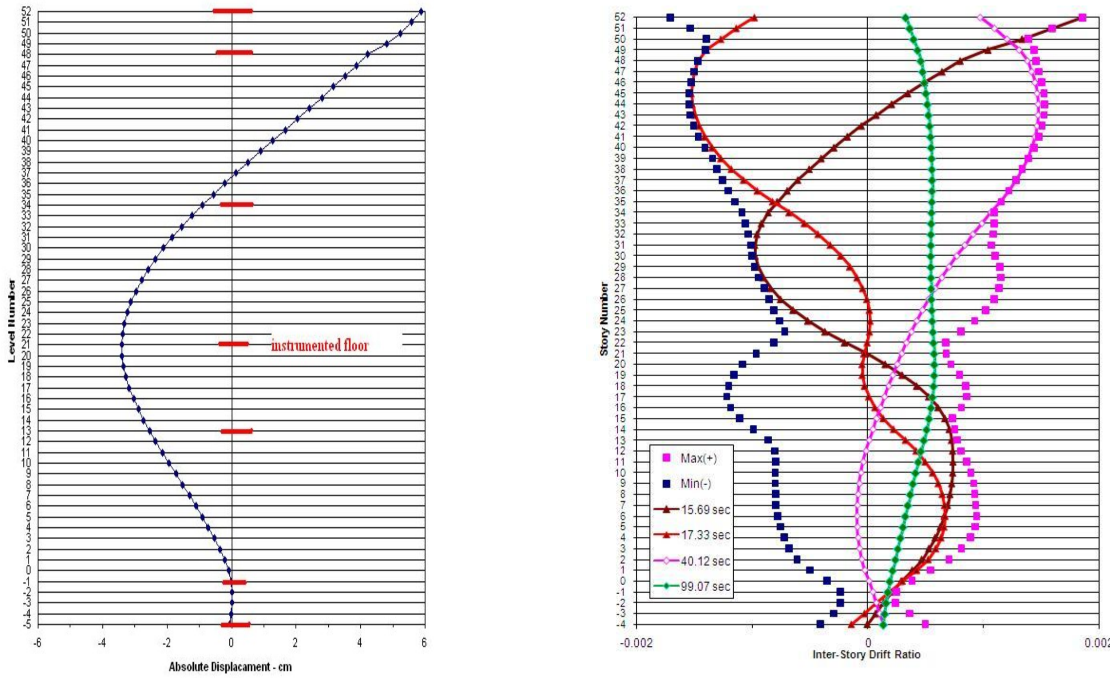
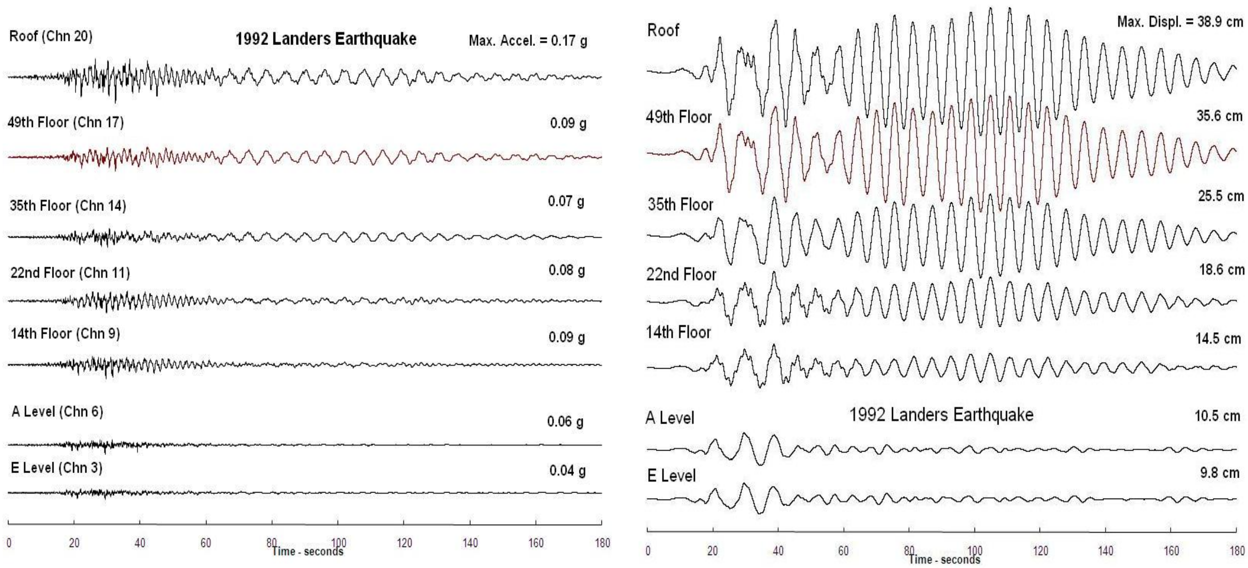


Figure 5. (a) Absolute displacements of the 52-story building, interpolated from the recorded motions at the seven instrumented floors, at time 20 seconds during the 1994 Northridge earthquake; (b) The maximum and minimum inter-story drift ratios along the height of the 52-story building (squares) and the inter-story drift ratio profile at four different times, from 15.69 to 99.07 seconds.

As seen in Figures 3, 4 and 5, the building response to the Northridge earthquake was dominated by second and third modes in the early part of the record, while the later part of the record, i.e., after 90 seconds, was mainly the response in the first mode with a period of about 6 seconds. The inter-story drift ratios along the height at four different times are plotted in Figure 5(b). The maximum (positive) and minimum (negative) inter-story drift ratios for all stories over the whole record are also plotted in Figure 5(b), which are the envelopes. In other words, the IDR profile at any time is between the maximum and minimum envelopes. It can be seen from this figure that the maximum inter-story drift ratio occurred at the early part of the record, especially for upper stories, in which the second and third modes were dominant. In other words, the maximum inter-story drift ratios of the building response to the Northridge earthquake were caused by the second or third modal responses. The maximum inter-story drift ratio of 0.186% occurred on the top story, while lower stories have lower inter-story drift ratios.

Figures 6(a) and 6(b) show the recorded accelerations and corresponding computed displacements from the 1992 Landers earthquake. The fundamental mode can be clearly seen in the acceleration records and it dominates in displacement records. The maximum roof displacement relative to the base (roof drift) is 40.0 cm. Similar to the Northridge records, the displacements at non-instrumented floors were interpolated from the records for the Landers earthquake. The maximum and minimum inter-story drift ratios for all stories during the Landers earthquake are plotted and compared with the ratios from the Northridge earthquake in Figure 7. The maximum inter-story drift ratio of 0.226% occurred on the 37th story, mainly due to the fundamental mode. It can be seen from Figure 7 that the inter-story drift ratios for all stories, except the top two stories, are larger in the Landers earthquake. Normally, we expect that the IDR for the basement levels to be nearly zero because of the basement embedment. However, Figure 7 shows that the IDR at the lowest 4 stories is not zero. It is not clear if this is due to the interpolation procedure or the noise level associated with the data.



(a) (b)

Figure 6. (a)Recorded accelerations and (b)displacements in the north-south direction from the 52-story Building in Los Angeles during the 1992 Landers earthquake.

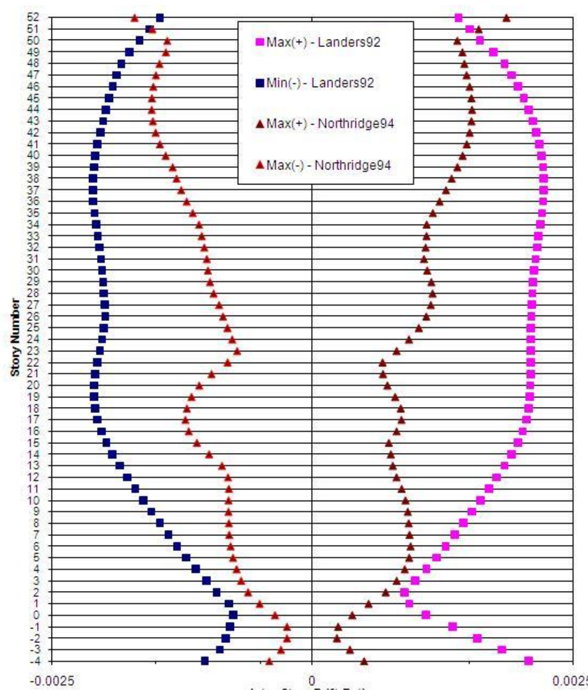


Figure 7. Comparisons of the maximum and minimum inter-story drift ratios along the height of the 52-story building during the 1992 Landers (squares) and 1994 Northridge earthquake (triangles).

3. 54-STORY BUILDING

The recorded accelerations by the sensors on the north wall in the east-west direction during the 1994 Northridge earthquake are shown in Figure 8. The corresponding displacements are plotted in Figure 9. The maximum accelerations were 0.09 g at the base and 0.14 g on the roof. The building has a fundamental period of about 5.1 seconds and a second modal period of 1.85 seconds. The maximum roof drift was 17.6 cm.

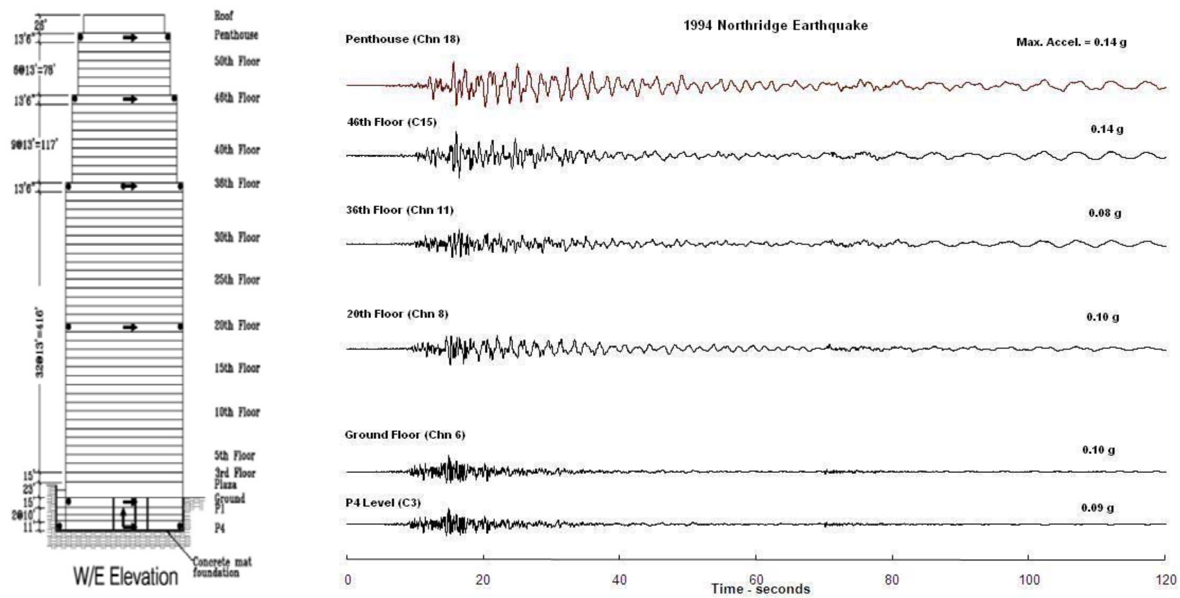


Figure 8. Recorded accelerations in the east-west direction from the 54-story Building in Los Angeles during the 1994 Northridge earthquake.

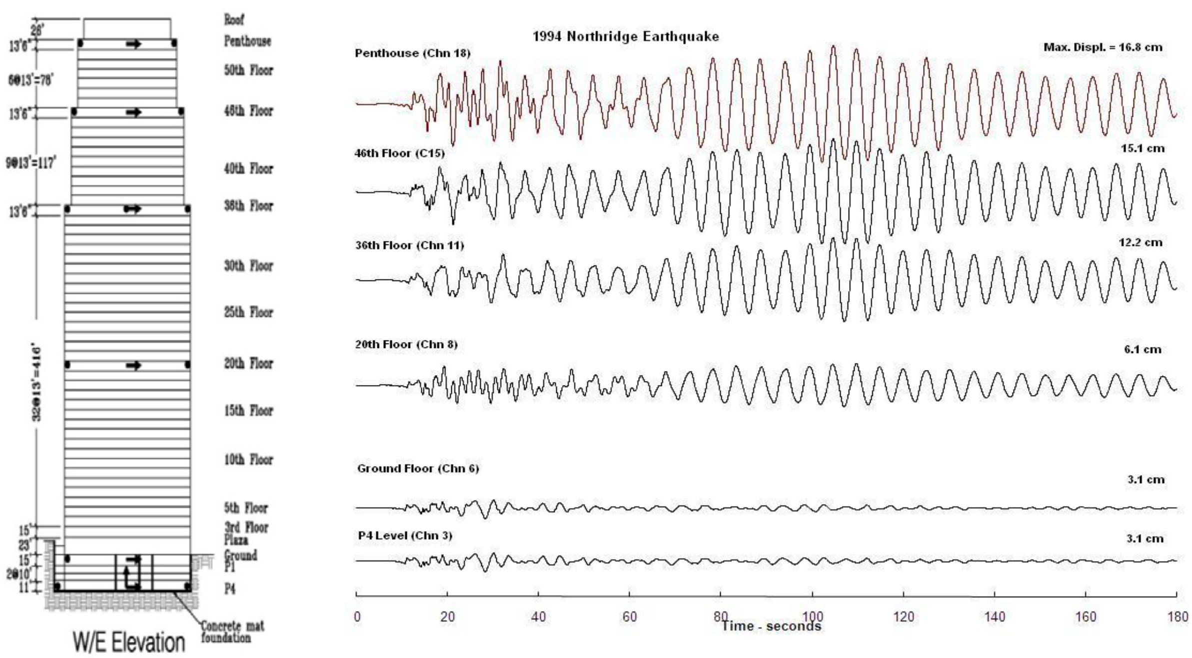
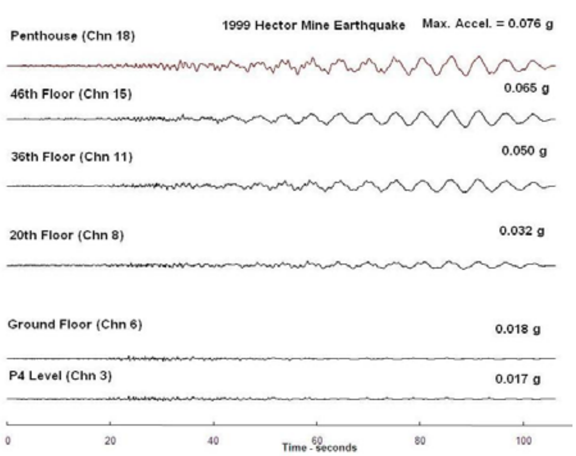
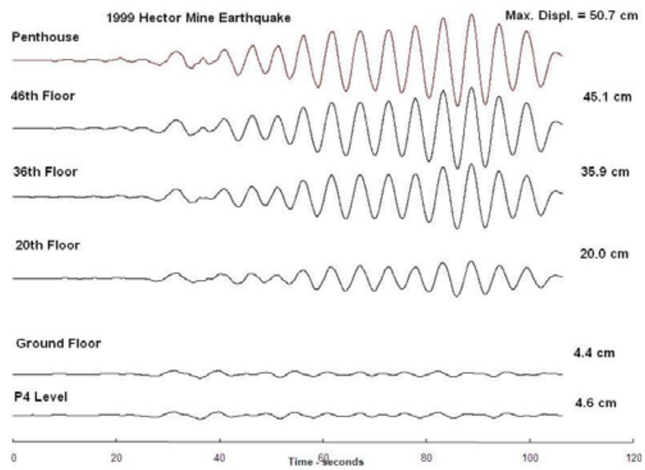


Figure 9. Displacements in the east-west direction, corresponding to the recorded accelerations in Figure 8.

The acceleration and displacement records from the 1999 Hector Mine earthquake are shown in Figures 10(a) and 10(b), respectively. The maximum accelerations were 0.02 g at the base and 0.08 g on the roof. The fundamental mode was dominant in both the acceleration and displacement records. The second mode was not excited by the 1999 Hector Mine earthquake. The maximum roof drift was 49.5 cm, almost three times as large as the drift during the Northridge earthquake. The maximum and minimum inter-story ratios for the Hector Mine earthquake are plotted and compared with those for the Northridge earthquake. The largest inter-story ratio of 0.303% occurred at the 16th story during the Hector Mine earthquake, while the largest ratio of 0.247% occurred at the highest story. The inter-story drift ratios for all stories, except the top five stories, are larger in the Hector Mine earthquake.



(a)



(b)

Figure 10. (a)Recorded accelerations and (b)displacements in the east-west direction from the 54-story Building in Los Angeles during the 1999 Hector Mine earthquake.

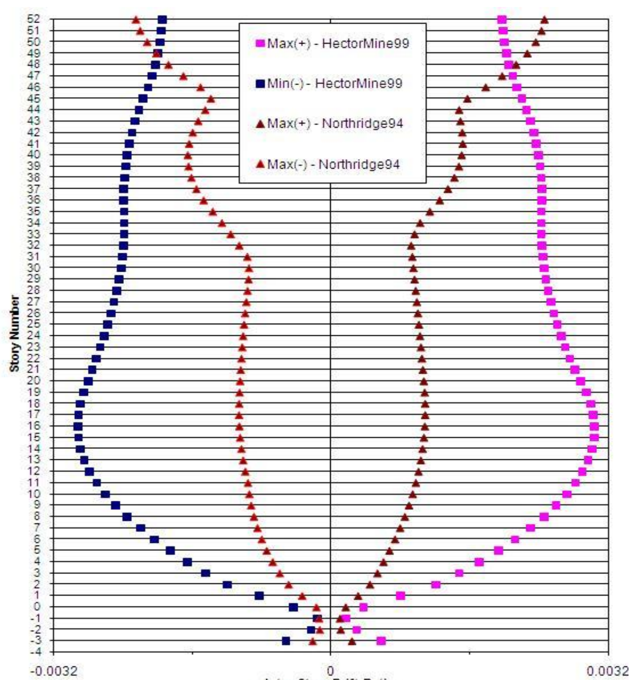


Figure 11. Comparisons of the maximum and minimum inter-story drift ratios along the height of the 54-story building in Los Angeles during the 1999 Hector Mine (squares) and 1994 Northridge earthquakes (triangles).

The response parameters for the two super tall buildings in downtown Los Angeles during the moderate close Northridge earthquake are summarized and compared with those for the large distant Landers and Hector Mine earthquakes in Table 1.

Table 1. Comparisons of Responses of Two Super Tall Buildings in Los Angeles for Distant Larger Events versus Closer Moderate Events

	Earthquake	**Max accel. at base**	**Max. accel. on roof**	**Max. roof drift**	**Max. inter-story drift ratio**
52-story Building	1994 Northridge (D=30km, M6.7)	0.14 g	0.41 g	14.2 cm	0.186% (roof)
	1992 Landers (D=170km, M7.3)	0.04 g	0.17 g	40.0 cm	0.226% (37th story)
54-story Building	1994 Northridge (D=30km, M6.7)	0.09 g	0.14 g	17.6 cm	0.247% (roof)
	1999 Hector Mine (D=190km, M7.1)	0.02 g	0.08 g	49.5 cm	0.303% (16th story)

CONCLUSIONS

Analyses and comparisons of the strong-motion data recorded from two super tall buildings in downtown Los Angeles during the moderate, close Northridge earthquake and the larger distant Landers and Hector Mine earthquakes show that the inter-story drift ratios and total roof drift were larger during larger distant earthquakes. The importance of including large distant earthquakes in the structural design or seismic safety assessment of super tall buildings is confirmed.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. Anthony Shakal of CSMIP for his comments and review of this article.

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