CSMIP STRONG-MOTION INSTRUMENTATION AND RECORDS FROM THE I10/215 INTERCHANGE BRIDGE NEAR SAN BERNARDINO

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The 2540-foot long, multi-span, curved I10/215 interchange bridge near San Bernardino was extensively instrumented by the California Strong Motion Instrumentation Program (CSMIP) in cooperation with the California Department of Transportation (Caltrans). The locations of the sensors on this freeway interchange bridge were carefully planned to achieve specific instrumentation objectives. Significant sets of strong-motion records were obtained from this bridge during the magnitude 7.5 Landers and the magnitude 6.6 Big Bear earthquakes of June 28, 1992. The epicenters of these earthquakes were about 50 and 30 miles (80 and 48 km) from the bridge, respectively. The maximum ground acceleration at the bridge was about 0.10 g for both earthquakes. The relative motion of the deck across the hinges was recorded and is characterized by sharp spikes in the acceleration records with a peak value as high as 0.81 g during the Landers and 1.02 g during the Big Bear earthquake. Without the spikes the peak acceleration on the bridge would be about 0.40 g during the Landers and 0.30 g during the Big Bear earthquake. The Landers records show that the bridge structure had a period of about 1.7 seconds in the transverse direction and 1.0 second in the longitudinal direction. The maximum relative displacement between the deck and the footing of a 57-foot column was about 16 cm in the transverse direction and 5 cm in the longitudinal direction during the Landers earthquake. The maximum relative displacement across one of the hinges during the Landers earthquake was 1.2 cm in the transverse direction and 3.6 cm in the longitudinal direction.

INTRODUCTION

The I10/215 interchange near San Bernardino is a large interchange with several bridge structures that link the east-west I10 freeway with the north-south I215 freeway

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about 53 miles (85 km) east of downtown Los Angeles. The interchange bridge instrumented by CSMIP is the connecting structure shown in Figure 1 that carries two lanes of traffic from eastbound I10 to northbound I215. The bridge is a long and curved concrete structure, typical of many in California and similar to the I5/Hwy14 interchange bridge which was damaged in the 1971 San Fernando earthquake. The I10/215 bridge, about 2540 feet long and 90 feet tall near the center, was seismically strengthened by Caltrans in 1991 and instrumented by CSMIP in early 1992 with support by Caltrans.

The Landers and Big Bear records are the first significant records from a curved multi-span reinforced concrete bridge in California. The maximum ground acceleration near the bridge was about 0.10 g during both earthquakes. Accelerations as high as 0.81 g during the Landers earthquake and as high as 1.02 g were recorded on the bridge superstructure. These high accelerations occurred in many sharp spikes inferred to be generated by the interactions of bridge superstructures at the separation joints (hinges). The bridge was inspected for damage after the earthquakes by Caltrans staff (Caltrans, 1992a). No evidence of damage to the cable restrainers at hinges was found. However, the north barrier near the hinge next to Bent 3 spalled with exposed rebars and the seat at this hinge had three hairline shear cracks.

I10/215 INTERCHANGE BRIDGE

The I10/215 interchange near San Bernardino includes three multi-span elevated concrete bridge structures that connect Interstate Freeways 10 and 215. An aerial view of the interchange is shown in Figure 1. Figure 2 shows plan and elevation views of the instrumented bridge. The bridge is a curved structure 2540 feet in length and 41 feet in width. The superstructure is a continuous multi-cell (4 cells) prestressed concrete box girder supported by 15 single-column bents and two abutments. There are five hinges (expansion joints) in the superstructure that separate the bridge structure into six frame structures of different lengths and different numbers of spans. The five hinges have a seat width of 30 or 34 inches. The hinge support for the girders is provided by elastomeric bearing pads. There are cable restrainers at the hinges. The substructure consists of 15 single-column bents. The typical column section is octagonal in shape (8 feet by 5.5 feet) and the column height ranges from 38 to 89 feet. The column footings are supported by concrete piles. Specifically, Bent 3 and Bent 8 are founded on footings with 36 piles. The abutments at the north and west ends of the bridge are connected monolithically to the box girder and are supported on concrete piles.

The I10/215 interchange bridge was designed in 1969 and built in 1973. As part of the Caltrans Single Column Retrofit Program, the retrofit work on this bridge was begun in 1991 and completed in early 1992. To increase the ductility of the columns, they were encased in 3/8" thick steel jackets and the gap between the existing concrete and the steel jacket was pressure grouted. Full-height steel jackets were

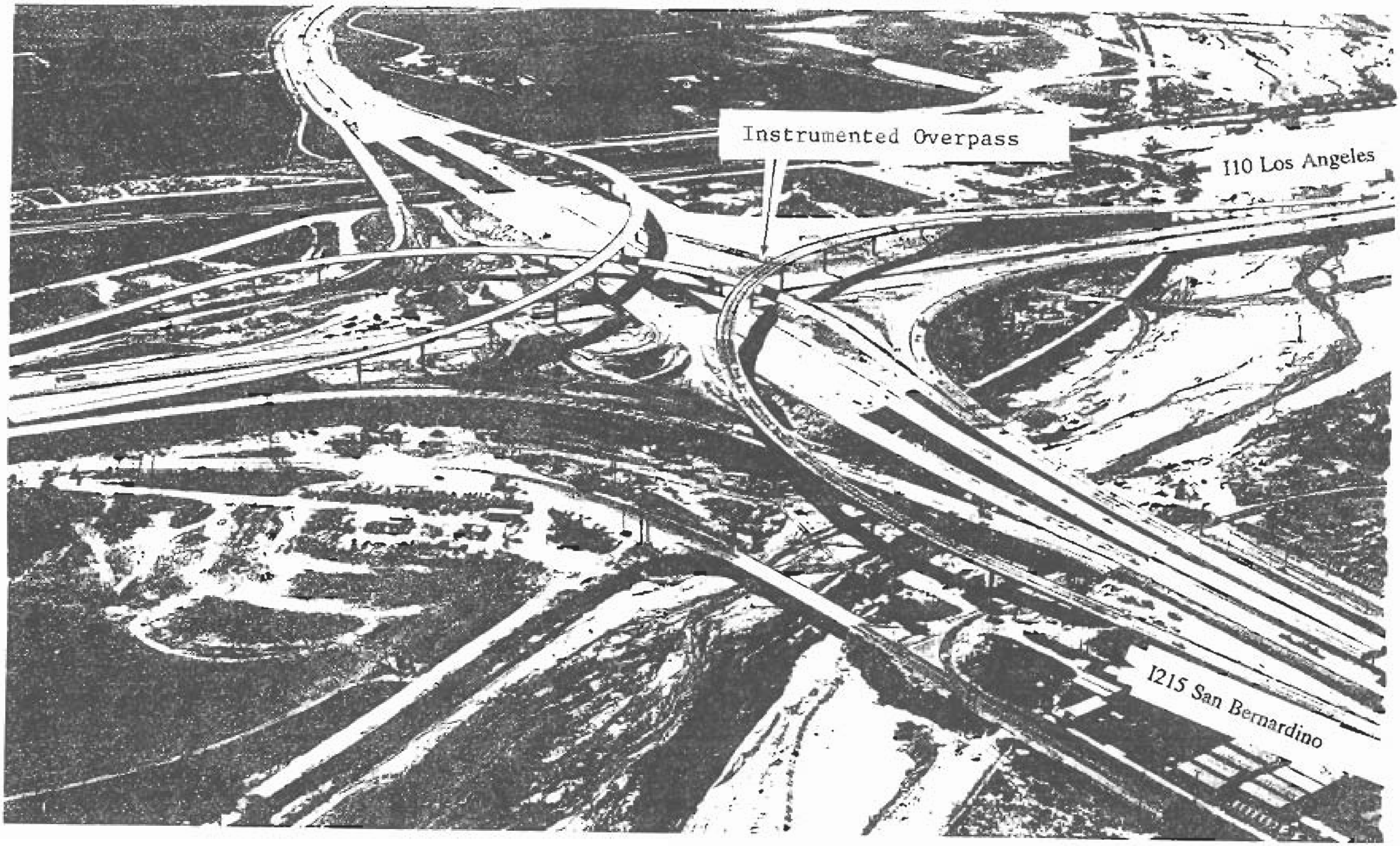

Figure 1 Aerial view of the I10/215 interchange near San Bernardino. The overpass instrumented is the connecting bridge that carries two lanes of traffic from eastbound I10 toward northbound I215. Photograph courtesy of Caltrans.

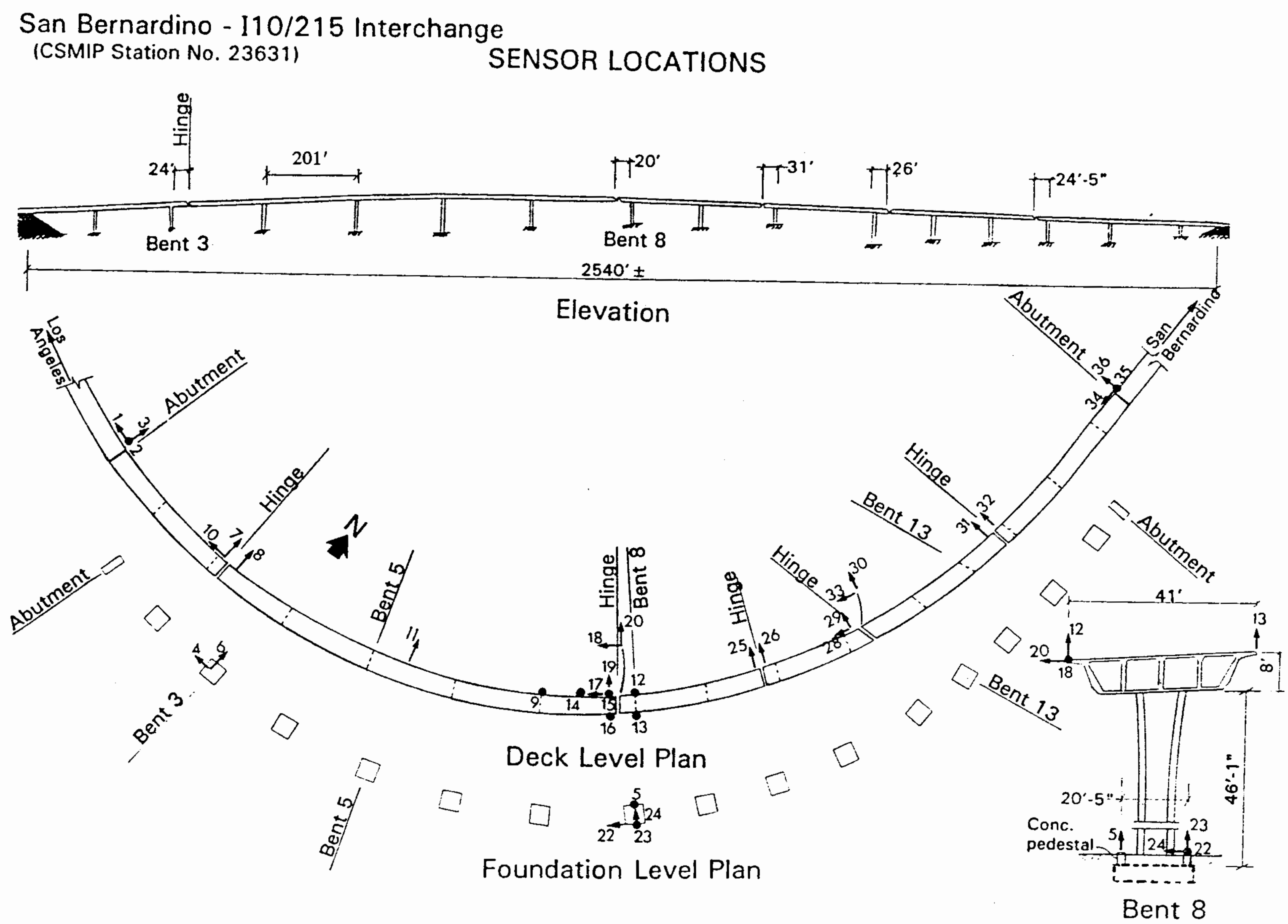

Figure 2 Plan and elevation views of the I10/215 interchange bridge near San Bernardino. Sensor locations and directions are indicated.

used to encase the columns at 12 of the 15 bents. Footings at 10 of the 12 bents with full-height steel jackets were increased in size with driven steel piles to increase the moment capacity of the footings. Steel jackets at three of the 15 bents (i.e., Bents 8, 12 and 14) are only 18 feet high from the footing. Footings at these three bents were not modified. The abutments were retrofitted by building a 60 feet by 6 feet supplemental support (abutment catcher) next to the abutment to prevent the superstructure from dropping excessively. In addition, the existing restrainers across all five hinges were replaced with longer cable restrainers. Details on the bridge retrofit strategy and design are given in Zelinski (1990) and Caltrans (1992b).

INSTRUMENTATION OF THE BRIDGE

A 36-sensor instrumentation plan for the bridge was developed by CSMIP in 1988. The instrumentation plan was based on past experience in instrumenting bridges and suggestions from researchers who studied strong-motion data from other instrumented bridges. It also considered the guidelines for instrumentation of highway bridges developed by Rojahn and Raggett (1981). The proposed sensor locations were reviewed by experts in the seismic response of bridges, including Caltrans staff. CSMIP staff then finalized the instrumentation plan based on the comments and recommendations of the reviewers. The final instrumentation plan includes 34 accelerometers on the structure as shown in Figure 2, two strain gauge sensors on Bent 8 and three sensors at a free-field site. The two strain gauge sensors at Bent 8 were not installed because of the column encasement. The 34 sensors on the bridge structure were connected with the central recorders located at Bent 3 by cables in conduit. Installation of the instrumentation system on the bridge was completed with Caltrans assistance in January 1992 following the completion of the seismic retrofit.

The overall goal of the instrumentation plan is to measure the seismic input motion and the response of the bridge structure, especially at the hinges. Specific objectives are to:

a) Measure tri-axial motions at both bridge abutments. Tri-axial sensors were installed at the West Abutment (Sensors 1, 2 and 3) and the North Abutment (Sensors 34, 35 and 36) to measure the abutment response.

b) Measure motions at the base and the top of columns. Two bents were selected for detailed instrumentation: Bent 8 near the center of the bridge and Bent 3 near the west abutment. The instrumentation at Bent 8 includes four sensors at the footing and four sensors at the deck. Sensors 22, 23 and 24 measure three components of motion on the south side of the footing. An additional vertical sensor, Sensor 5, was installed on the north side of the footing. The difference in the motion recorded by Sensors 5 and 23 allows determination of the rocking motion of the footing in the transverse direction. At the deck level, Sensors 12, 18 and 20 measure three components of motion on the north side of the deck. An additional vertical sensor, Sensor 13, was installed on the south side. The difference in the motion recorded by Sensors 12 and 13 gives the torsional response of the concrete box girder. Bent 3 was instrumented with two horizontal sensors at the footing and two horizontal sensors at the deck. No vertical sensors were installed at Bent 3.

c) Measure lateral motions of the deck. Each of the six frame structures was instrumented with at least three sensors (one longitudinal and two transverse sensors). In particular, for the longest frame structure which includes Bents 4 to 7, a horizontal sensor (Sensor 11) was installed at the mid-span between Bent 5 and Bent 6 in addition to the three horizontal sensors at both ends (Sensor 8, 17 and 19).

d) Measure vertical and torsional motions of the deck. The span between Bent 7 and Bent 8 was instrumented to measure the vertical and torsional motions of the box girder. Four vertical sensors (Sensors 9, 14, 15 and 16) measure the vertical and torsional motion of the box girder. In addition, Sensors 12 and 13 also measure these motions directly above Bent 8 .

e) Measure relative motions across the hinge. Across each of the five hinges, sensors were installed on both sides of the hinge to obtain the relative motions in the transverse direction across the hinge. At the hinge near Bent 8 and the skewed hinge near Bent 11, a pair of sensors was also installed in the longitudinal direction. One longitudinal sensor (Sensor 10) was installed on the west side of the hinge near Bent 3. These sensors installed at the hinges measure the hinge motion that can greatly influence the seismic response of the whole bridge structure.

f) Measure the free-field motion. A ground-response station with 3 sensors is located about 1400 feet east of the bridge structure.

In can be seen from Figure 2 that some sensors address for more than one objective. For examples, Sensors 7, 10, 17, and 18 installed near the hinges serve three objectives: b), c), and e). Although there were a limited number of sensors available, the final sensor locations were selected optimally to achieve the above specific objectives and to allow determination of important dynamic characteristics of the bridge from strong-motion records.

STRONG-MOTION RECORDS

On June 28, 1992, the magnitude 7.5 Landers earthquake occurred about 50 miles from the bridge. Three hours later, the magnitude 6.6 Big Bear earthquake occurred about 30 miles from the bridge. The location of the bridge and the epicenters of the earthquakes are shown in Figure 3. Complete sets of the strong-motion records

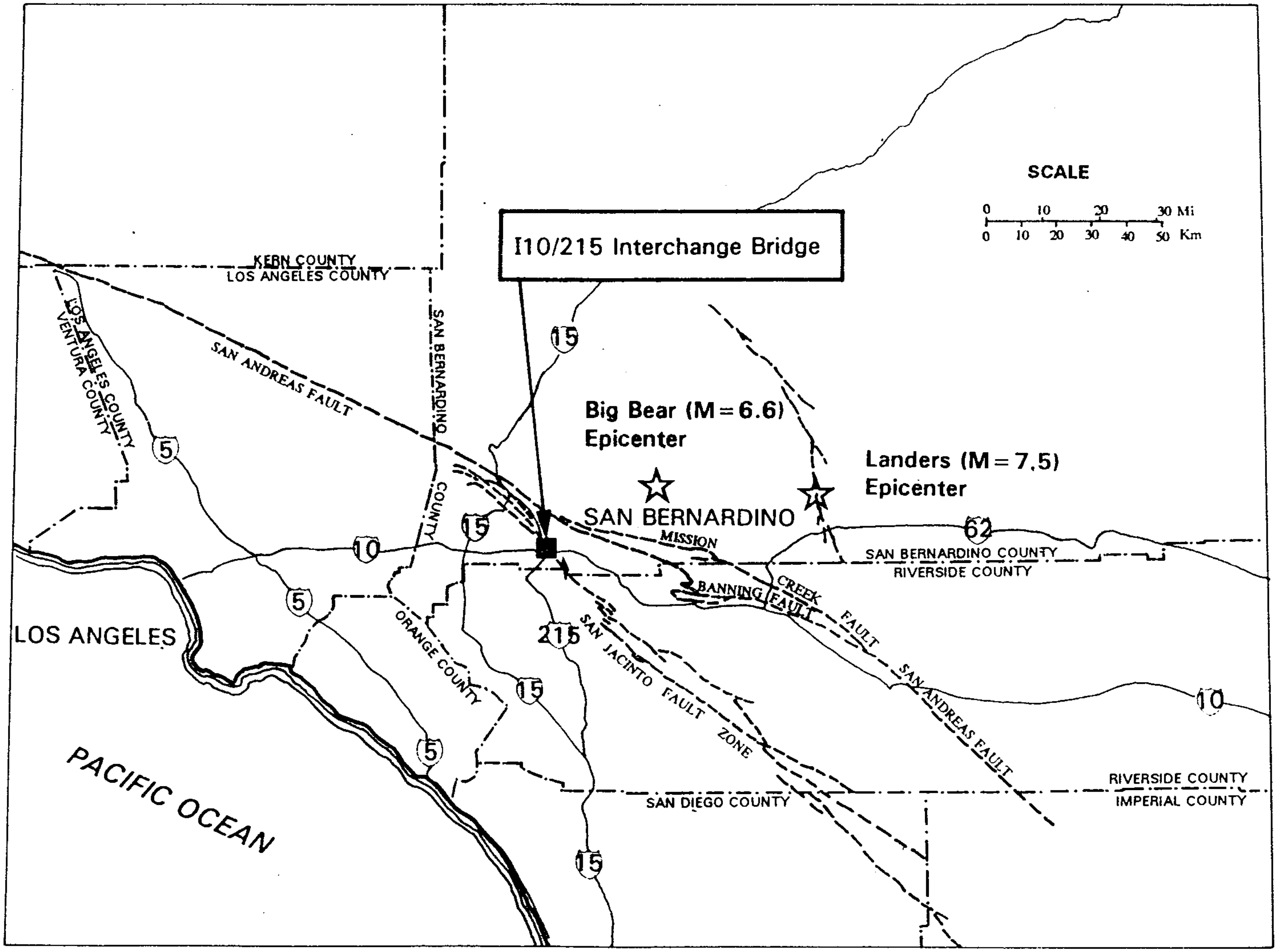

Figure 3 Map showing location of the I10/215 interchange and the epicenters of the 1992 Landers and the 1992 Big Bear earthquakes.

obtained at the bridge and at the free-field site during both earthquakes are included in the data reports by Shakal et al. (1992) and Huang et al. (1992).

Recorded peak acceleration values are summarized in Table 1. Peak horizontal accelerations were 0.09 g at the free-field site and 0.81 g on the bridge deck during the Landers earthquake, and 0.10 g at the free-field site and 1.02 g on the bridge deck during the Big Bear earthquake. Large peak acceleration values at the deck are reflect the spikes generated by interactions of the bridge superstructures at the hinges. In general, the Landers record were larger in amplitude and longer in duration than the Big Bear record. Significant features of only the Landers earthquake records are presented and discussed below. More interpretations of these records and computer modeling of the bridge are given in Malhotra et al. (1994) and Fenves, et al. (1994).

Table 1. Maximum Acceleration in Strong-Motion Records From I10/215 Bridge

	Maximum Acceleration (g)	
	Horizontal	Vertical
1992 Landers Earthquake (M 7.5, 80 km distant)		
Free Field	0.09	0.07
Abutment	0.16 (0.57*)	0.07 (0.19*)
Bent Footing	0.18	0.11
Deck	0.40 (0.81*)	0.45
1992 Big Bear Earthquake (M 6.6, 46 km distant)		
Free Field	0.10	0.07
Abutment	0.24 (0.43*)	0.11
Bent Footing	0.15 (0.25*)	0.08
Deck	0.30 (1.02*)	0.33

* The spikes due to hinge interactions are included in these maximum values.

Bent 8

Figure 4 shows the acceleration records from the four horizontal sensors at Bent 8, near the mid-length of the bridge. It can be seen in the record from Sensor 20 that the bridge response in the transverse direction was dominated by motion of about 1.7 seconds period beginning about 30 seconds into the record. In the transverse direction, the peak acceleration at the deck level was about twice that at the footing. In the longitudinal direction, the record from Sensor 18 shows that the bridge has a period of about one second. This indicates that the bridge structure is

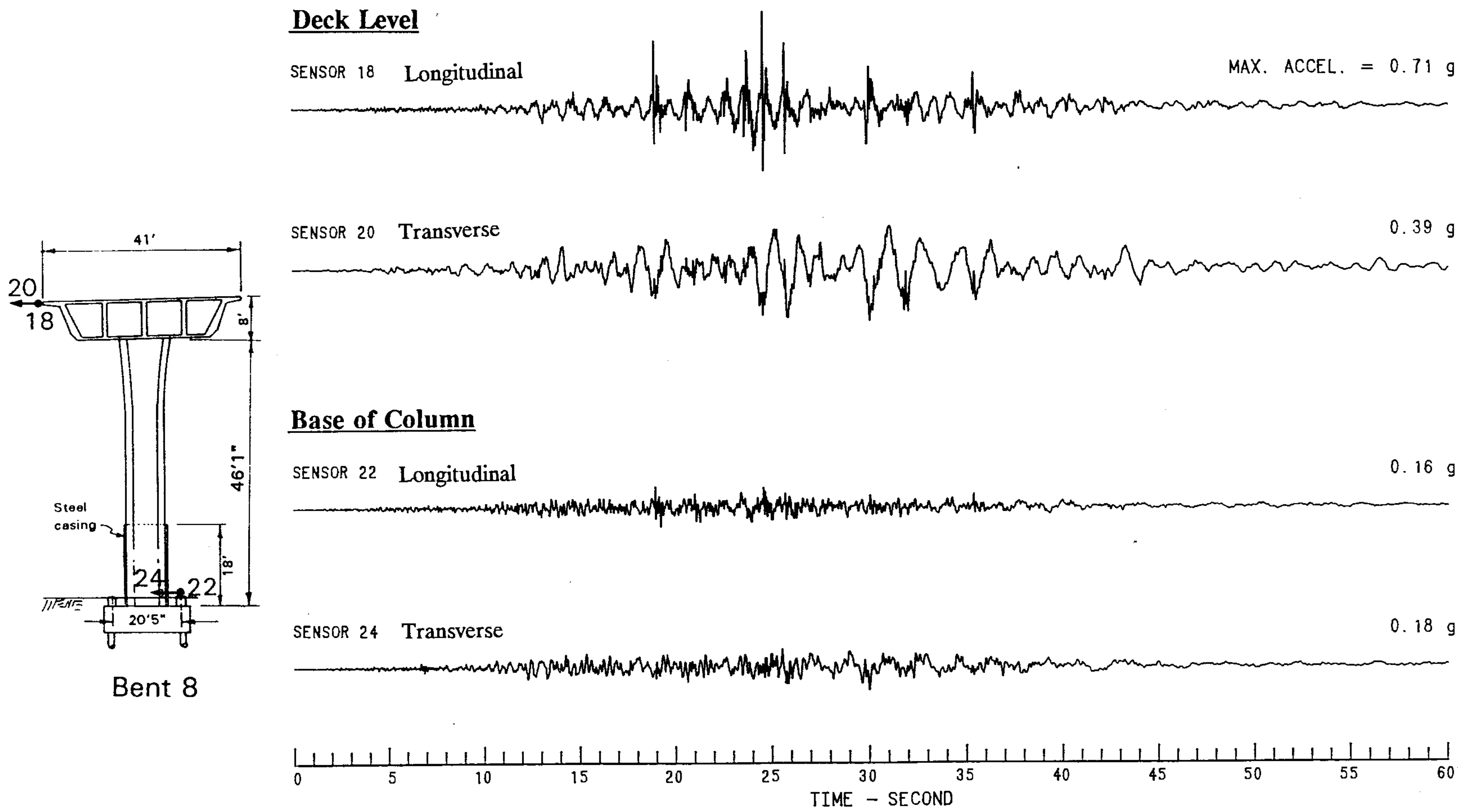

Figure 4 Accelerations in the transverse and longitudinal directions at the deck and footing of Bent 8 of the I10/215 interchange bridge during the 1992 Landers earthquake. Spikes are noticeable in the deck-level motion.

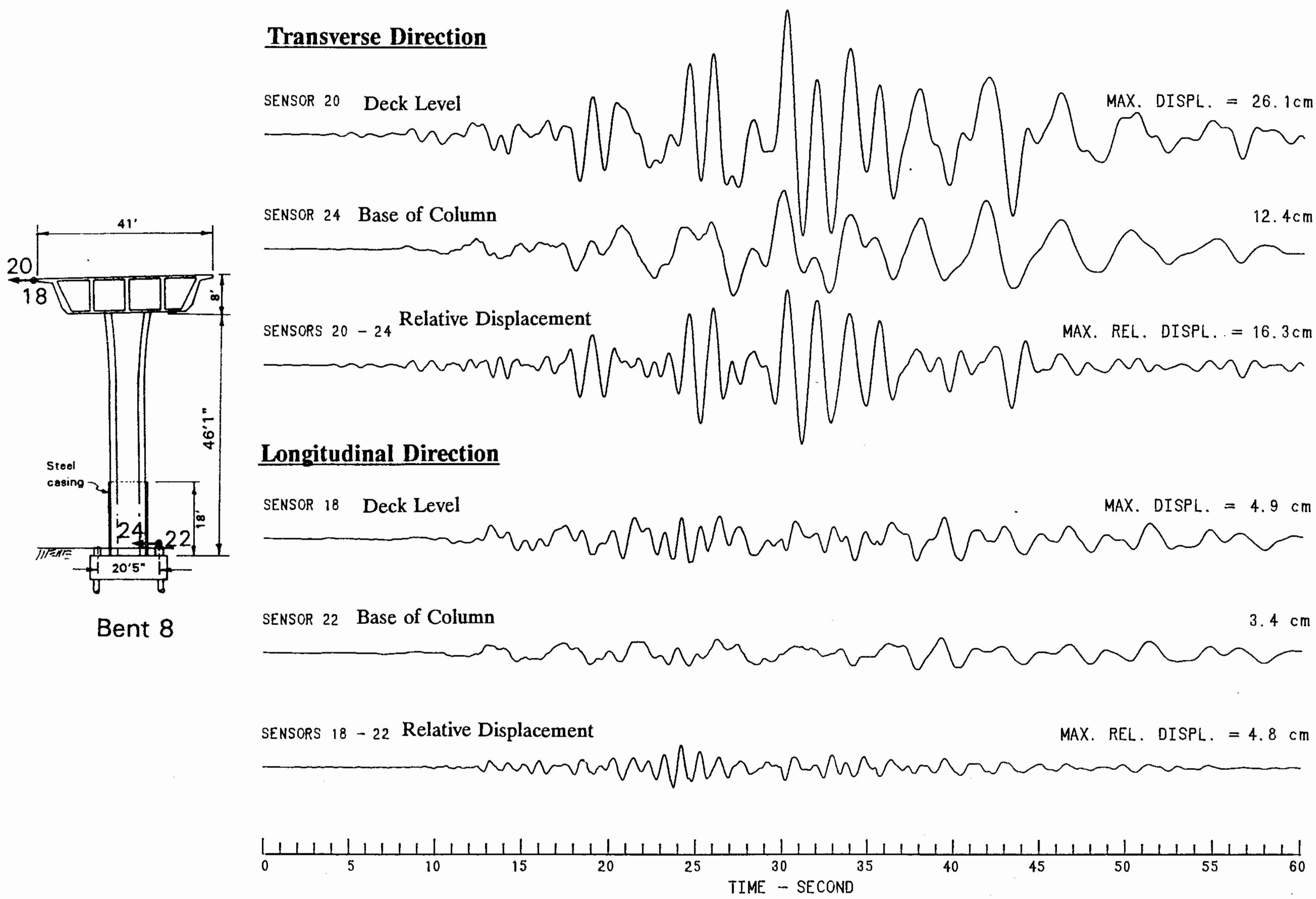

Figure 5 Absolute and relative displacements in the transverse and longitudinal directions at the deck and footing of Bent 8 of the I10/215 interchange bridge during the 1992 Landers earthquake.

stiffer in the longitudinal direction than in the transverse direction. Sharp spikes are prominent in the record from Sensor 18. These spikes are due to the interaction of the bridge structures at the hinge near Bent 8. The spikes are also seen in the records obtained at other hinges.

The displacements integrated from the measured accelerations in Figure 4 are shown in Figure 5. From these displacements, the relative displacements between the deck and the footing of Bent 8 can be computed and they are also shown in this figure. The deck of the bent experienced about 16 cm maximum displacement relative to the footing in the transverse direction and about 5 cm in the longitudinal direction. The relative displacement in the transverse direction shows that the period of bridge structure was approximately 1.4 seconds about 25 seconds into the record and approximately 1.7 seconds about 30 seconds into the record.

Figure 6 shows the acceleration records from the four vertical sensors at Bent 8. Accelerations at the deck level were larger than those at the footings. In general, the accelerations are similar at opposite sides of the footing, but are quite different at opposite sides of the deck. The displacements for these vertical sensors and the computed relative displacements are shown in Figure 7. It can be seen that the displacements at both sides are almost in phase at the footing and out of phase at the deck. Thus, the vertical displacement at the deck consists primarily of torsional motion of the box girder.

By comparing the relative displacements between Sensors 12 and 13 (torsional motion of the girder), between Sensors 5 and 23 (rocking motion of the footing), and between Sensors 20 and 24 (lateral motion of the column shown in Figure 5), one can conclude that Bent 8 responded primarily in the first response mode shown in Figure 8(a). It can also be estimated that the rocking of the footing contributed to approximately 8% of the relative displacement at the deck in the transverse direction. This portion of the deck displacement did not induce any stress in the column. The displacement due to the second response mode in Figure 8(b) was relatively small, but it can be identified from the acceleration record.

Bent 3

Figure 9 shows the acceleration records from the four sensors at Bent 3, near the west end of the bridge. The peak acceleration was 0.10 g at the footing. At the deck level, the peak acceleration was 0.30 g in the transverse direction and 0.45 g in the longitudinal direction. Similar to Bent 8, the peaks in the longitudinal direction occurred in the spikes generated by the hinge interactions. The absolute displacements and relative displacements for Bent 3 are shown in Figure 10. The deck had a maximum displacement of about 12 cm relative to the footing in the transverse direction and only 2 cm in the longitudinal direction. The periods of vibration estimated from the relative displacements in the transverse direction are about the same as those for Bent 8.

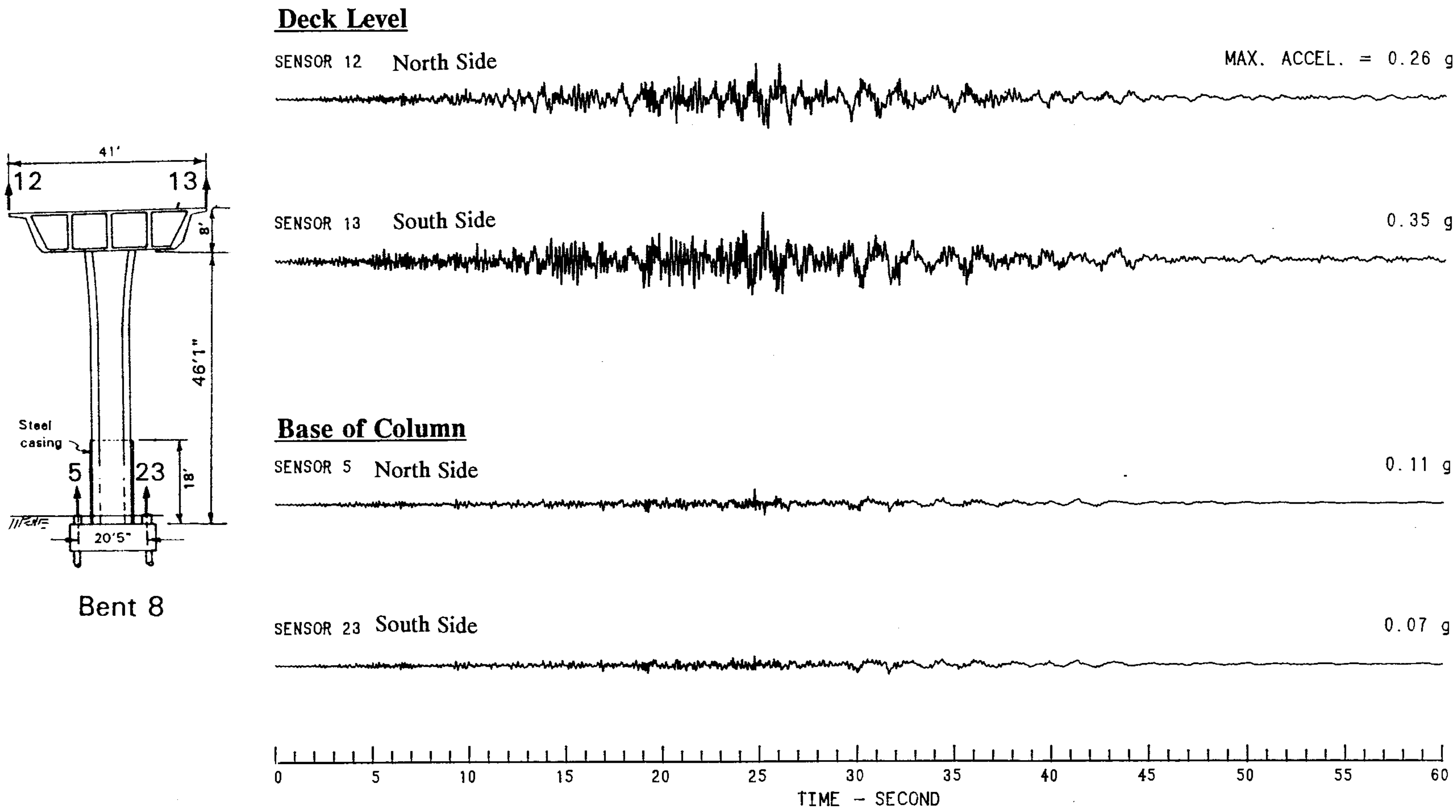

Figure 6 Accelerations in the vertical direction at the deck and footing of Bent 8 of the I10/215 interchange bridge during the 1992 Landers earthquake.

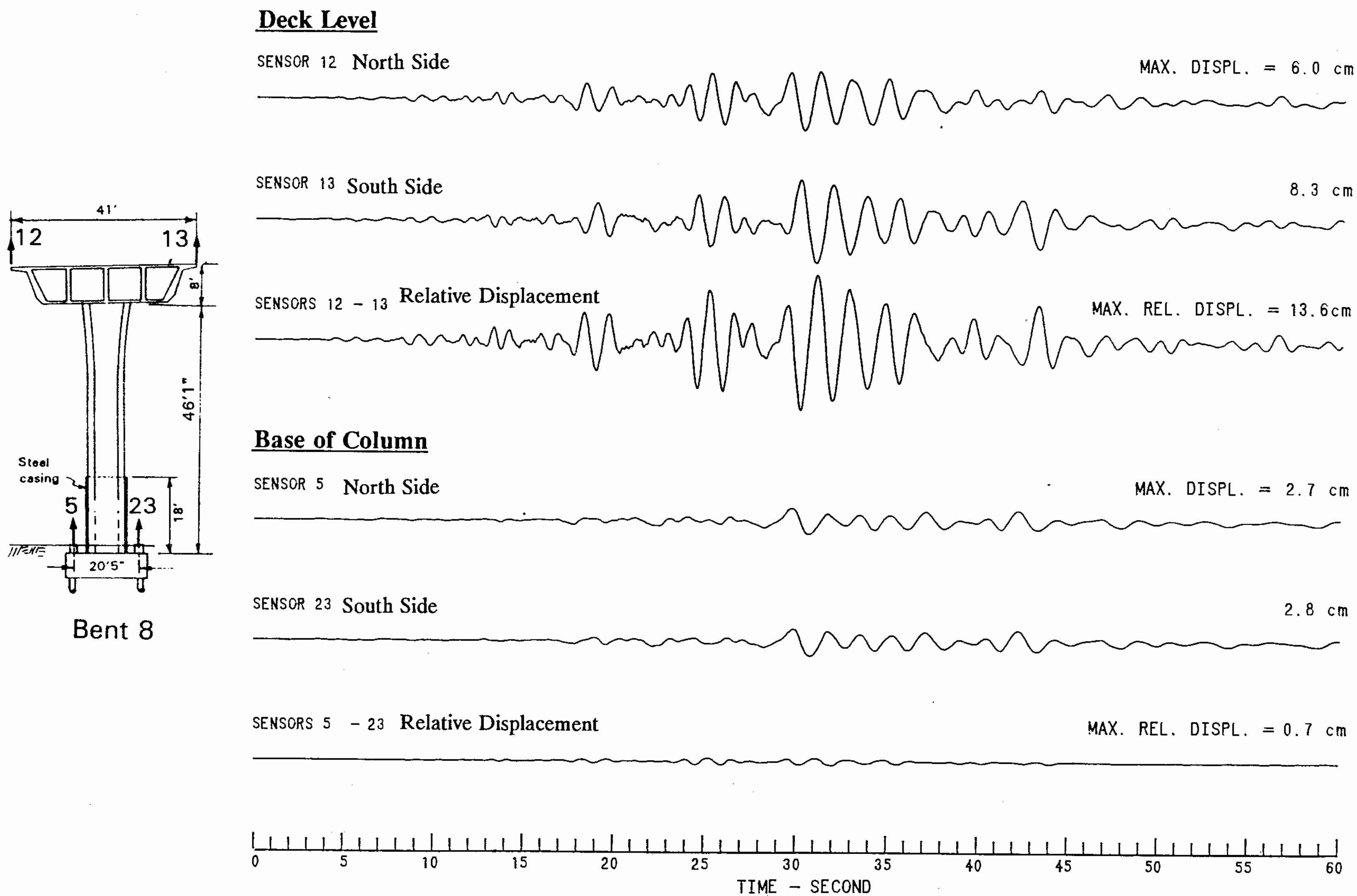

Figure 7 Absolute and relative displacements in the vertical direction and at the deck (rotation) and the footing (rocking) of Bent 8 of the I10/215 interchange bridge during the 1992 Landers earthquake.

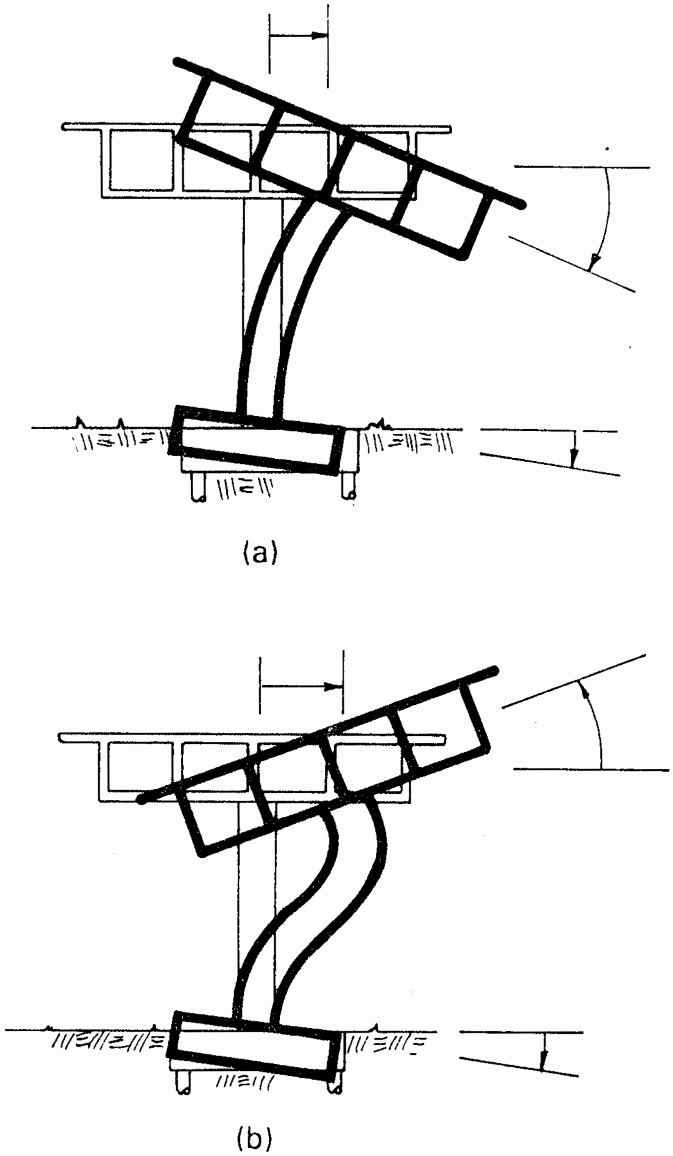

Figure 8 Response modes of a bridge bent to strong ground shaking: a) first and (b) second modal combination of lateral response of the column, torsional response of the girder, and rocking response of the footing. Lateral motion of the footing and other modes are not shown.

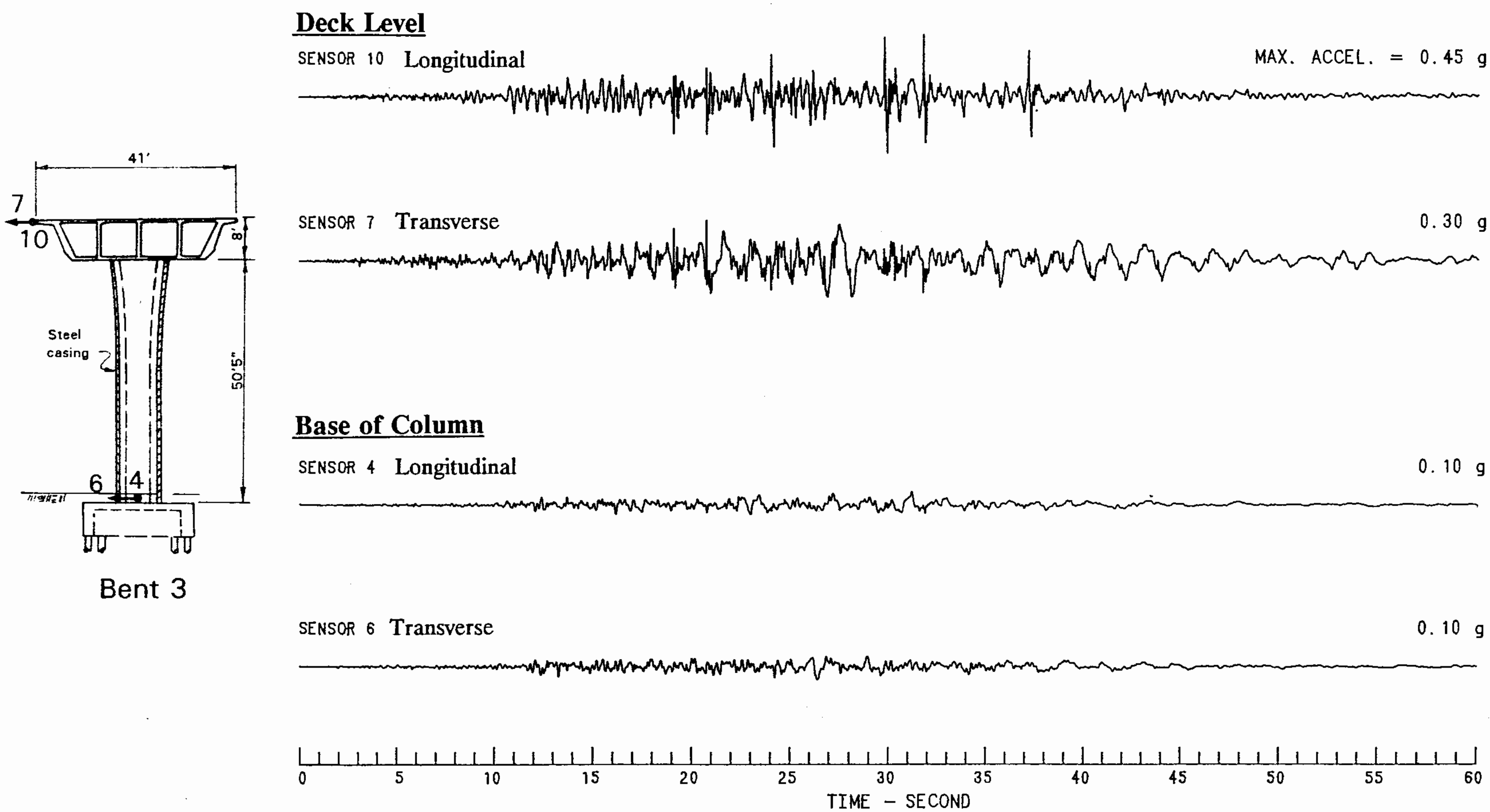

Figure 9 Accelerations in the transverse and longitudinal directions at the deck and footing of Bent 3 of the I10/215 interchange bridge during the 1992 Landers earthquake. Spikes are noticeable in the deck-level motion.

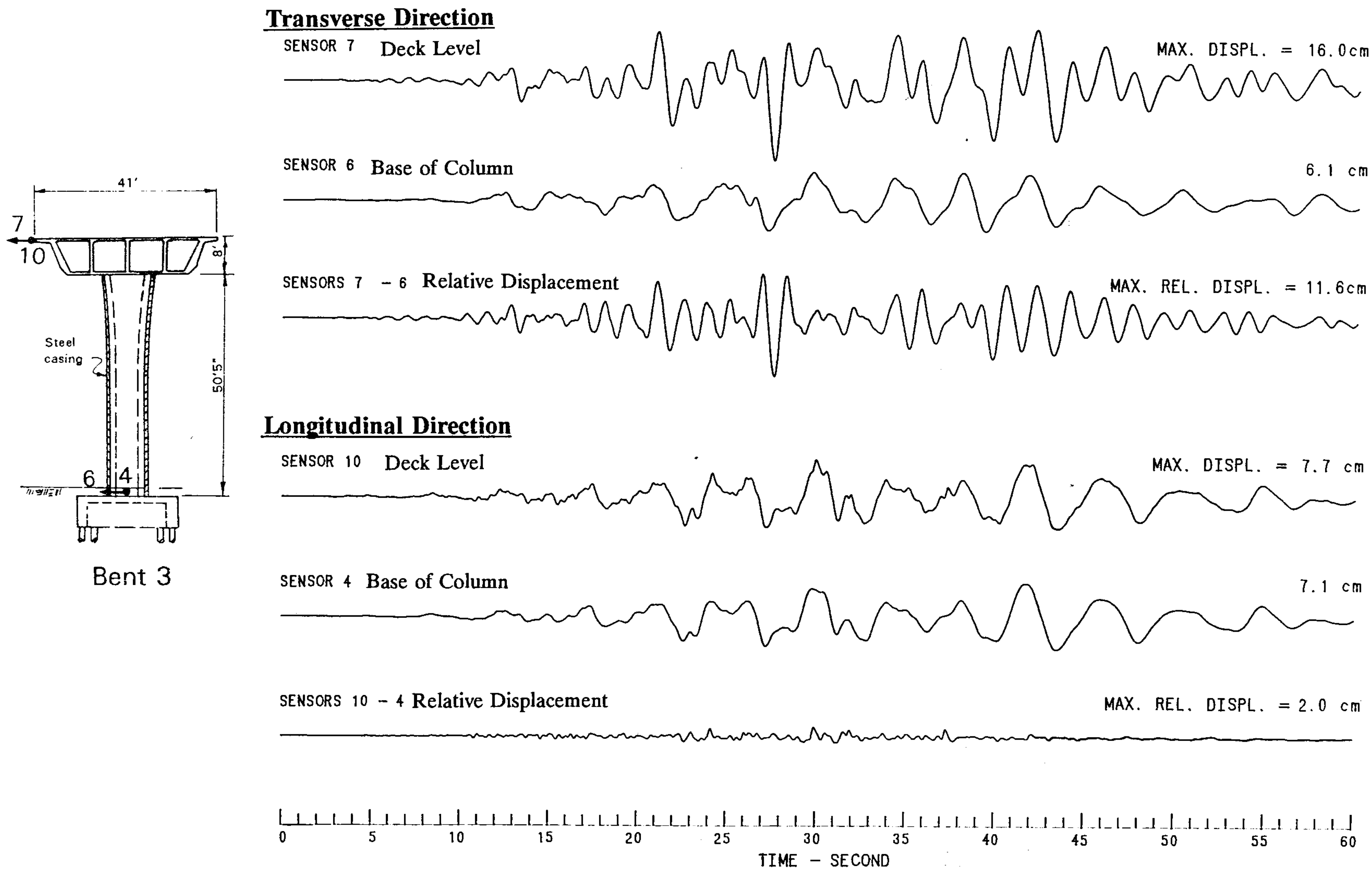

Figure 10 Absolute and relative displacements in the transverse and longitudinal directions at the deck and footing of Bent 3 of the I10/215 interchange bridge during the 1992 Landers earthquake.

Hinges

Two of the five hinges (the straight hinge near Bent 8 and the skewed hinge near Bent 12) were instrumented with horizontal sensors on both sides of the hinge. For the hinge near Bent 8, Figure 11 shows the acceleration records from Sensors 17 and 18 in the longitudinal direction and Sensors 19 and 20 in the transverse direction. It can been seen in the figure that long-period components of the motion are about the same across the hinge. Sharp spikes are present in the acceleration records, especially in the longitudinal direction. It is inferred that these spikes were generated by the impact of the bridge segments and the engagement of cable restrainers at the hinges. Several mechanisms of the hinge response may be associated with different spikes in the records, as discussed in Malhotra et al. (1994).

Figure 12 shows the absolute displacements and relative displacements across the hinge near Bent 8. For the longitudinal relative displacement, positive reflects opening and negative reflects closing of the hinge gap relative to the pre-earthquake rest position. The peak relative displacement was 3.6 cm in the longitudinal direction and 1.2 cm in the transverse direction. To obtain the response of all five hinges along the structure, relative displacements in the transverse direction are computed from transverse sensors on each side of the hinges and the results are shown in Figure 13. It can been from this figure that responses are quite different at different hinges. The responses of the hinges near the abutments are more complex. As discussed by Penzien (1979), non-linear modelling of the hinges is essential for predicting the seismic response of a multi-span concrete bridge. These measured responses at hinges are very useful in developing or verifying the nonlinear modelling of the hinge and the analysis procedures for predicting the response of a multi-span concrete bridge to strong earthquake shaking.

Abutments

Figure 14 shows the acceleration records from the three sensors at the West Abutment. For comparison, the acceleration records from the three sensors at the hinge near Bent 3 are also shown. Several large spikes can be seen in the longitudinal motion recorded by Sensor 1 at the abutment. These spikes occurred at almost the same time as those in the record from Sensor 10, the longitudinal sensor at the hinge near Bent 3, which is 329 feet from the abutment. In addition, in both records each positive spike is followed by a negative spike. Since the bridge girder is monolithic with the abutment, the spikes measured by Sensor 1 did not originate at the abutment. Detailed investigation of the data shows that the spikes in the Sensor 1 record are 0.03 second later than the spikes in the Sensor 10 record. It can be inferred that these spikes propagated from the end of the frame structure where impact occurred at the hinge near Bent 3. More detailed discussions of the spikes are given in Malhotra et al. (1994).

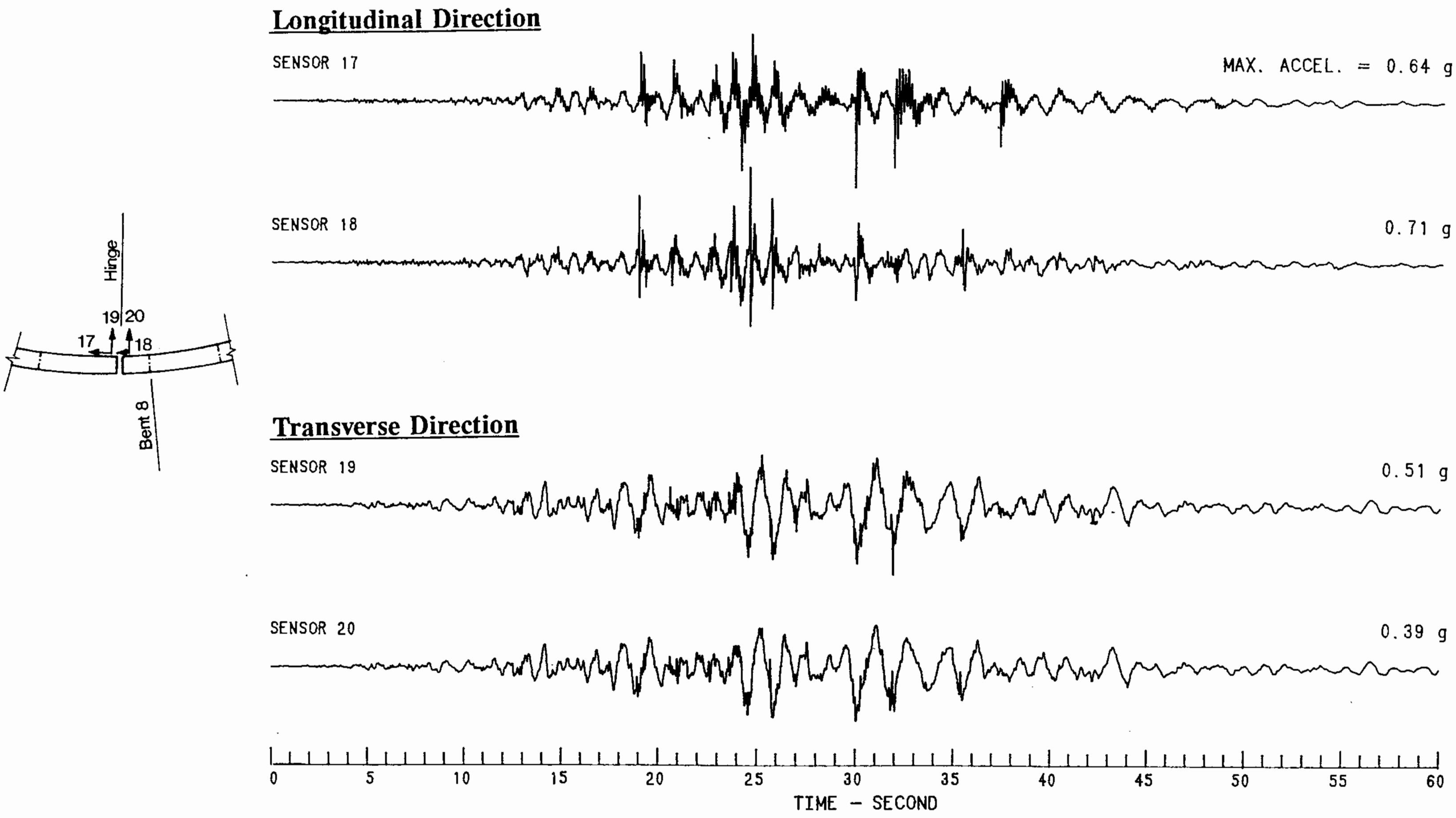

Figure 11 Accelerations in the transverse and longitudinal directions at the hinge near Bent 8 of the I10/215 interchange bridge during the 1992 Landers earthquake. Spikes are noticeable.

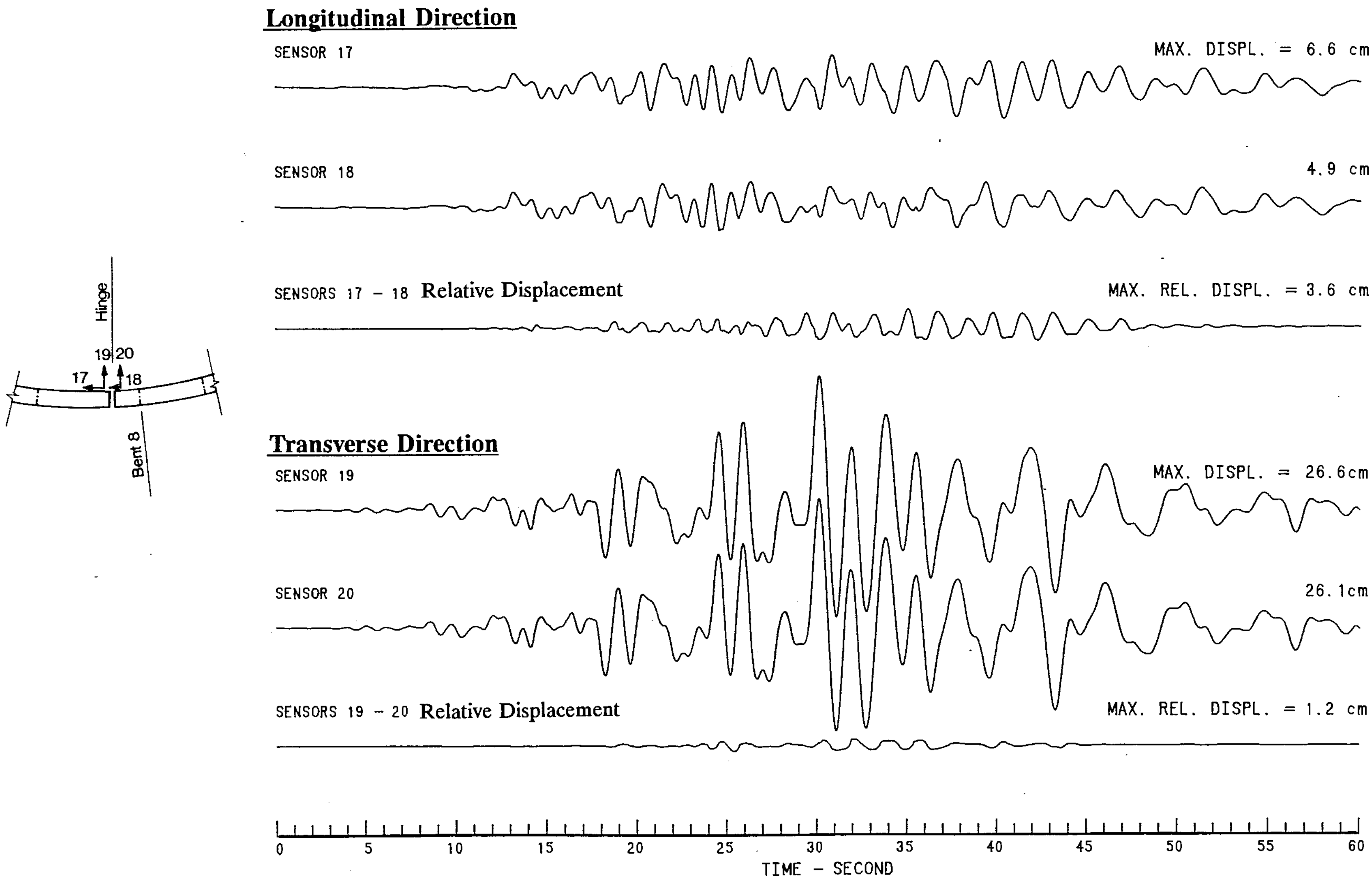

Figure 12 Absolute displacements and relative displacements across the hinge near Bent 8 of the I10/215 interchange bridge during the 1992 Landers earthquake.

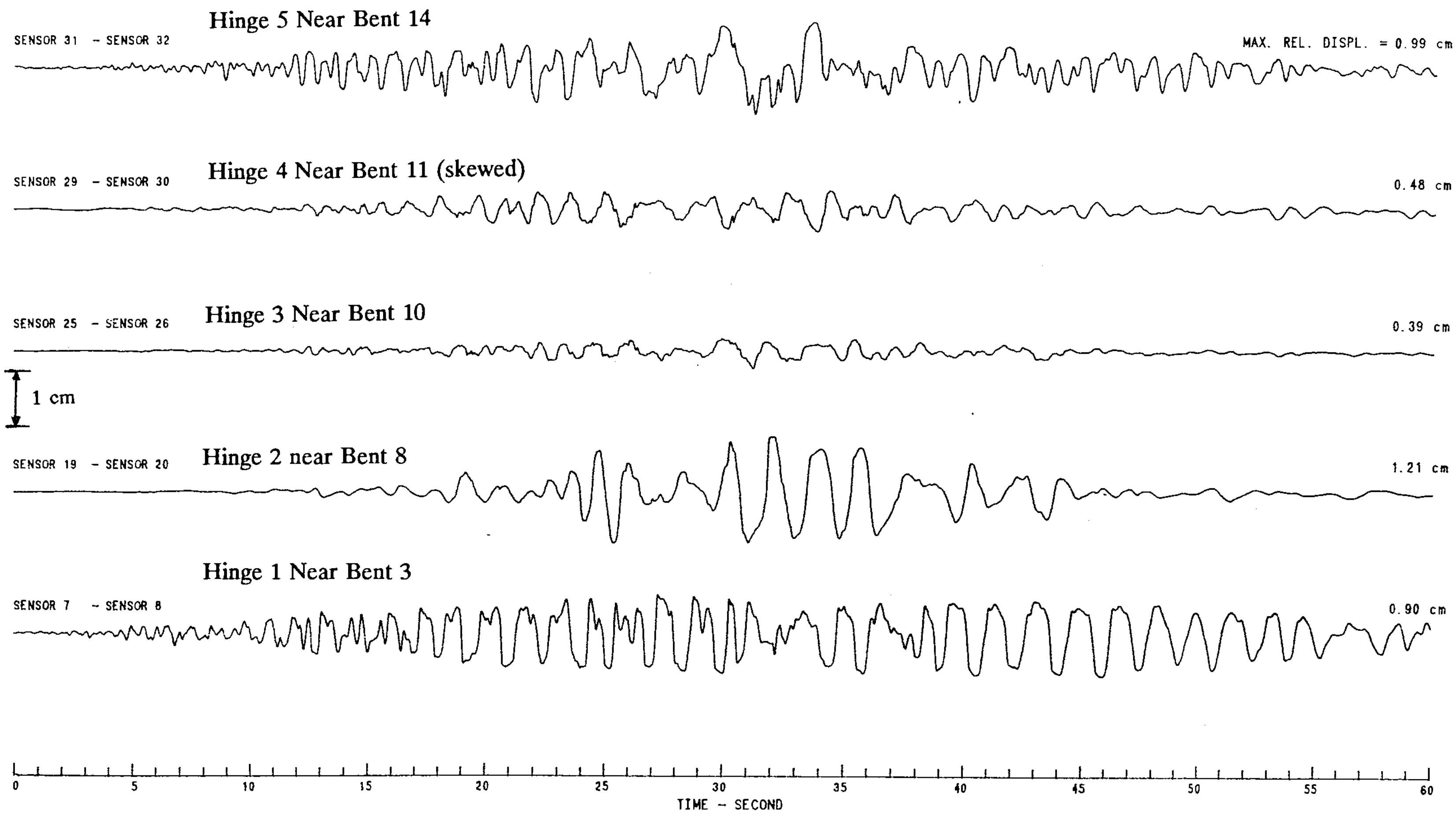

Figure 13 Relative displacements in the transverse direction across five hinges of the I10/215 interchange bridge during the 1992 Landers earthquake.

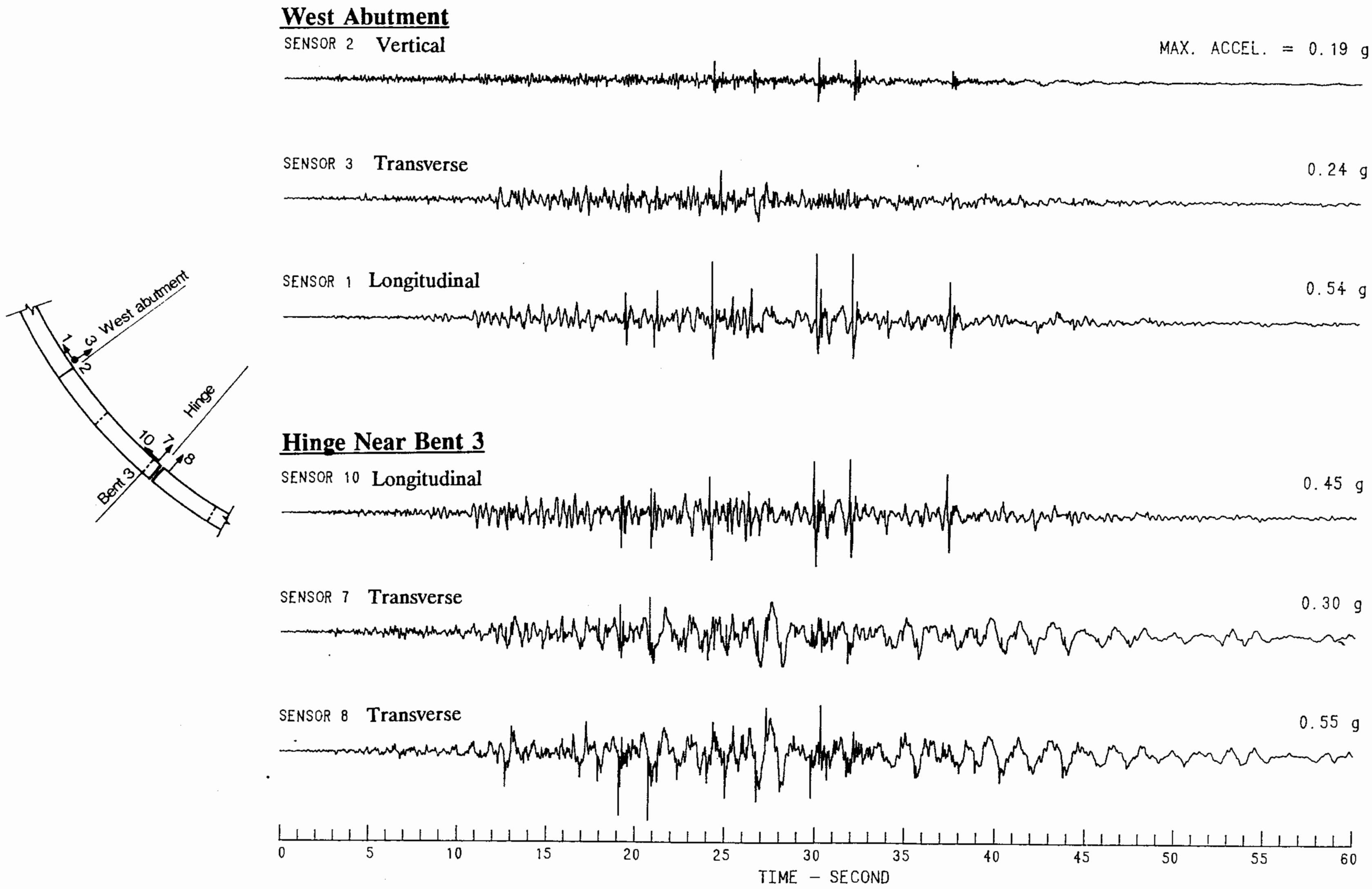

Figure 14 Accelerations at West Abutment and the hinge near Bent 3 of the I10/215 interchange bridge during the 1992 Landers earthquake.

SUMMARY

The records obtained at the I10/215 interchange bridge near San Bernardino during the 1992 Landers and Big Bear earthquakes provide valuable information on the seismic response of multi-span curved concrete bridges. The seismic responses of the hinges, box girders, columns, abutments and column footings were well recorded. The numerical modelling and analysis procedures for predicting seismic response of curved multi-span concrete bridge can be verified by using and analyzing these records in greater detail. The data can also be utilized effectively in developing and improving seismic design criteria and practices for this type of bridge structures. The complete results of processing the records from this bridge during the Landers and Big Bear earthquakes are available on floppy disks and in a processed data report (Darragh et al., 1993).

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The records obtained at the bridge were made possible through the efforts of many CSMIP technicians who installed and maintained the equipments at the bridge. C. Petersen and R. Payne coordinated the extensive efforts of installations and record recovery.

REFERENCES

Caltrans. 1992a. Supplementary Bridge Report for Northwest Connector Overcrossing, California Department of Transportation, July.

Caltrans. 1992b. Memo to Designers 20-4. Division of Structures, California Department of Transportation, September.

Darragh, R., T. Cao, M. Huang, and A. Shakal. 1993. Processed CSMIP Strong-Motion Records from the Landers and Big Bear, California Earthquakes of 28 June 1992: San Bernardino - I10/215 Interchange Bridge. California Strong Motion Instrumentation Program, Report No. OSMS 93-08, September.

Fenves, G. and R. DesRoches. 1994. Response of the Northwest Connector in the Landers and Big Bear Earthquakes. *Proceedings of SMIP94 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, Los Angeles, pp. 61-74, May 26.

Huang, M., A. Shakal, T. Cao, P. Fung, R. Sherburne, R. Sydnor, P. Malhotra, C. Cramer, F. Su, R. Darragh, and J. Wample. 1992. CSMIP Strong-Motion Records from the Big Bear, California Earthquake of 28 June 1992. California Strong Motion Instrumentation Program, Report No. OSMS 92-10, August.

Malhotra, P., M. Huang, and A. Shakal. 1994. Interaction at Separation Joints of a Concrete Bridge during 1992 Earthquakes in California. *Proceedings of the Fifth U.S. National Conference on Earthquake Engineering*, Vol. I, pp. 347-356, July 10-14.

Penzien, J. 1979. Seismic Analysis of Multi-Span Reinforced Concrete Bridges. *Proceedings of a Workshop on Earthquake Resistance of Highway Bridges*, ATC-6-1, pp. 423-432, January.

Rojahn, C. and J. Raggett. 1981. Guidelines For Strong-Motion Instrumentation of Highway Bridges. U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA/RD-82/016, December.

Shakal, A., M. Huang, T. Cao, R. Sherburne, R. Sydnor, P. Fung, P. Malhotra, C. Cramer, F. Su, R. Darragh, and J. Wample. 1992. CSMIP Strong-Motion Records from the Landers, California Earthquake of 28 June 1992. California Strong Motion Instrumentation Program, Report No. OSMS 92-09, August.

Zelinski, R. 1990. California Highway Bridge Retrofit Strategy and Details. *Proceedings of the 59th Annual Convention*. Structural Engineers Association of California, pp. 342-355, September.