RESPONSE OF BASE ISOLATED BUILDINGS DURING THE 1994 NORTHRIDGE EARTHQUAKE

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ABSTRACT

The objectives of this study are (1) to evaluate the seismic performance of base isolated USC hospital building and Fire Command Control building, in Los Angeles, during the 1994 Northridge earthquake, and (2) to evaluate the analysis techniques and design criteria used in base isolated structures. USC hospital base isolated building is a 8 story steel braced frame; the seismic isolation system consists of 68 lead-rubber isolators and 81 elastomeric isolators. Fire Command Control (FCC) base isolated building is a two story steel braced frame with 32 high damping rubber isolators. Both the USC hospital building and Fire Command Control building experienced strong motion during the Northridge earthquake. The approach adopted in this study is (1) system identification, (2) nonlinear analytical modeling, (3) interpretation of structural behavior during the Northridge earthquake, and (4) evaluation of the effectiveness of seismic isolation. It is shown that (1) USC hospital performed well, deamplified the accelerations, and reduced the overall response, (2) FCC building performed to expectations; however, accidental pounding reduced the effectiveness of seismic isolation, and (3) the analysis techniques used in base isolated structures are accurate and can reliably predict the response.

INTRODUCTION

Post earthquake evaluation studies play a very important role in (1) evaluation of the effectiveness of seismic isolation, and (2) assessment of the analysis techniques and design criteria used in base isolated structures (Buckle et al. 1990, Huang, et al. 1993, Kelly 1990, Kircher et al. 1989, Mayes 1990). California Strong Motion Instrumentation Program records (Shakal et al. 1994) of the response of the base isolated USC hospital and the FCC building in Northridge Earthquake provide a wealth of data for such a performance evaluation.

The objectives of this study are (1) to evaluate the seismic performance of base isolated USC hospital building and FCC building during the 1994 Northridge earthquake, and (2) to evaluate the analysis techniques and design criteria used in base isolated structures. The approach adopted in this study is (1) system identification of the USC hospital building from the recorded response (to verify the dynamic characteristics obtained from detailed analytical modeling of the base isolated building), (2) nonlinear analytical modeling of 8 - story USC hospital building based on as built structural details and prototype bearing test results, (3) simplified modeling of FCC building including accidental pounding, (4) comparison of computed response with recorded response of the USC hospital and FCC building in Northridge Earthquake, (5) interpretation of structural behavior and effectiveness of seismic isolation during Northridge

Earthquake, (6) examination of modeling techniques used in base isolated structures, and (7) development of simplified models to predict structural behavior.

The seismic performance evaluations comparing response of the base isolated buildings with probable response if the buildings were to be fixed-base are presented. The isolation system of the USC hospital was activated beyond its yield level and responded in the inelastic range with the superstructure being elastic. Recorded/computed response which support the fact that the base isolated USC hospital building performed to expectations and reduced the response as compared to a fixed base structure are presented. The isolation system of the FCC building was activated beyond its yield level; however, accidental pounding in portions of the base caused sharp acceleration spikes. The effects of accidental pounding on the structural response are presented. Evaluations of analytical modeling techniques, used in base isolated structures, and their validity are presented.

ANALYSIS TECHNIQUES

The computer program 3D-BASIS [Nagarajaiah, et al. 1990, 1991] is used for analyzing both USC hospital and FCC building. Computer program 3D-BASIS has been used for analysis and design of several base isolated buildings in California and else where. Nonlinear analytical modeling using 3D-BASIS consists of (1) linear condensed superstructure model with 3 degrees of freedom per floor, and (2) isolation system modeled explicitly using nonlinear force-displacement relationships of individual isolators.

A detailed model of the superstructure is developed using ETABS (Wilson et al. 1975) with rigid floor slab assumption. ETABS uses 6 degrees of freedom (DOF) per node with 3 degrees of freedom per node slaved to the master node at the center of mass of the floor; hence, in the condensed model only 24 DOF (8x3 DOF per floor) and 6 DOF (2x3 DOF per floor) are retained for modeling USC hospital and FCC building, respectively. Eigenvalues and eigenvectors of the condensed model from ETABS are used in modeling the superstructure in 3D-BASIS. Elastomeric isolators are modeled in 3D-BASIS using nonlinear force-displacement relationship based on prototype bearing test results for USC hospital and FCC building. Response to Northridge earthquake is computed using 3D-BASIS.

BASE ISOLATED USC HOSPITAL BUILDING

Superstructure and Isolation System Details

USC hospital base isolated building (Asher et al. 1990) is a 8-story (7 stories above ground and basement) steel braced frame building as shown in Fig. 1. The floor plan is asymmetric with two wings which are connected by a necked down region of the floor/base. The building has setbacks after the 5th floor. The steel superstructure is supported on a reinforced concrete base slab, integral with reinforced concrete beams below, and drop panels below each column location. The isolators are connected in between these drop panels and footings below. The footings also support reinforced concrete pedestal provided for back up safety. The seismic isolation system consists of 68 lead-rubber isolators and 81 elastomeric isolators as shown in Fig.

1. The building has been extensively instrumented by CSMIP (Shakal et al. 1994); the sensor locations are shown in Fig. 1.

System Identification

Frequency domain system identification technique (Ljung 1987) is used to identify the frequencies and damping ratios of the base isolated building from recorded response. The identified frequencies and damping ratios are average dynamic characteristics of an equivalent linear system based on the entire measuring period. Transfer functions are estimated using cross spectrum and power spectrum. Complex-curve fitting is performed and complex poles are extracted. Frequencies and damping ratios are calculated from the poles (Nagarajaiah 1996). Fig. 2 shows the recorded and identified transfer functions in the East-West (EW) and North-South (NS) directions in magnitude and phase angle form. It is to be noted that the transfer function peak at 4.3 Hz in the EW direction is not a mode, but, the effect of interference/noise; this is inferred from examination of coherence function which has a value of 0.13 (Nagarajaiah 1996). Table 1 shows the identified frequencies and damping ratios for the first four modes in the EW and NS directions.

Analytical Modeling

The superstructure properties --such as beam, column, bracing, floor slab details- used for analytical modeling are computed from building drawings provided by CSMIP. Detailed modeling of the superstructure is performed using ETABS both in fixed-base condition (used for modeling the superstructure in 3D-BASIS) and base isolated condition with equivalent linear isolation system (only for comparison with system identification results). The computed periods for the first nine modes, and the damping ratios, in the fixed-base condition, shown in Table 2, are used for modeling the superstructure in 3D-BASIS. The isolation system properties are extracted from prototype test results provided by CSMIP. The test results of both lead-rubber bearings and elastomeric bearings recorded in the form of nonlinear force-displacement loops are used for explicitly modeling all 68 lead-rubber bearings and 81 elastomeric bearings in 3D-BASIS. The properties of the bearings, used in modeling, extracted from test results are: (1) the properties of the lead-rubber bearings at 1.1 inch (2.8 cm) displacement --average displacement experienced by the isolators in Northridge earthquake-- shown in Fig. 3 and Table 3; and (2) the properties of elastomeric isolators at 1.1 inch (2.8 cm) displacement is 17 kip/in and an estimated damping of 3%.

The computed periods and damping ratios for the first four modes in the EW and NS directions, in the base isolated condition with equivalent linear isolation system (based on bearing properties at 1.1 inch maximum displacement), are shown in Table 1. A comparison between computed frequencies and damping ratios obtained from detailed analytical model of the base isolated building with equivalent linear isolation system and the corresponding identified frequencies and damping ratios obtained from system identification is presented in Table 1. It is evident from Table 1 that the dynamic characteristics obtained from detailed analytical modeling are satisfactory.

Response during Northridge Earthquake

The response of USC hospital to Northridge earthquake (foundation level acceleration CHN 5 and CHN 7 --see Fig. 1) is computed using the nonlinear analytical model developed. Fig. 4 shows a comparison of the recorded and computed response in the EW and NS directions; absolute accelerations and relative displacements at sensor locations shown in Fig. 1 are compared. Comparison shows that the correlation between the computed and recorded response is good --both is phase and amplitude (excepting for the roof acceleration in the NS direction in one peak cycle of motion). Fig. 5 shows the recorded and computed displacement and acceleration profiles at instants of occurrence of the peak base displacement, peak acceleration, peak structure base shear (above base), and peak drift. The accuracy with which the analytical model captures the displacement response --as in Fig. 5-- is notable; however, differences in acceleration response occur --given the complexity of the analytical model. The correlation of recorded and computed time histories and profiles demonstrate the accuracy of the analysis techniques used and nonlinear models used in 3D-BASIS.

Fig.6 shows the floor response spectra at the roof, 6th floor, 4th floor, and base for three cases (1) recorded, (2) computed response with bilinear hysteretic model for 68 lead-rubber isolator and linear model for 81 elastomeric isolators, and (3) computed response with the entire isolation system being modeled by global equivalent linear springs, with appropriate effective stiffnesses, and global equivalent damping elements at the center of mass of the base. It is evident that the floor response spectra of the recorded and computed cases --case 2 bilinear-- compare well over most regions of the period range. This shows the appropriateness of modeling the lead-rubber bearings using bilinear hysteretic elements.

The time history of response shown in Fig. 4 indicates that the isolators yield (the yield displacement is 0.34 inch or 0.86 cm) and the isolation system responds in the inelastic range for significant portion of the time history with a period of ~ 1.3 to 1.5 secs. The peak ground acceleration in the EW direction is 0.163 g and 0.37g in the NS direction. The peak acceleration at the base is 0.073g in the EW direction and 0.13g in the NS direction. The peak acceleration at the roof is 0.158g in the EW direction and 0.205g in the NS direction. The accelerations were deamplified because the fundamental periods of the base isolated building in the EW and NS directions are higher than the corresponding fixed-base fundamental periods and predominant periods of the ground motion. Furthermore, this deamplification stems from the dynamic characteristics of the base isolated structure shown in Table 1. The fundamental periods in the EW and NS directions are ~ 1.3 secs with a damping of ~ 11% --essentially similar to the case if the structure were to be rigid. The structural modes or the second modes in the EW and NS directions, however, are reduced to ~ 0.55 secs (reduced from fundamental modes of ~ 0.9 secs in the fixed-base case --see Table 2) with a damping of ~ 16% (increased from 5% in the fixed-base case --see Table 2-- because of high damping in the lead-rubber isolators). An examination of the transfer function in the EW direction reveals that the structural mode at 1.83 Hz or 0.55 secs has large damping ~ 16%; hence, the suppressed transfer function peak. Similar observation holds for the NS direction. The Northridge earthquake which has energy in the structural mode range cannot transmit the energy effectively because of this dynamic characteristic of the base isolated structure; this is the main reason for the effectiveness of the isolation system (Kelly 1990).

Fig. 7 shows a comparison between the computed peak response envelops of base isolated USC hospital and probable response if the building were to be fixed-base. The benefits of seismic isolation become clear by examining the peak story shear and peak story drift envelops, in both cases, in the EW and NS directions. The superstructure remains elastic in the base isolated case; however, the fixed-base structure will yield. Furthermore, the higher mode effects are dominant in the fixed base case; whereas, in the base isolated case the higher mode effects are not as dominant. The changes in stiffness after the fifth floor, because of setbacks, are the cause for these higher mode effects; this is clear in the displacement and acceleration profiles in NS direction, presented in Fig. 7. The profiles in Fig. 7 are at instants of occurrence of the peak acceleration, peak structure base shear (above base), and peak drift, in the base isolated and fixed-base case. In Fig. 7 examination of the displacement profile reveals that when the peak structure base shear occurs, in the base isolated building, the isolation mode is dominant.

The maximum flexible floor diaphragm displacements inferred from the records are of the order of 0.5 inch or 1 cm, which is negligible compared to the length of the building of 303 ft (3636 inch or 9235 cm); hence, no significant flexible diaphragm effects occurred during the earthquake (Nagarajaiah et al. 1995). Examination of the records for torsional response revealed that nominal torsional response occurred (Nagarajaiah et al. 1995). The corner displacements at different floors/base were approximately 25% more than the displacement at the center of mass.

Simplified Modeling

In Fig. 7, as described earlier, floor response spectra of three cases are examined. The last case is intended to examine the effectiveness of simplified linear modeling of such a complex structure. In the simplified model only nine modes shown in Table 2 are used for modeling the superstructure with the isolation system being represented by global springs and damping elements at the center of mass of the base. The floor response spectra using the simplified linear model do not match the recorded case as well as the bilinear case. It is, however, found (Nagarajaiah et al. 1995) that the simplified model yields satisfactory peak response values -- provided proper effective stiffness and damping properties are used for the isolators-- making it useful for design.

BASE ISOLATED FIRE COMMAND BUILDING

The FCC is a 2-story steel frame base isolated building with 32 high damping rubber bearings as shown in Fig. 1. The superstructure of FCC is modeled using ETABS and building drawings provided by CSMIP. The isolation system properties are extracted from prototype test results (Bachman et al. 1990, 1995). Equivalent linear analytical model is developed in 3D-BASIS using 6 modes from ETABS analysis and equivalent properties of the isolation system. The period of the fundamental mode in the base isolated condition with equivalent linear isolation system in both the EW and NS directions is 1.56 secs (Nagarajaiah et al. 1995). The equivalent linear isolation system is based on bearing properties at 1.38 inch (3.5 cm) maximum displacement experienced by the isolators in Northridge earthquake. Estimated level of damping at this amplitude is 15%.

The building has been extensively instrumented by CSMIP (Shakal et al. 1994); the sensor locations are shown in Fig. 1. An examination of the records indicates sharp acceleration spikes. The cause for these acceleration spikes is accidental pounding against entry bridge --repaired incorrectly after the Landers earthquake-- across the isolation gap at the North-East corner of the building (Bachman 1995). As described earlier a simplified model is used to study the effect of accidental pounding. The simplified model has two floors and base, with three DOF per floor/base, as shown in Fig. 8. The isolation system is modeled by equivalent global linear springs and damping elements at the center of mass of the base. The accidental pounding is modeled by a nonlinear gap element with a contact spring at the North-East corner of the building as shown in Fig. 8. It is evident from the recorded response (see Fig. 8) that the building pounded upto approximately 16 secs into the time history response and then moved freely and behaved as a typical base isolated building --acceleration spikes cease after approximately 16secs. Hence, the contact spring is moved back to equal the isolation gap at approximately 16 secs into time history response. Fig. 8 shows a comparison of the recorded and computed response in the EW direction; absolute accelerations and relative displacements at sensor locations shown in Fig. 1 are compared. Comparison shows that the correlation between the computed and recorded response is good --both is phase and amplitude. Simplified model yields good results provided proper effective stiffness and damping properties are used for the isolators.

The effects of pounding are examined in Fig. 9 by comparing the case of the base isolated building with and without pounding and the fixed-base case without pounding. The floor response spectra are shown in Fig. 9. The peak story shear and peak drift envelopes are shown in Fig. 9. It is evident from the results in Fig. 9 that pounding causes (1) an increase in high frequency/low period response, and (2) an increase in peak story shear and drift. The effectiveness of base isolation is thus reduced; however, even with pounding, response of the base isolated building is less than that of the fixed-base case. As described before the reason for this is the dynamic characteristics of the base isolated building.

CONCLUSIONS

The seismic response and performance evaluation of base isolated USC hospital and FCC building has been presented. It is evident from the evaluation that (1) the USC hospital performed very well and the seismic isolation is effective in reducing the response and providing earthquake protection, (2) the FCC building performed as a base isolated structure should, excepting for the accidental pounding, (3) accidental pounding should be avoided by ensuring free movement at the seismic isolation gap, and (4) the analysis techniques, such as 3D-BASIS, used in base isolated structures are accurate and can reliably predict the response of base isolated structures.

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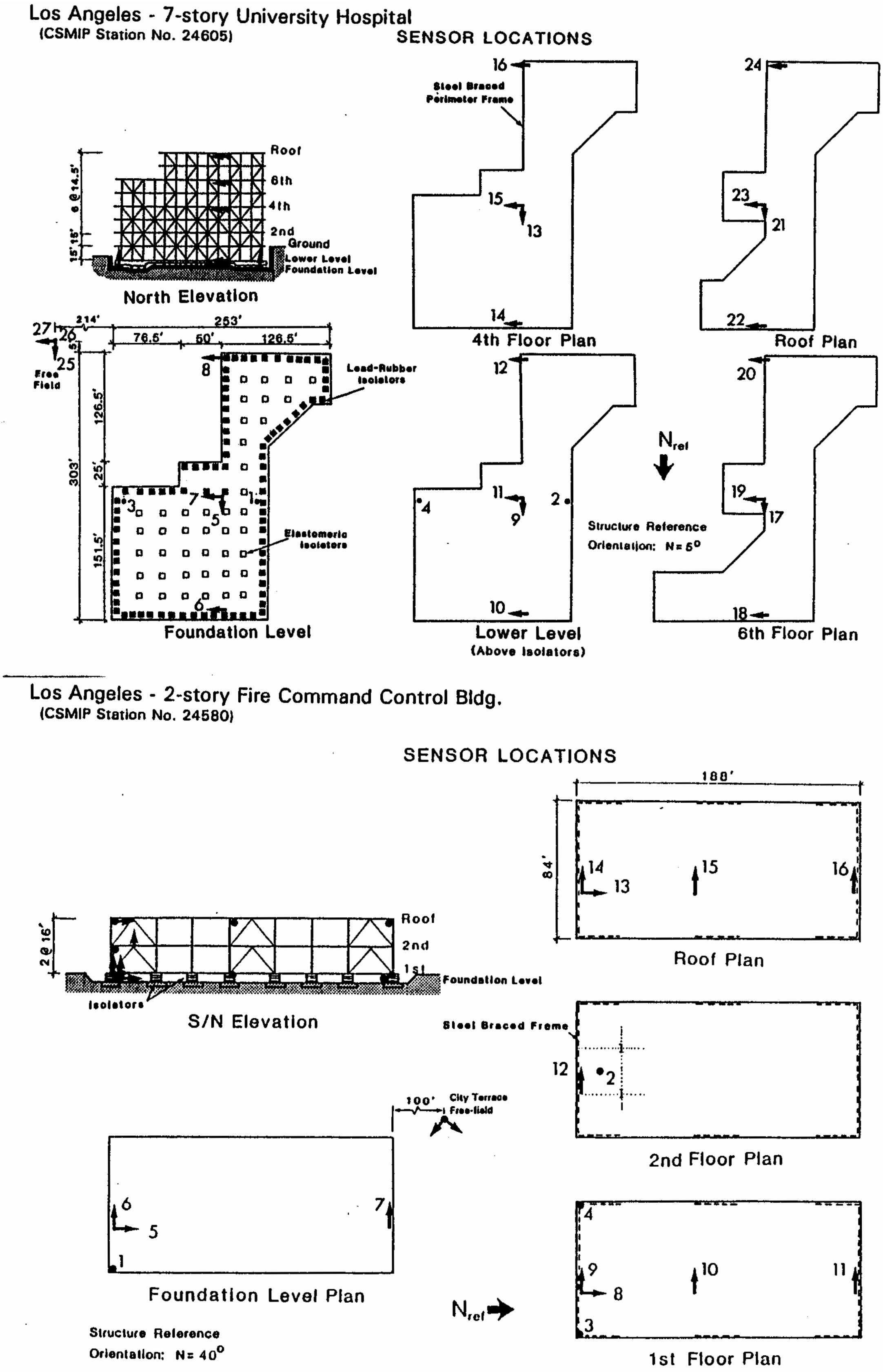


Fig. 1. USC Hospital and FCC Building: Superstructure and Isolation System Details, Sensor Locations.

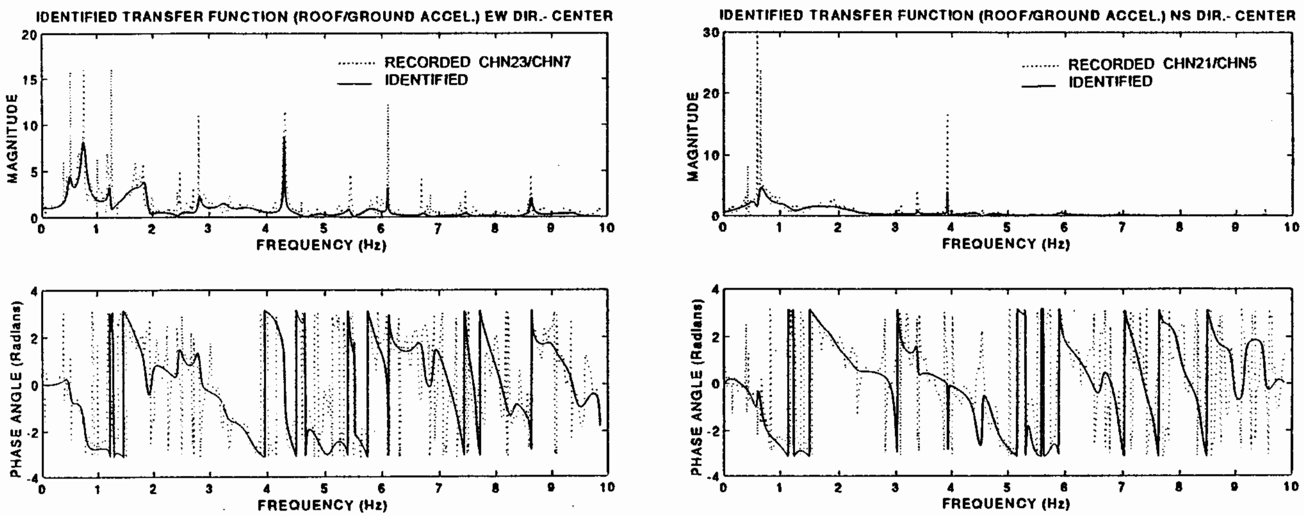


Fig. 2. USC Hospital: Recorded and Identified Transfer Functions -- Northridge Earthquake.

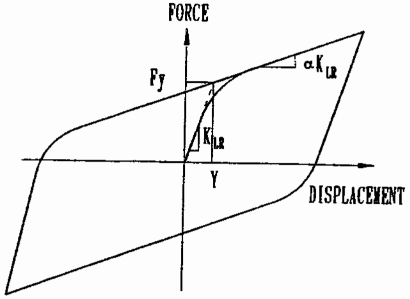


Fig. 3. Bilinear Model for Lead-rubber Isolators.

TABLE 1 Computed and Identified Periods and Damping Ratios of Base Isolated USC Hospital Building

Mode	Computed Period				Identified Period			
	EW - Dir		NS - Dir		EW - Dir		NS - Dir	
	Period(s)	Damping Ratio	Period(s)	Damping Ratio	Period(s)	Damping Ratio	Period(s)	Damping Ratio
1	1.250	0.110	1.370	0.110	1.320	0.100	1.560	0.100
2	0.546	0.160	0.514	0.160	0.546	0.150	0.549	0.150
3	0.262	0.050	0.245	0.050	0.262	0.050	0.256	0.050
4	0.163	0.050	0.152	0.050	0.164	0.070	0.145	0.070

TABLE 3. PROPERTIES OF LEAD - RUBBER ISOLATOR (AT 1.1 INCH DISP.)

Qd - Characteristic strength	13.9 kips
F_Y - Yield force	18.0 kips
αK_{LR} - Post-yield stiffness	12.0 kip/in
K_{LR} - Elastic stiffness	53.0 kip/in
K_{eff} - Effective stiffness	24.7 kip/in

TABLE 2 Fixed Base Periods and Damping Ratios of USC Hospital Building

Mode	1	2	3	4	5	6	7	8	9
Period	0.92	0.82	0.62	0.37	0.35	0.28	0.20	0.18	0.16
Damping Ratio	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

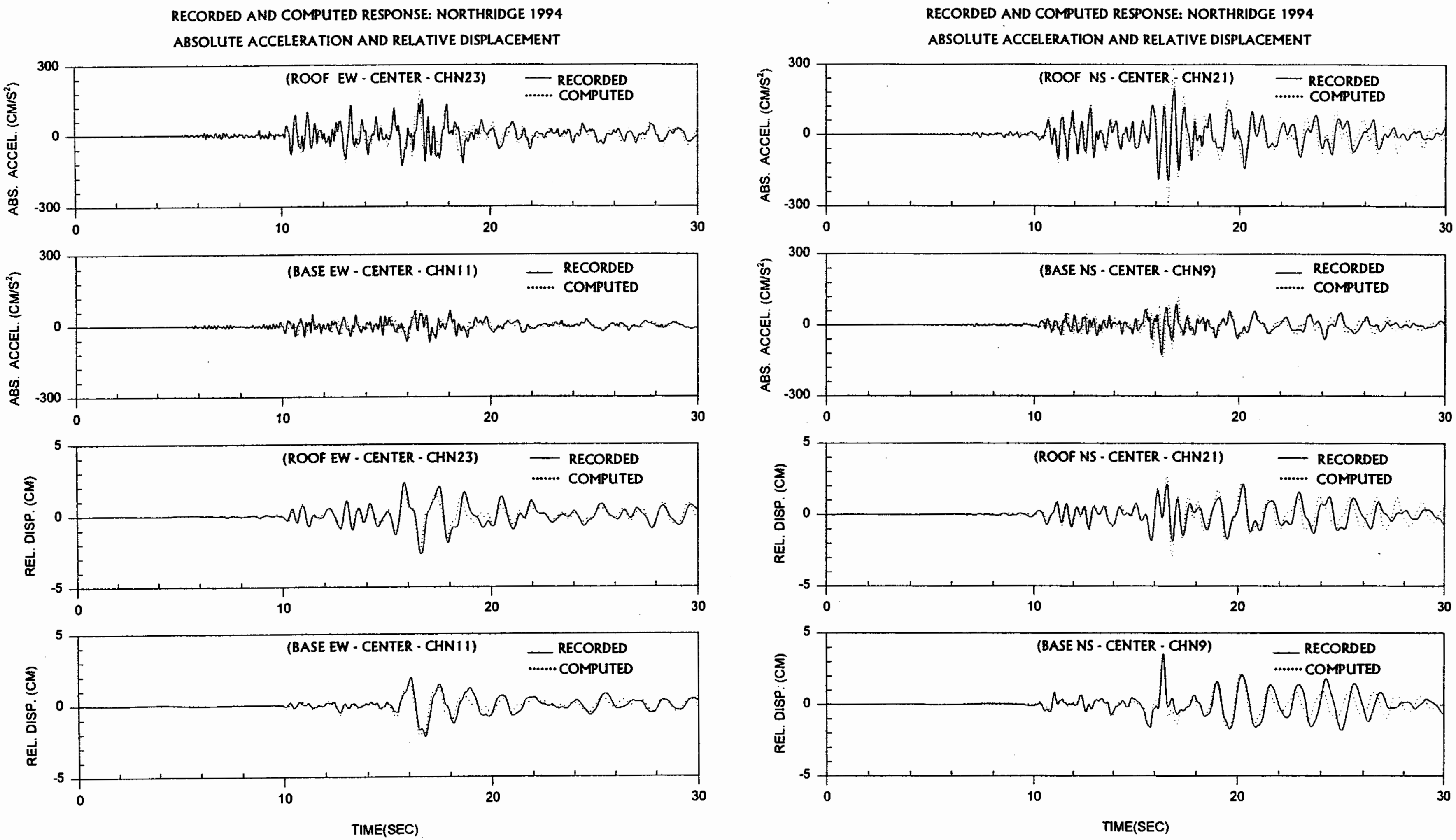


Fig. 4. USC Hospital: Recorded and Computed Response in the EW and NS directions at Sensor Locations shown in Fig. 1.

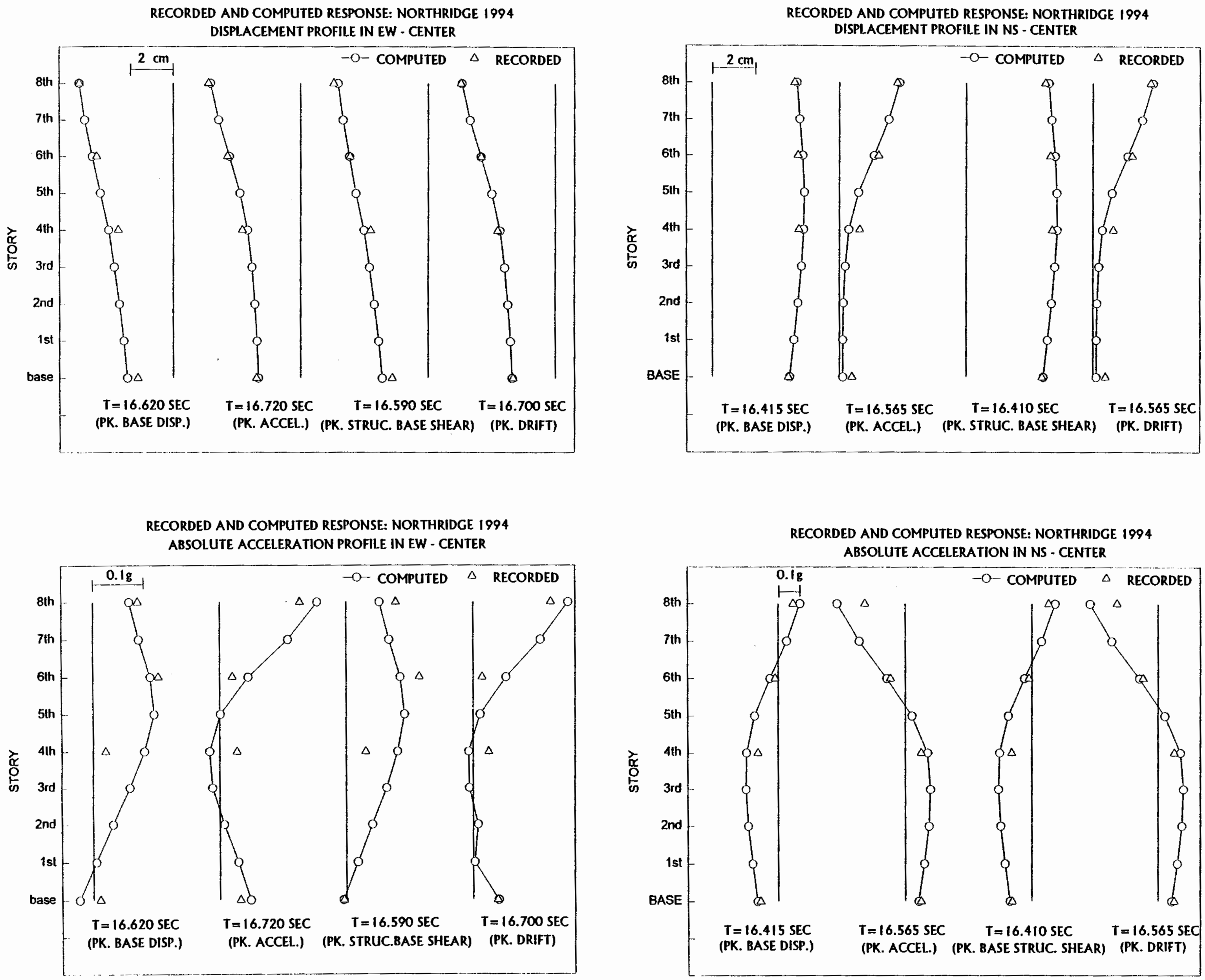


Fig. 5. USC Hospital: Recorded and Computed Displacement and Acceleration Profiles at Instants of Occurrence of the Peak Base Displacement, Peak Acceleration, Peak Structure Base Shear (above base), and Peak Drift --in the EW and NS Directions.

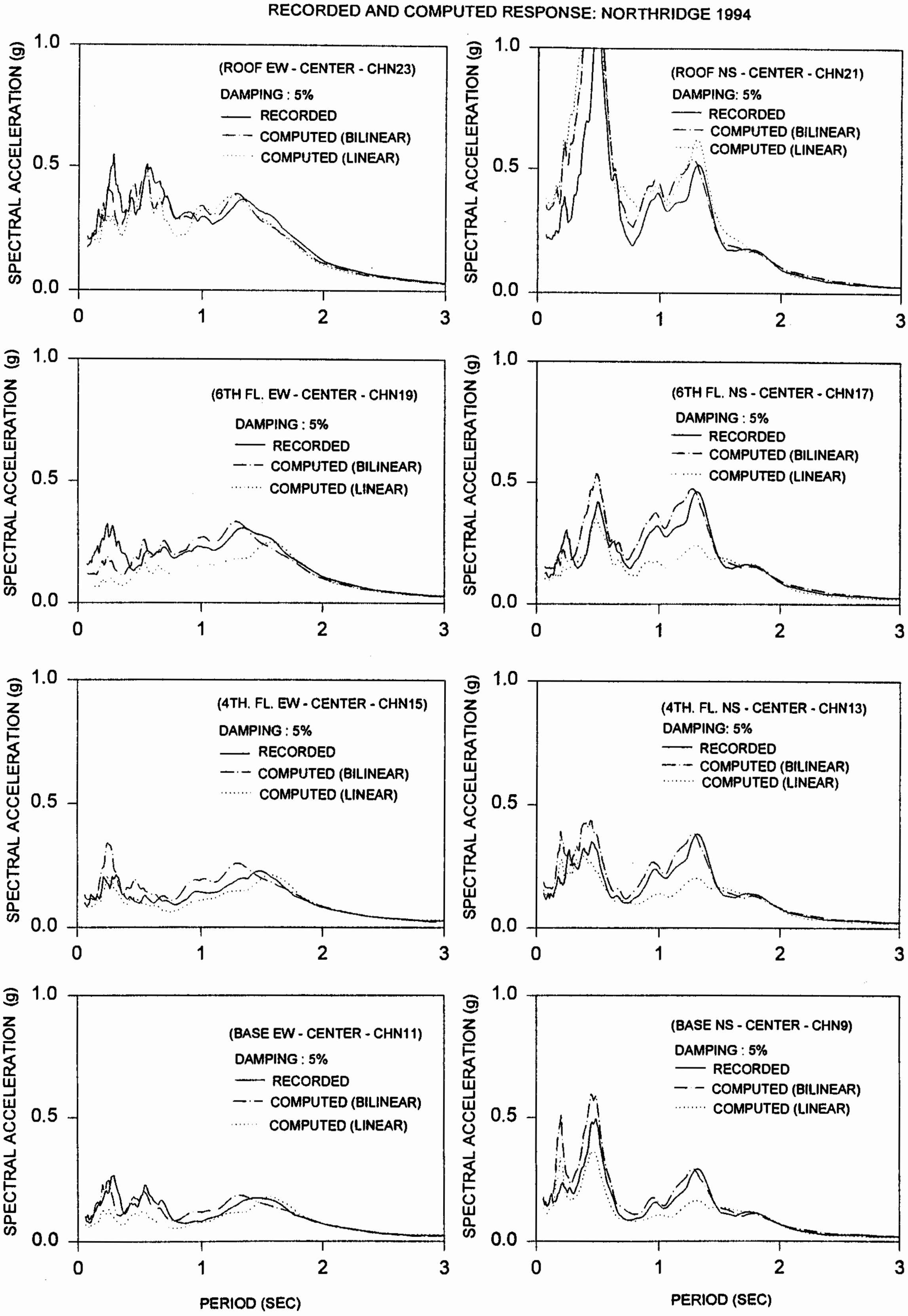


Fig. 6. USC Hospital: Floor Response Spectra for Three Cases (1) Recorded, (2) Computed Response with Bilinear Model for 68 Lead-rubber Isolators and Linear Model for 81 Elastomeric Isolators, (3) Computed Response with Linear Equivalent Global Springs and Damping Elements for Modeling the Isolation System --in the EW and NS Directions at Sensor Locations shown in Fig. 1.

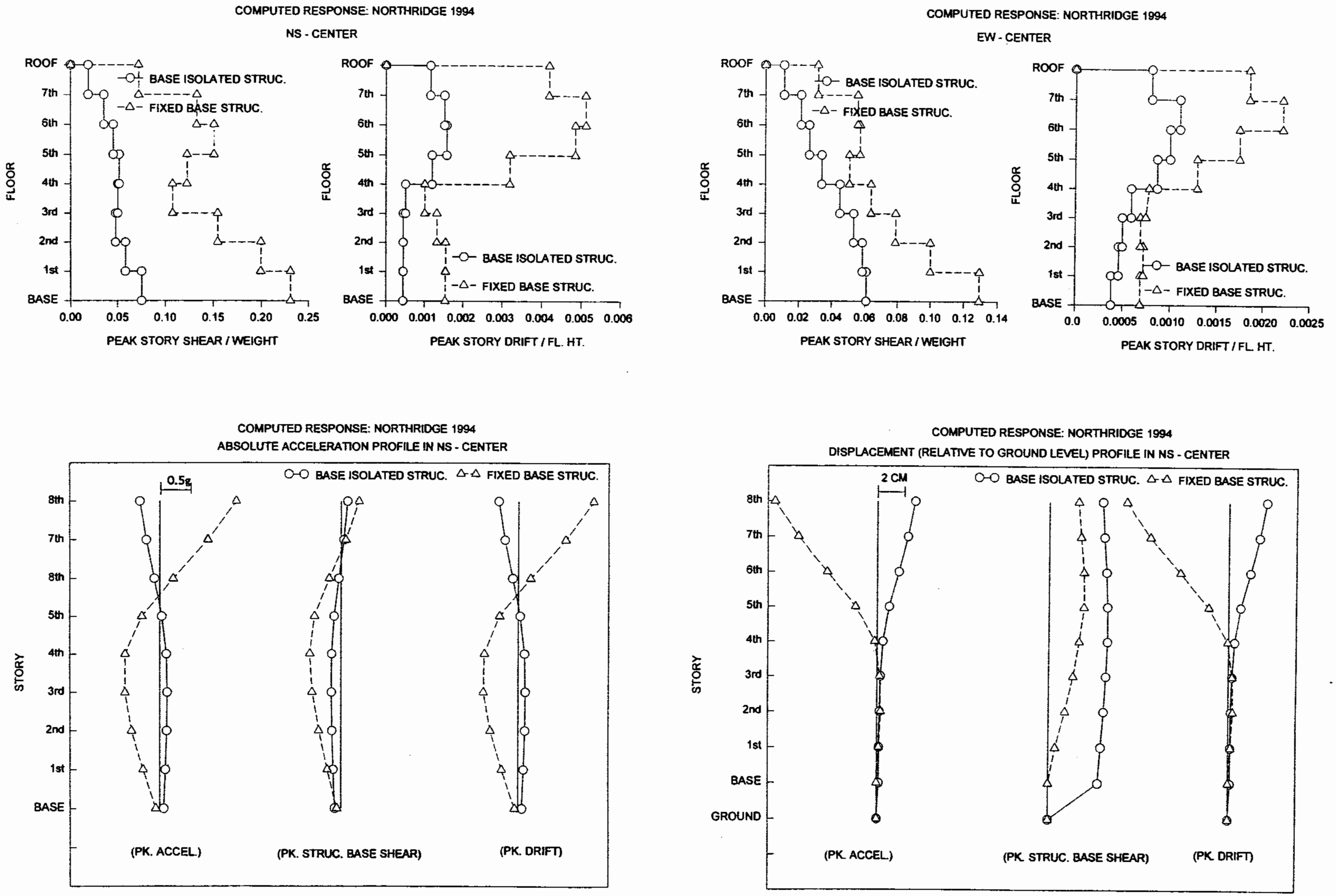
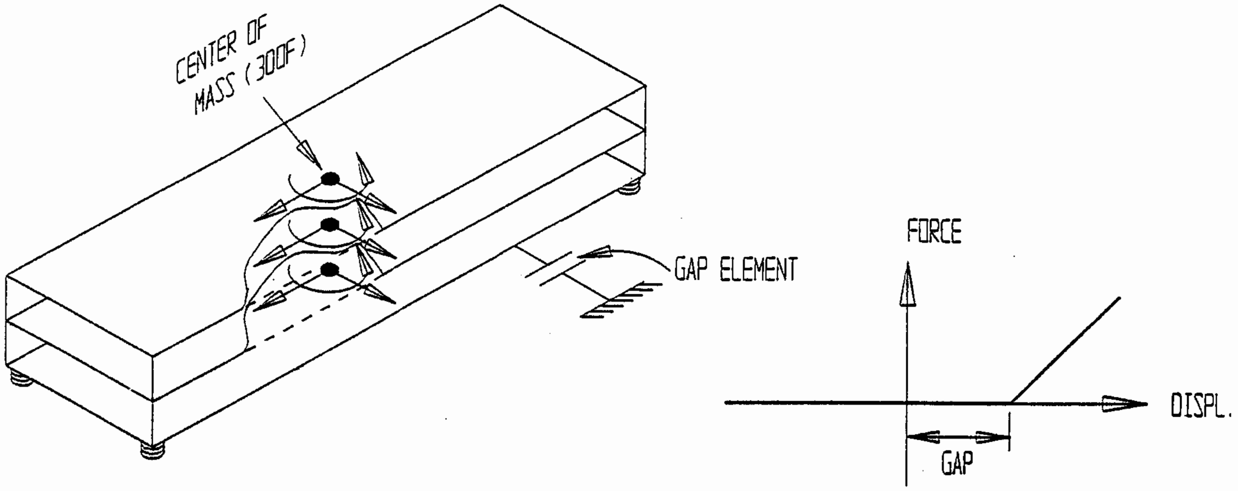


Fig. 7. USC Hospital: Comparison Between Base Isolated and Fixed-base Case (1) Normalized Peak Story Shear and Drift Envelopes in NS and EW Directions, (2) Displacement and Acceleration Profiles at Instants of Occurrence of the Peak Acceleration, Peak Structure Base Shear (above base), and Peak Drift in the NS Direction.



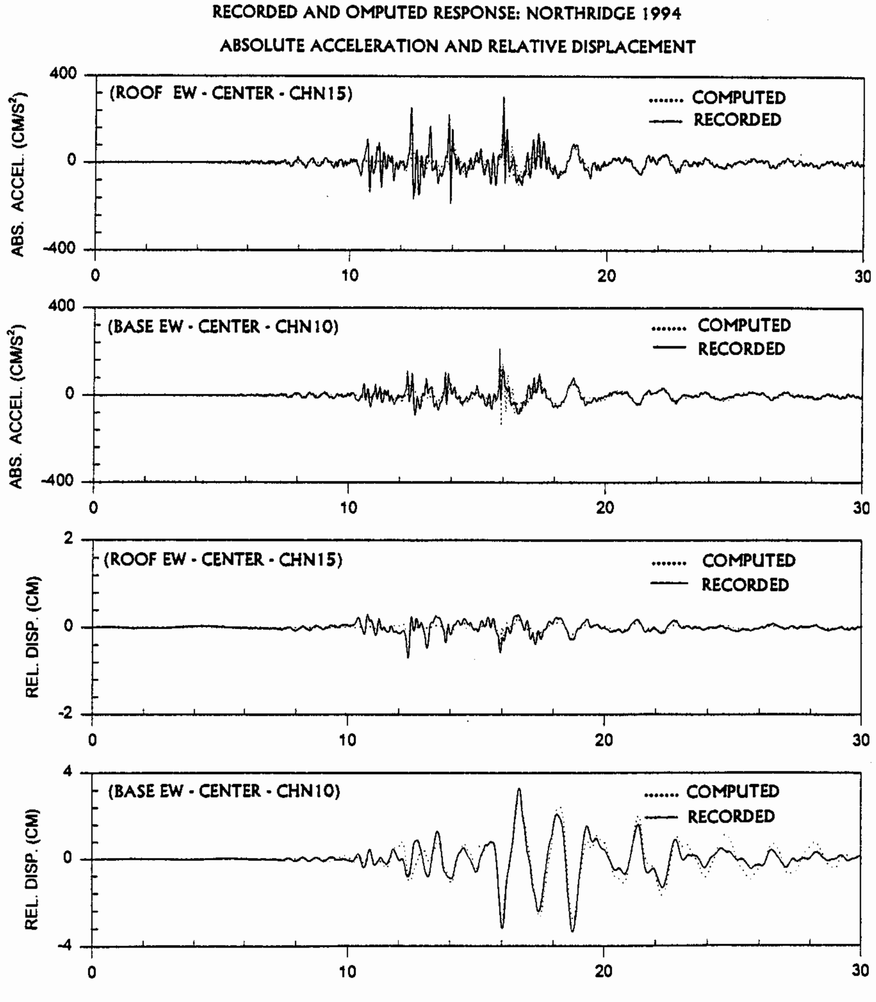


Fig. 8. FCC Building: Simplified Model with Gap Element; Recorded and Computed Response in the EW direction at Sensor Locations shown in Fig. 1.

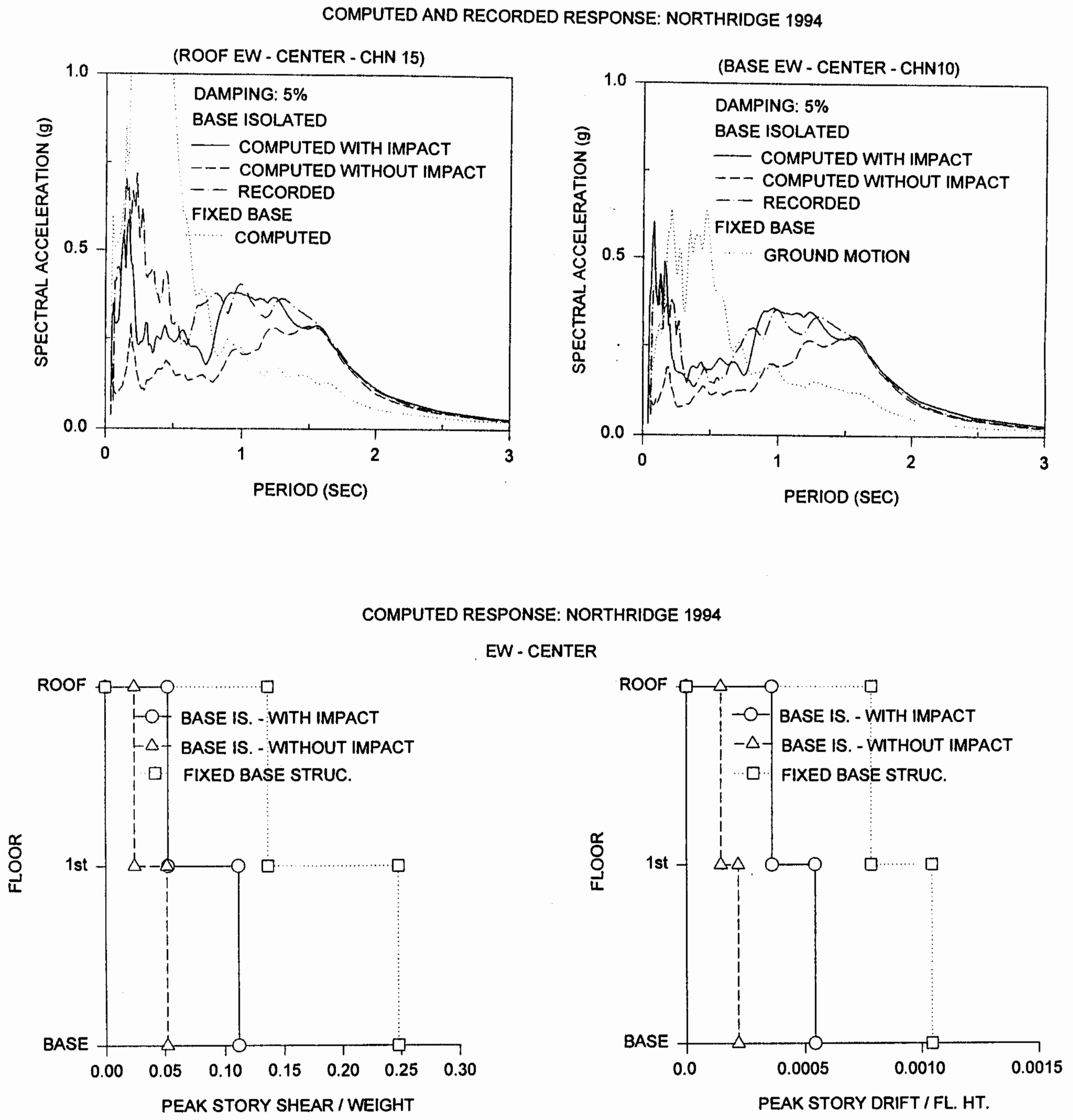


Fig. 9. FCC Building: Comparison between Base Isolated and Fixed-base Case (1) Floor Response Spectra in the EW Direction at Sensor Locations shown in Fig. 1, (2) Normalized Peak Story Shear and Drift Envelopes in the EW Direction.