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Paper No. 598. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SEISMIC PERFORMANCE OF BASE ISOLATED BUILDINGS IN 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.

KEY WORDS

Northridge Earthquake, Base Isolated Structures, Lead Rubber Bearings, High Damping Bearings, Seismic Performance, Nonlinear Analytical Modeling, 3DBASIS, USC Hospital, FCC Building, Pounding.

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 1993). 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) 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 NorthridgeEarthquake.

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

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 in fixed-base condition (used for modeling the superstructure in 3D-BASIS). The computed periods for the first nine modes, and the damping ratios, in the fixed-base condition, shown in Table 1, are used for modeling the superstructure in 3D-BASIS. The computed periods and damping ratios are verified using system identification techniques (Nagarajaiah, *et al.* 1996). 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 Table 2; and (2) the properties of elastomeric isolators at 1.1 inch (2.8 cm) displacement, 17 kip/in stiffness, and an estimated damping of 3%.

TABLE 1. 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

TABLE 2. PROPERTIES OF LEAD - RUBBER ISOLATORS (AT 1.1 INCH DISP.)

Qd - Characteristic Strength	13.9 kips
Fy - 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

Response during Northridge Earthquake

The response of USC hospital to Northridge earthquake (foundation level acceleration CHN 5 and CHN 7 -- see Fig. 1a) is computed using the nonlinear analytical model developed. Fig. 2a shows a comparison of the recorded and computed response in the NS directions; absolute accelerations and relative displacements at sensor locations shown in Fig. 1a 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 one peak cycle of motion). The correlation of recorded and computed time histories demonstrate the accuracy of the analysis techniques used and nonlinear models used in 3D-BASIS.

The time history of response shown in Fig. 2a 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 ground accelerations were deamplified by the base isolated USC hospital due to base isolation. The Northridge earthquake which has energy in the structural mode range cannot transmit the energy effectively because of the higher modes having reduced participation and increased damping, which are the main reasons for the effectiveness of the isolation system (Kelly 1990).

Fig. 2b 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. 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 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.* 1996). Examination of the records for torsional response revealed that nominal torsional response occurred (Nagarajaiah *et al.* 1996). The corner displacements at different floors/base were approximately 25% more than the displacement at the center of mass.

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. 1b. 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 ~1.35 secs (Nagarajaiah *et al.* 1996). The equivalent linear isolation system is based on bearing properties at 1.4 inch (3.5 cm) maximum displacement experienced by the isolators in Northridge earthquake. Estimated level of damping at this amplitude is ~10%.

The building has been extensively instrumented by CSMIP (Shakal *et al.* 1994); the sensor locations are shown in Fig. 1b. An examination of the records indicates sharp acceleration spikes. The cause for these acceleration spikes is accidental pounding against entry bridge, 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. 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 impact-spring-dashpot element at the North-East corner of the building. It is evident from the recorded response 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 impact-spring-dashpot is moved back to equal the isolation gap at approximately 16 secs into the time history response. The correlation between the computed and recorded response shown in Fig. 3a is good. The computed response of FCC building without pounding is also shown in Fig. 3a.

The effects of pounding are examined in Fig. 3b by comparing the case of the base isolated building with and without pounding and the fixed-base case without pounding. The peak story shear and peak drift envelopes are shown in Fig. 3b. It is evident from the results in Fig. 3b that pounding causes 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.

ACKNOWLEDGMENT

This research is supported by a grant from the Strong Motion Instrumentation Program of the California Department of Conservation (Contract No. 1093-556). The authors wish to thank Drs. Huang, M. J., Maldonado, G., Darragh, R. B., and Shakal, A. of CSMIP for providing data for the study. 3D-BASIS and portions of the analysis capabilities used in this study are supported by the National Center for Earthquake Engineering Research (NCEER grant 93-5003). This support is gratefully acknowledged.

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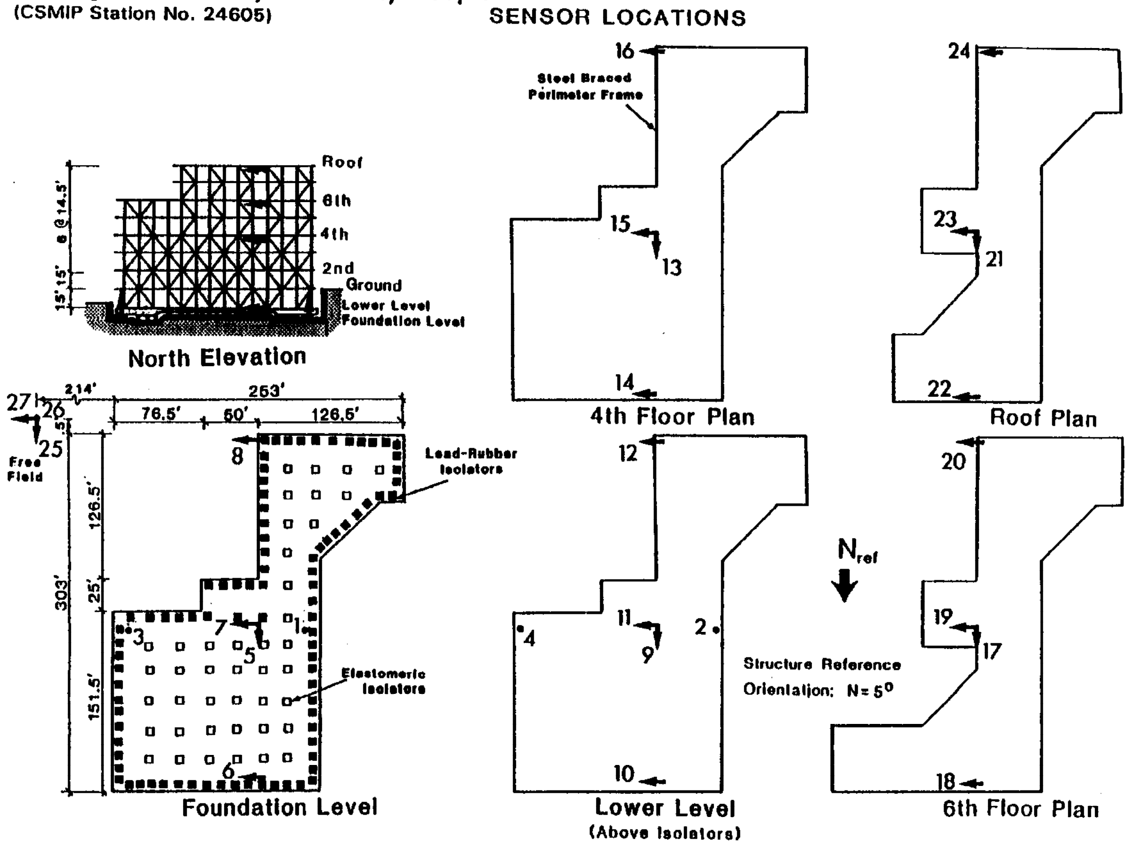
Los Angeles - 7-story University Hospital
(CSMIP Station No. 24605)



Los Angeles - 2-story Fire Command Control Bldg.
(CSMIP Station No. 24580)

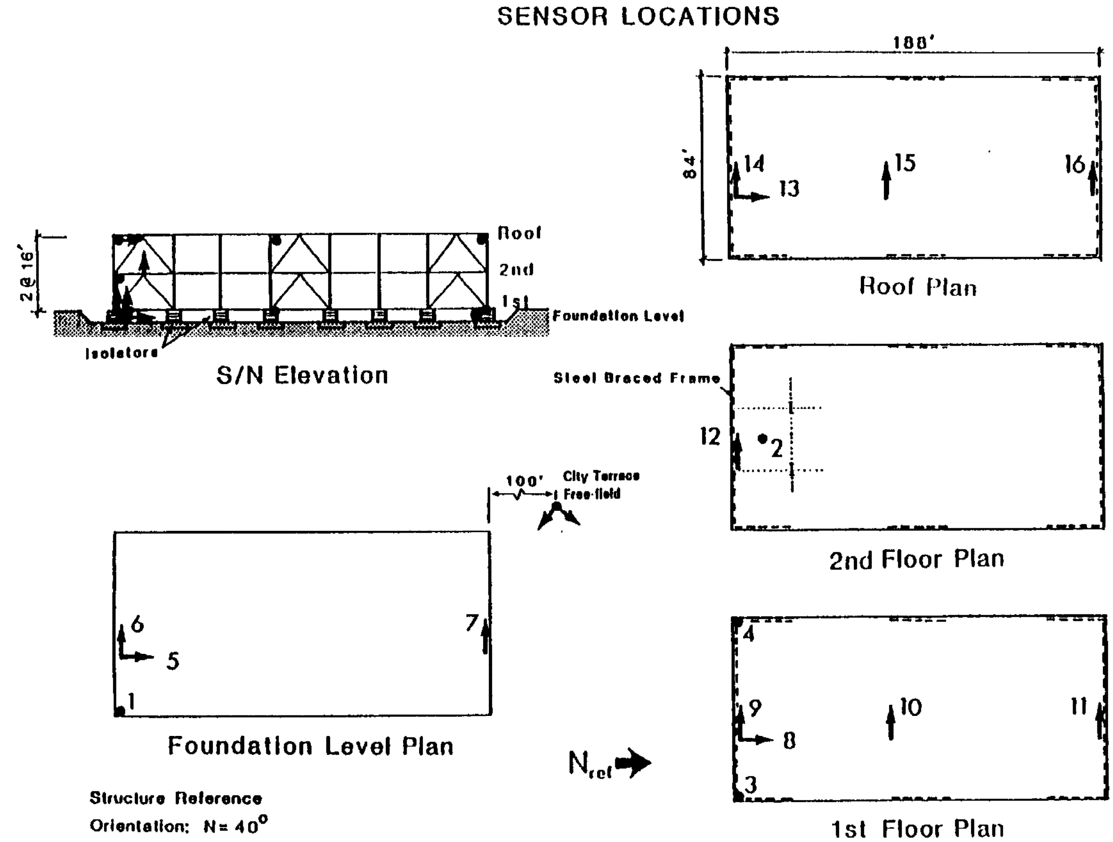


Fig. 1. (a) USC Hospital, (b) FCC Building. Superstructure and Isolation System Details, Sensor Locations.

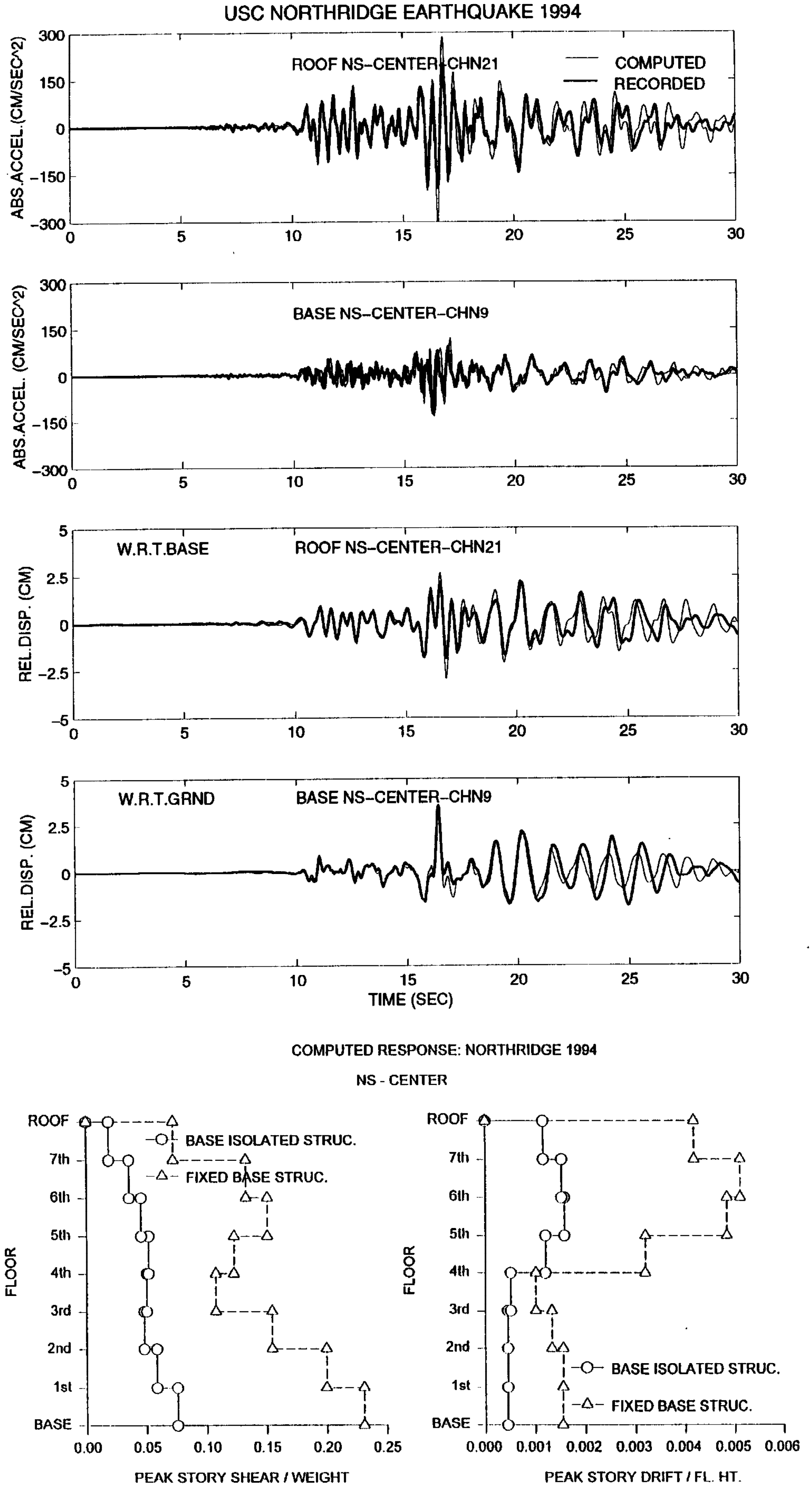


Fig. 2. USC Hospital (a) Recorded and Computed Response in the NS direction at Sensor Locations shown in Fig. 1a, (b) Comparison Between Base Isolated and Fixed-base Case -- Normalized Peak Story Shear and Drift Envelopes in NS Direction.

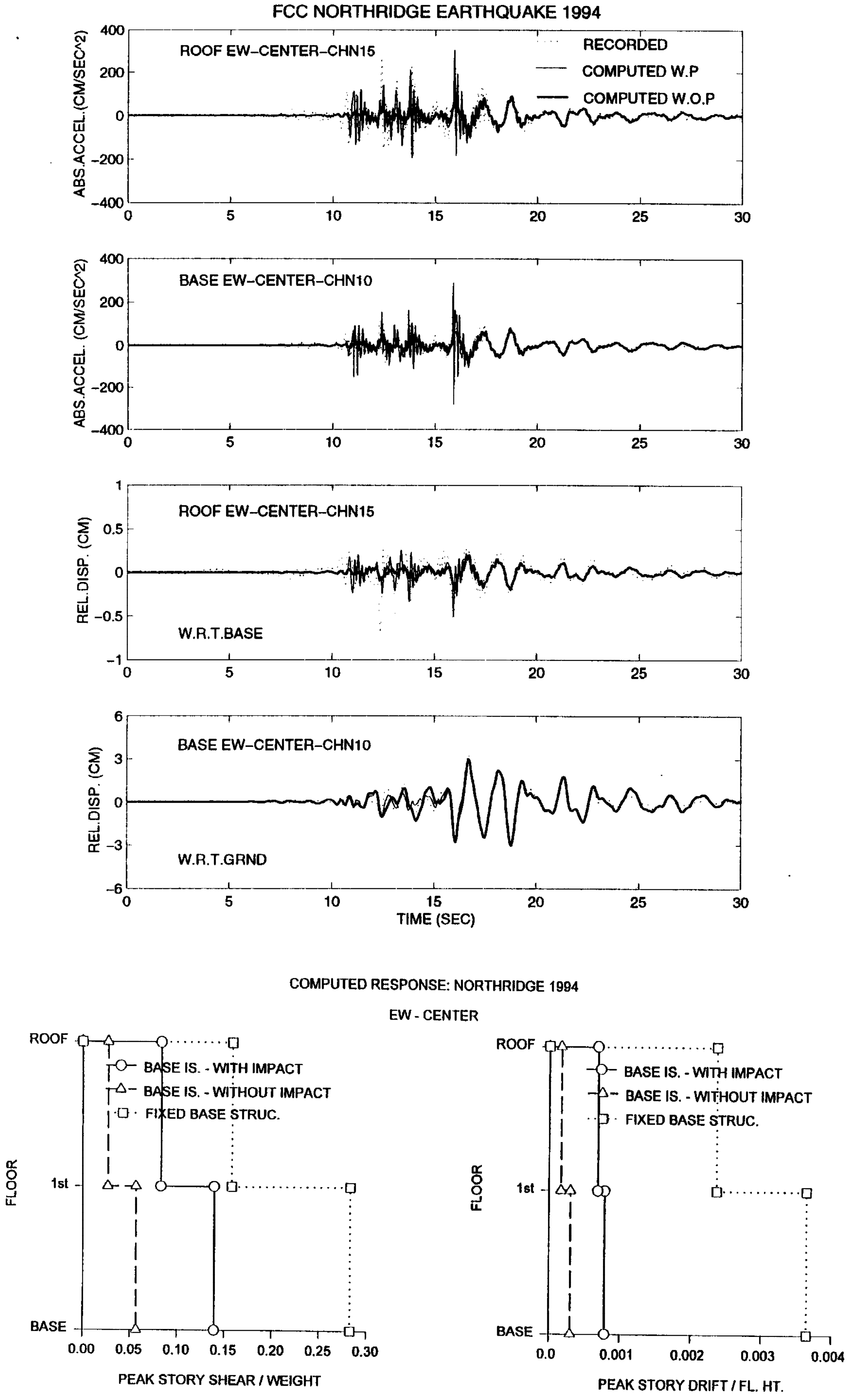


Fig. 3. FCC Building (a) Recorded and Computed Response in the EW direction at Sensor Locations shown in Fig. 1b, (b) Comparison Between Base Isolated and Fixed-base Case -- Normalized Peak Story Shear and Drift Envelopes in the EW Direction.