Earthquake Response Evaluation of an Isolated Building

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1 INTRODUCTION

There are many examples in the construction industry that painfully illustrate that problems occur when technologies are prematurely applied. Before nuclear power plant structures are seismically isolated, it is, therefore, necessary that the performance of isolated structures during earthquakes be documented and critically evaluated.

With a second earthquake recently experienced by the Rancho Cucamonga Law and Justice Building (LJB) in Southern California, an opportunity exists to evaluate the performance of this building in some detail.

2 BUILDING DESCRIPTION AND SEISMIC INSTRUMENTATION

Figure 1 shows a cross section of the LJB. The building is four stories high with a full basement and sub-basement for the isolation system. The isolation system consists of 98 isolators of multi-layered natural high-damping rubber bearings reinforced with steel plates. The superstructure has a structural steel frame stiffened by braced frames in some bays. The building is located 25 km from the San Andreas fault and is designed for a magnitude 8.3 earthquake. Tests of full-scale sample bearings demonstrated that the expected maximum horizontal displacement demand of 15 in (380 mm) can be accommodated (Kelly, 1991). Figure 2 shows the locations of the acceleration sensors. Arrows show the location and positive direction of the accelerometers. Dots indicate the positive direction out of the plane of the figure.

3 RECORDED EARTHQUAKES

Two earthquakes have been recorded since the completion of construction of the LJB. The first earthquake (Redlands Earthquake, October 2, 1985) was a small magnitude, $M_L = 4.8$, event with its epicenter 30 km from the building. The free-field peak ground acceleration (PGA) in the NS direction was only 0.045g, EW direction 0.035g, and vertical 0.03g. The second earthquake (Upland Earthquake, February 28, 1990) was a relatively more significant event. The magnitude was $M_L = 5.5$ and was centered only 12 km from the building. The free-field PGA in the NS direction was 0.26g, EW direction 0.25g, and vertical 0.19g. Figure 3 shows a sample of the time-history accelerations recorded in the building. The locations of the recordings are shown in Fig. 1. Figure 4 compares the 2% damped spectra of the free-field motions from these two events. For the Redlands event the free-field motion is characterized by a very narrow-band high frequency signal, centered at about 14 Hz, and with an energy span from 10 to 20 Hz. For the Upland Earthquake the free-field motion energy has a much more broad band frequency content and spans from 3 to 20 Hz. The frequency content of the Upland earthquake would be more representative of the great earthquake on the San Andreas Fault for which the isolation system was designed. The 2% damped spectral acceleration amplitude in this range is more than 1.0g as against an average of 0.25g from the Redlands event.

Despite the significant differences in amplitude and frequency content, the LJB responded to these two events very much the same way, except, of course, in terms of the absolute values of the response amplitudes.

4 RESPONSE EVALUATION

Because of space limitations only the results from the Upland earthquake will be presented. The evaluation is based on comparisons of responses, in terms of the 2% damped response spectra, at different locations.

In Fig. 5 the response spectra of the free-field and the foundation center are compared. Significant reduction of response occurs from the free-field to the foundation level, which is 15'-5" (4.70m) below the ground surface. This is primarily due to the excavated space of 110' x 414' (35.5m x 126.2m). It is to be noted that the reduction of the free-field motion is significantly more in the EW than in the NS direction. This is to be expected. Assuming plan waves, and using a 2D finite element model it was shown (Hadjian et al, 1986) that, for an infinitely long trench, the ground motion in the excavation tends to the free-field ground surface motion as the width of the excavation increases. As the width of an infinitely long trench decreases, the ground motion tends to the free-field motion at the depth level of the bottom of the trench. Because of free surface reflection of waves, the latter motion is therefore expected to be significantly less than that of the surface motion. In the case of the LJB, the cross section in the NS direction can be assumed to represent a long infinite trench with, relative to the depth, a large width (110' vs. 15'-5"). Thus, the reduction of motion from the free-field is only moderate. For the EW direction, although the width of the "trench" is large, the "trench" is not infinitely long. In fact, it could be considered to be a narrow slit in the ground without significantly affecting the ground motion at the same depth level in the free-field. Thus, a more significant reduction of motion occurs in the EW direction. For frequencies above 3 Hz, the reduction is about 50%. If the building was founded on the ground surface, the type of drastic reduction of motion shown in Fig. 5 would not have occurred. Consequently, from the isolation viewpoint, it is important to consider the foundation motion rather than the free-field motion in response evaluations.

In Fig. 6 the response spectra of the foundation and basement, at three locations in the NS direction, are compared. Below 0.23 sec (above 5 Hz) the foundation motion is drastically filtered out. And above 0.67 sec (below 1.5 Hz) the foundation motion is enhanced. As will be discussed later, this is due to the rocking of the building, which, as is to be expected, is more pronounced at the east and west walls of the building. Similar results are obtained in the EW direction (not shown).

Figure 7 is primarily intended as a comparison of roof and basement responses. It is abundantly clear that the building rocked at about 0.75 sec (1.3 Hz) in both EW and NS directions during the Upland earthquake. The basement to roof amplification is five fold. For the Redlands earthquake this same phenomenon occurred at 1.8 Hz with seven-fold amplification of the 2% damped spectral response. The frequency difference (1.8 vs. 1.3) is due to the softening characteristics of the isolators with increasing response. Using the response spectra peaks at 1.3 Hz, the response at the roof in the NS direction can be broken down to its constituent parts as follows: 6% rigid body swaying across the isolators, 73% due to rocking and 21% due to structural deformation. These results are shown in Fig. 8. Also from Fig. 7, it can be concluded that higher modes were also excited, e.g. an EW translational mode at 0.32 sec (3.1 Hz).

In Fig. 9 the response spectra in the EW and NS directions are compared both at the basement and at the roof. The peak spectral amplitudes at 1.3 Hz are plotted in Fig. 10, from which it could be deduced that the LJB responded as an inverted spherical pendulum during the Upland earthquake.

It can thus be concluded that the seismic response of the building was simply shifted from being a high frequency response to a lower frequency response by inserting the isolators underneath the structure. Since the input motion (Fig. 5, Foundation) was not strong, structural damage was not experienced at LJB. In fact, across the street from the LJB, stacked roof tiles on the roof ridge of a two story structure under construction did not even fall off the ridge. Therefore, to assess the level of isolation provided to this building, a survey of the personnel in the building during the earthquake was conducted.

5 SURVEY OF BUILDING OCCUPANTS

The results of the survey are summarized in Table 1. Out of a total of 24 numbered questionnaires, 14 completed questionnaires were returned. The questionnaire first asked questions about the respondents' environment (columns 1-4). In the 2nd column, the numbers preceding the letters designate the number of the questionnaire.

The second part of the questionnaire asked questions about the level of shaking (columns 5-11). Duration and level of shaking is summarized in columns 5 and 6. Responses to questions about their personal behavior during the earthquake and what happened around them is summarized in columns 10 and 11, respectively. Column 9 gives the Peak Floor Accelerations as obtained from the recorded data. Columns 6 and 7 need some explanation:

The MMI scale descriptions were edited to eliminate behavior descriptions outside in the open--thus, references to birds, trees, etc. were deleted. Intensity levels IX-XII were completely removed. The respondents were asked to estimate the MM intensity level according to this edited version. Their responses are given in column 8. The responses range from intensity IV-VI, with a 5.2 average.

Column 7 is a new scale of isolation intensity. As shown in Fig. 11, the commonly used cartoon to show the advantages of isolation was placed at the two ends of a scale ranging from zero to ten. The definitions of zero and ten scales were provided. The respondents were asked to determine a numerical value describing their situation during the earthquake between these two limits. These are given in column 7. Since respondent No. 20 "got under my desk (counter). I was very scared. I thought this was the Big One," his characterization of the isolation intensity as 0 cannot be valid. Eliminating it gives an average isolation intensity of 4. Obviously, this earthquake did not go unnoticed by the occupants of this building. For a magnitude $M_L = 5.5$, 12 km from the building and a basement peak acceleration of 0.13g an isolation intensity of 4 is not very encouraging.

6 CONCLUSIONS

Based on the data and information summarized in Table 1, together with the evaluation of response results given in Figures 5-10, it is concluded that the isolators under the LJB did not function as expected during the Upland Earthquake. The frequency range of 1-3 Hz seems to be particularly critical for this structure. A large event on the San Andreas, 25 km away, or the San Jacinto, 20 km away, may contain significant energy in this range of frequencies. What the isolation system did was change a high-frequency response problem to a lower frequency response problem.

REFERENCES

Kelly, J. M. (1991). Base Isolation: Origins and Development. Earthquake Engineering Research Center NEWS, Vol. XII, No. 1, pp. 1-3.

Hadjian, A. H., Lin, S. T. and Luco, J. E. (1986). Modeling for Finite-Element Soil-Structure Interaction Analysis. Proc. 3rd Conf. on Dynamic Response of Structures, ASCE (Editors Hart and Nelson) March 31-April 2, UCLA, pp. 716-723.

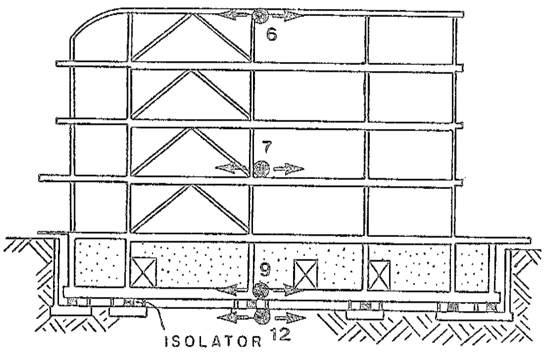

Fig. 1 Cross-section of LJB

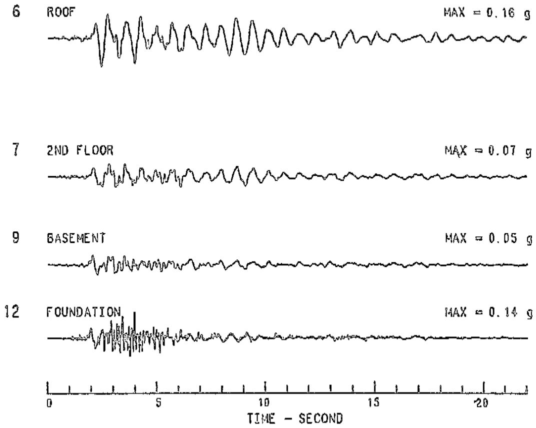

Fig. 3 Acceleration records from the Upland Earthquake, Feb. 28, 1990

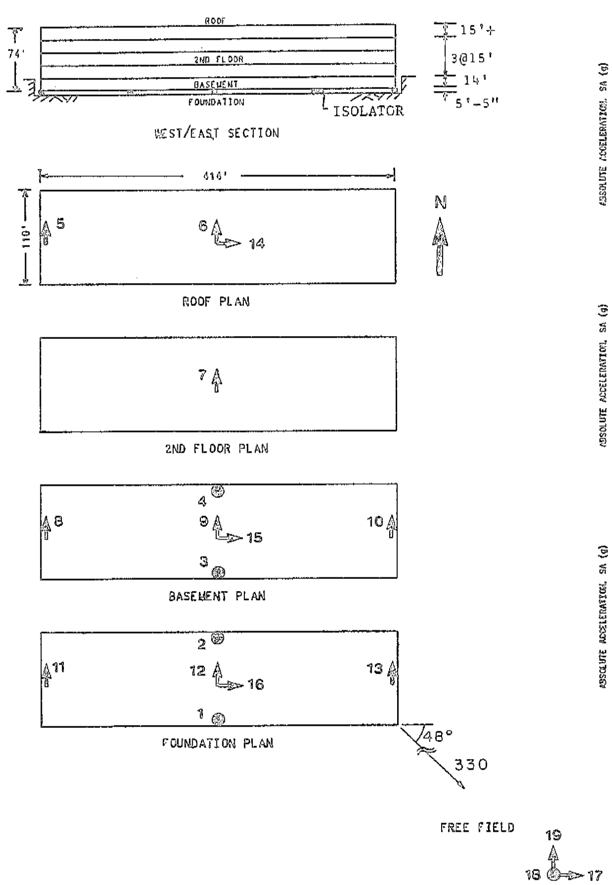

Fig. 2 Location of accelerometers

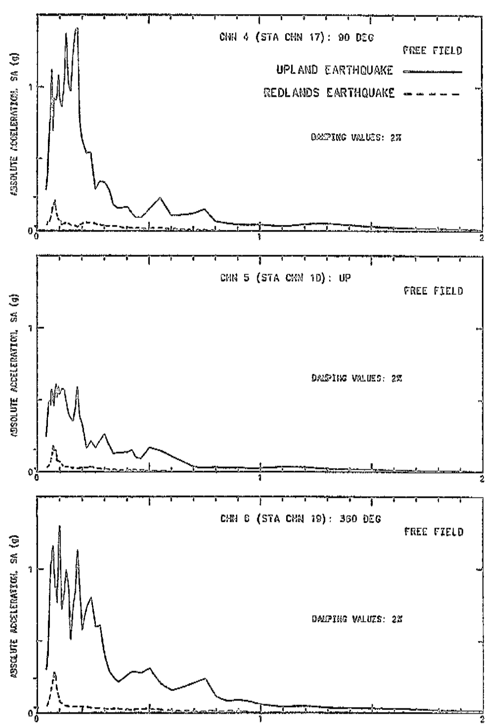

Fig. 4 Comparison of 2% damped response spectra from the Redlands and Upland Earthquakes

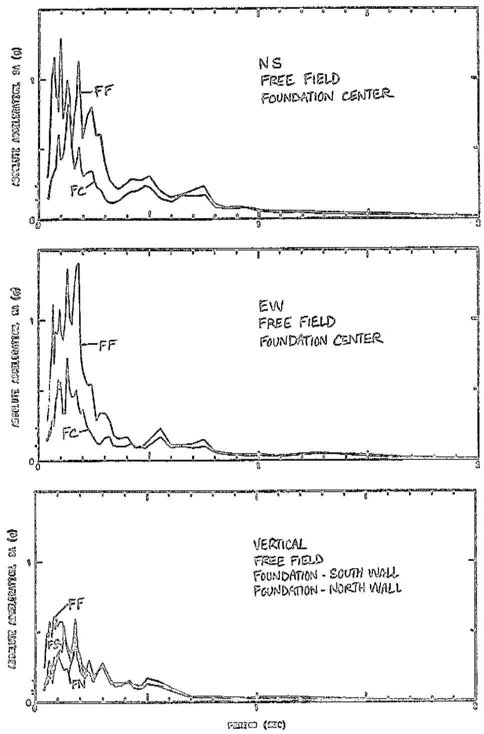

Fig. 5 Free-field and foundation response

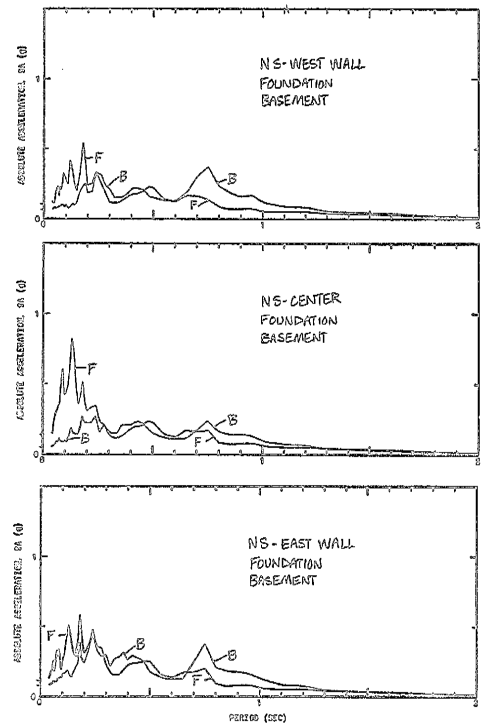

Fig. 6 Foundation and basement response

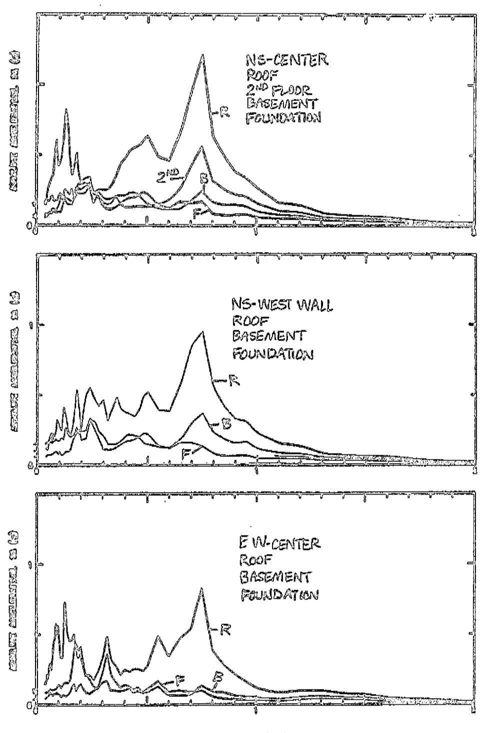

Fig. 7 Roof and basement response

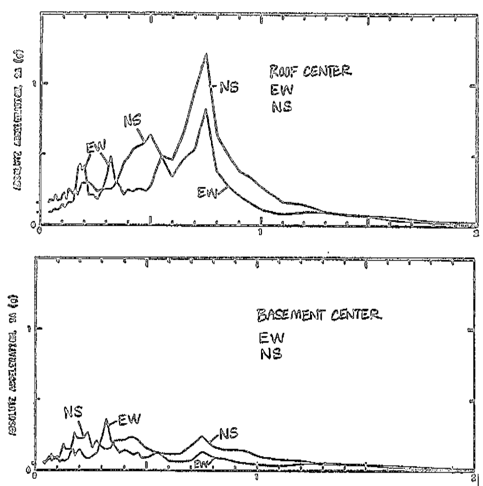

Fig. 9 EW-NS response

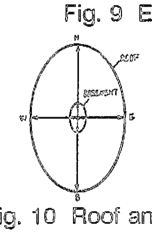

Fig. 10 Roof and basement peak spectral amplitudes at 1.3 Hz

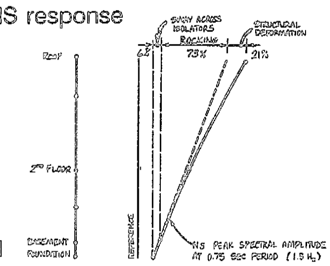

Fig. 8 NS response at roof

Table 1. Employee response characterization of the Law and Justice Center during the February 28, 1990 Upland Earthquake

1	2	3	4	5	6	7	8	9	10	11
FLOOR	RESP. LOCATION	SPACE	POSITION	DURATION	BUILDING TREMBLED	ISOLATION INTENSITY	MMI	PFA	PERSONAL BEHAVIOR	STATUS OF IMMEDIATE ENVIRONMENT
	W - West C - Center E - East			○ Sudden <10 sec ○ Short 10-30 sec ○ Long 30-60 sec	○ Slightly ○ Moderately ○ Strongly					
4th Floor								NS 0.16g EW 0.10g		
3rd Floor	3W	Closed	Sitting on casters	Short	Strongly	6	V		Remained seated and felt severe rolling.	Intact.
	4C	Open	Sitting on casters	Short	Strongly	5	V		Felt like standing close to a fast freight train.	Everything was okay.
	13W	Closed	Sitting on casters	Short	Strongly	3	VI		Building rolling. Got under my desk.	Office door slammed shut. Pictures off center.
	15W	Open	Sitting on casters	Short	Slightly	2	VI		Building swayed. Just sat at my desk.	Everything in its place.
2nd Floor	5W	Closed	Leaning against door	Short	Strongly	3	VI	NS 0.07g	Got to a door frame and braced myself.	Everything intact.
	6W	Closed	Leaning against wall	Short	Moderately	6	V		Got to a door frame.	Wall hangings swung out of place.
	7E	Closed	Sitting on window ledge	Short	Moderately	3	IV		Got to a door frame.	Few materials fell off walls, ceiling tile fell.
	8W	Closed	Sitting on casters	Short	Strongly	6	VI		Moved to interior hallway, got prone at wall.	Water lapped over rim of aquarium.
1st Floor	18.1W	Open	Sitting on casters	Long	Strongly	3	V		Quickly crawled under desk.	Books between bookends disturbed.
	18.2W	Open	Sitting on casters	Long	Strongly	3	V		Quickly crawled under desk.	Books between bookends disturbed.
	18.3W	Open	Standing at desk	Long	Strongly	3	V		Quickly crawled under desk.	Books between bookends disturbed.
	20C	Open	Standing at desk	Long	Moderately	0	VI		Got under counter. I was very scared. - Big One.	Everything appeared okay.
Basement	1C	Open	Standing	Long	Moderately	5	V	NS 0.08g	Sensation of rocking.	Everything remained in place.
	2C	Open	Sitting on casters	Long	Moderately	4	IV	EW 0.06g V 0.12g	High level of rolling motion.	Nothing seemed to be disturbed. Computers did not shut down.
Sub-Basement								NS 0.13g EW 0.12g V 0.09g		Free field NS 0.26g EW 0.25g V 0.19g

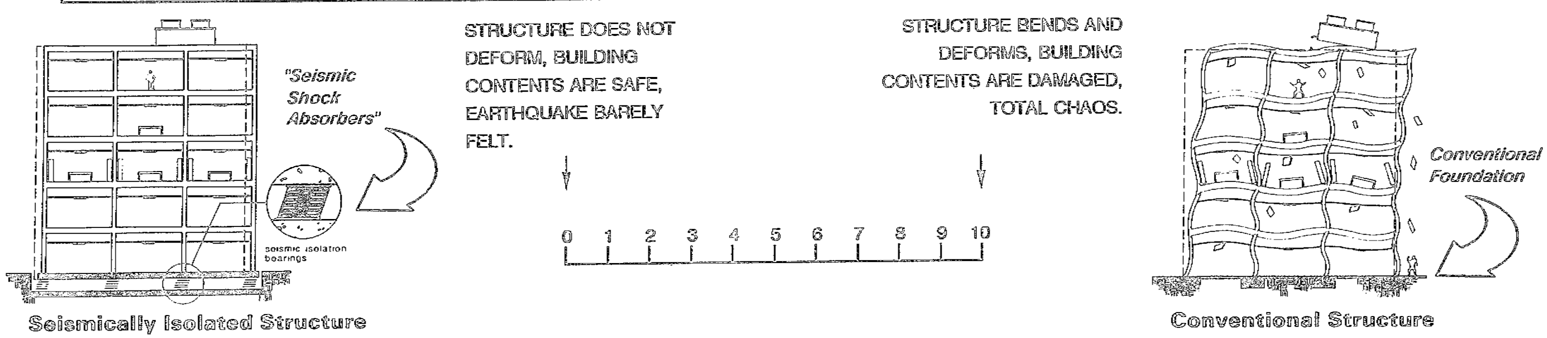

Fig. 11 New scale of isolation intensity