Structural Eng./Earthquake Eng. Vol. 9, No. 3, 169s—180s, October 1992
Japan Society of Civil Engineers (Proc. of JSCE No. 455/ I —21)

IDENTIFICATION STUDY ON BASE ISOLATION SYSTEMS BY FULL-SCALE BUILDINGS

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Seismic response characteristics of two types of base-isolated buildings are investigated by using identification techniques. Equivalent linear system was first assumed in connection with the dynamic behavior of the structural system, then the nonlinear Bouc-Wen's model was also assumed as second stage to model the isolation system and estimate the hysteretic damping of the system. Both "modal minimization method" and "Extended Kalman Filtering techniques" are used for structural identification. The natural frequency of the isolation system of Law and Justice Center Building was designed greater than the natural frequency of the building while the natural frequency of the test building of Tohoku University was designed smaller than the natural frequency of the building. These results are obtained from identification.
Keywords : *base-isolation system, system identification, earthquake engineering*

1. INTRODUCTION

Base isolation techniques provide an alternative approach for seismic design of buildings and bridges. When appropriated, the use of special energy dissipation devices between the superstructure and the substructure can significantly reduce the forces induced in the building structures, as compared with non-isolated structures. Many studies on the base isolation system with isolators and dampers have already been published[1)~5)]. Generally, the base isolation system is composed of three elements : the isolator that lengthens the period of structure out of the dominant frequency components of ground motion, elastic-plastic or viscous damper which dissipates vibration energy during an earthquake, and fail-safe mechanism. In recent years, base-isolated buildings have been constructed, and considerable amounts of earthquake response data have been published. To evaluate dynamic behavior of base-isolated buildings during earthquake, it is required to investigate the response characteristics which the mathematical model of the isolation system can be shown. For this purpose, system identification techniques[6)~11)] can be adopted to this problem. In this study we focus on the identification of two isolated buildings, one is the Foothill Communities Law and Justice Center in Rancho Cucamonga, USA, and the other is the test building at Tohoku University, Japan. The recorded earthquake responses of these two buildings had been discussed before and the dynamic characteristics of the super-structure and the isolation system had been identified[12)~16)].The purpose of this paper is to verify the dynamic characteristics of these two building by using the earthquake data of two recent earthquakes. Discussions on damping effects of the isolation system and the effects of nonlinearity of isolator on the response are issued in this paper.

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2. DESCRIPTION AND EARTHQUAKE OBSERVATIONS OF THE BUILDINGS

The earthquake observations were carried out for the two different buildings whose locations are at Tohoku University of Japan and at Rancho Cucamonga of USA respectively. The datails of each building are described as follows :

San Bernardino County Law and Justice Center : The Foothill Communities Law and Justice Center in Rancho Cucamonga, California, is a four-story building supported on elastomeric bearings which are interposed between the basement of the structure and the foundation. The structure above the isolation system consists of a steel space-frame stiffened at various bays by braced frames. The isolation system consists of eight different types of isolators that are placed under the building's 98 columns. The isolators are 17 in high and 30 in diameter. This Law and Justice Center is instrumented by the California Strong Motion Instrumentation Program with a total of 19 accelerometers, as shown in **Fig.1**. Strong shaking of this building was recorded during the 5.5 local magnitude Upland earthquake on February 28, 1990[17)]. The peak horizontal acceleration at the free-field site is 0.26 g and with dominate frequency between 5 Hz and 10 Hz. The foundation of the

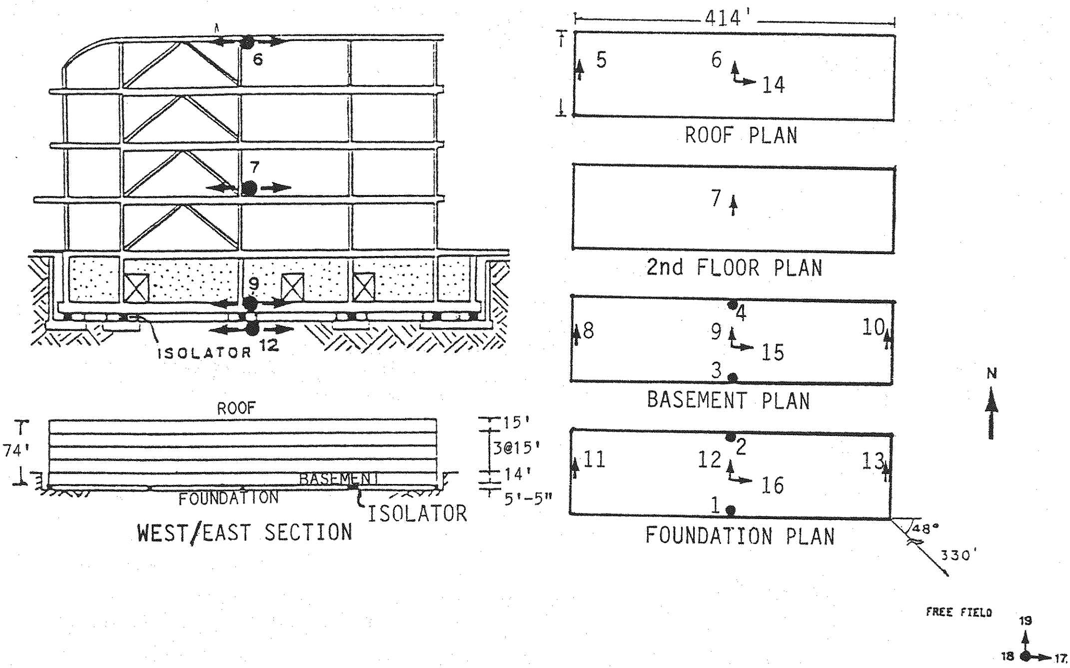


Fig.1 Locations of accelerometers in the San Bernadino County Law and Justice Center.

building provides kinematic interaction effect that filtered out high frequency signals of free-field motion and peak acceleration recorded at the foundation level (below the isolators) is 0.14 g. The peak acceleration values recorded by the three transverse sensors in the basement (above the isolators) range from 0.05 to 0.08 g. Some high frequency signals are filtered through the observation of Fourier spectra between the foundation motion and the basement motion because of the isolation system. The peak motion at the roof is 0.16 g. Fourier spectra of the earthquake responses at the 2nd floor and the roof of the building of this earthquake are calculated and the natural frequency of the building appears at 1.4 Hz for the first mode (highest peak of Fourier amplitude).

The Test Buildings at Tohoku University : The test buildings were constructed on the campus of Tohoku University in Sendai, Japan. They are composed of two buildings, one base-isolated and the other conventional, whose super-structures and the level of the base mats are exactly the same. The two buildings are both three-story reinforced concrete structures. Eleven accelerographs were installed at the bed rock, near the surface of the building, the first floors and roofs of both buildings. The plan and elevation of test buildings are shown in **Fig.2**. The isolation devices consisting of six laminated rubber bearings (LRB) and twelve oil dampers were installed in the basement of the building. For the purpose of investigating the dynamic behavior of the building during earthquake observations were conducted for the test buildings and their surrounding ground. The earthquake observation started in May 1986. The earthquake of February 6, 1987, with magnitude of 6.7 and epicentral distance 168 km and focal depth

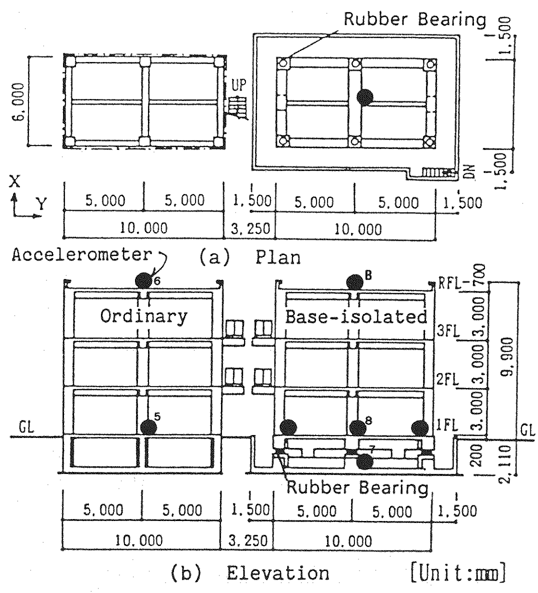


Fig.2 Plan and elevation of test buildings at Tohoku Univ.

of 31 km is used to study the dynamic response of this building. During this earthquake, the maximum accelerations at the roof of the base-isolated building were 35.76 gal and 31.84 gal for x- and y-directions respectively, which were from 1/5.7 to 1/4.9 of the value at the roof of the un-isolated building. It was observed from the Fourier amplitude spectrum of responses that the predominant frequency of the ground motion appears at 2.5 Hz. The dominant frequency of the isolation system appears at 1.0 Hz.

3. MATHEMATICAL MODELS

(1) Linear Model

The transmission of ground motion to structures can be effectively controlled through the isolation of the structure at its base. Generally speaking, rubber bearings offer the simplest method of isolation. The laminated rubber bearing (LRB) consists of alternating layers of rubber and steel with the rubber being vulcanized to the steel plates. The mathematical behavior of this system is a simple model with linear spring and linear viscous damping. Since most isolation systems are intrinsically nonlinear, and the effective stiffness and damping will have to be estimated by some equivalent linearization processes. In the linear analysis of isolation system, consider a linear multi-story shear type structure mounted on a base-isolated foundation with laminate rubber bearings. This base isolation system provides stiffness and viscous type damping in the horizontal direction. Adopting the normal mode approach and assuming that the super-structure vibrates in the first mode, one may acquire the following system for the base and modal displacement[3) :

$$a\ddot{x}_b+\ddot{y}+2\xi_1\omega_1\dot{y}+\omega_1^2y=-a\ddot{x}_g \quad \text{(1a)}$$

$$\ddot{x}_b+2\xi_b\omega_b\dot{x}_b+\omega_b^2x_b-2\xi_1\omega_1d\mu\dot{y}-\omega_1^2yd\mu=-\ddot{x}_g \quad \text{(1b)}$$

in which $\ddot{x}_g$=the acceleration of the ground, ξ_1 and ω_1=the damping factor and frequency of first mode, ξ_b and ω_b=the equivalent linear viscous damping factor and frequency of the isolation system, x_b=relative displacement between foundation and the basement, and a=the participation factor which related to the mode shapes of the structure, y=the dimensionless modal displacement, and $\mu=m_N/m_b$, $\omega_b=\sqrt{k_b/m_b}$. m_N=mass of the top floor. The complex frequency respones functions for y and x_b, corresponding to $\ddot{x}_g=e^{i\omega t}$ can be calculated, i.e. $x_b=H_b(\omega)\ddot{x}_g$ and $y=H_1(\omega)\ddot{x}_g$.

(2) Nonlinear Model

The base isolation system consists of laminated rubber bearings which can be modelled as equivalent linear system with viscous damping and horizontal stiffness, and oil damper system in which hysteretic dampers were assumed to absorb large amount of energy. This hysteretic dampings provide hysteretic restoring force and can be modelled by a nonlinear differential equation which had been proposed by Wen[18]. **Fig.3** shows the structural system considered here. The super-structure is assumed to remain elastic during an earthquake ; the nonlinearity is only associated with the base isolation system. If the super-structure is assumed to vibrate in the first mode, the equations of motion of the system under consideration are :

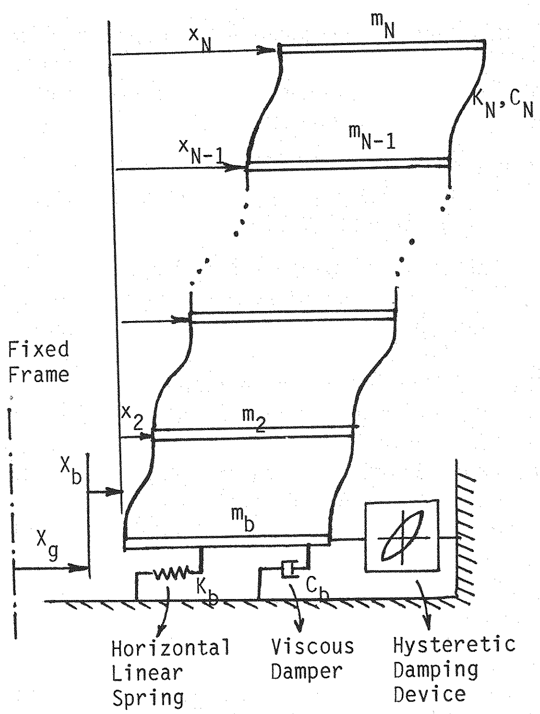


Fig.3 Structural and Isolation Model of Building System.

$$a\ddot{x}_b+\ddot{y}+2\xi_1\omega_1\dot{y}+\omega_1^2=-a\ddot{x}_g \quad \text{(2a)}$$

$$\ddot{x}_b+2\xi_b\omega_b\dot{x}_b+\alpha\omega_b^2x_b+(1-\alpha)\omega_b^2Z$$
$$-2\xi_1\omega_1\mu\dot{y}-\omega_1^2\mu dy=-\ddot{x}_g \quad \text{(2b)}$$

$$\dot{Z}+\gamma|\dot{x}_b|Z|Z|^{n-1}+\beta\dot{x}_b|Z|^n-A\dot{x}_b=0 \quad \text{(2c)}$$

in which Z is the hysteretic component, and n, A, β, γ are constants, and α is the pre-yield and post-yield stiffness ratio. The parameters ω_1, ξ_1, a, ξ_b, ω_b, α, β, γ, A and n are chosen such that predicted respones from the modal closely matches experimental results (actual seismic responses). This nonlinear model can consider the energy-absorbing devices that dissipates energy through hysteresis.

In this study on isolation system, the parameter n in Wen's nonlinear hysteretic model is set equal to one, $n=1$. The discussion on the estimation of n was presented in the reference 20.

4. IDENTIFICATION SCHEMES AND RESULTS OF THE ISOLATION SYSTEMS

(1) Modal Minimization Technique

In this study, under the assumption of linear responses in both super-structure and isolation system, the model minimization technique is used. It is based on the concept of minimizing the error between the actual response and the response predicted by the model in either time domain or frequency domain for a given set of parameters.

a) Frequency domain analysis :

The definition of error used in the automated procedure employed is given by

$$J(p)=\int_{f_1}^{f_2}\sum_{i=1}^{2}[R_{a_i}(\omega)-R_{p_i}(\omega,\ \ddot{x}_g;\bar{p})]^2\cdot W_i d\omega \quad \cdots\cdots(3)$$

where $R_a(\omega)$ and $R_p(\omega, \ddot{x}_g; p)$ are the actual and predicted responses of the system in the frequency domain from f_1 to f_2, respectively, $i=1$ is for the response of roof and $i=2$ is for the response of basement. The predicted response is computed from the model with modal parameters $\bar{p}$ and the excitation signal $\ddot{x}_g(\omega)$. In the present study, the response corresponds to the Fourier transform of the roof acceleration and the basement acceleration respectively (i.e., only two terms of summation are needed in Eq.(3)). W_i is the weighting function and is defined as the inverse of the response variances.

b) Time domain analysis :

Since the super-structure of the isolation system is assumed as a linear response during shaking, time domain analysis can also be performed. The error function can be defined in time domain and expressed in the following form :

$$J(p)=\int_{t_i}^{t_f}[\bar{r}(t;\bar{p})-r(t)]^2dt \cdots\cdots\cdots\cdots(4)$$

in which $\bar{p}$ is the vector formed by model parameters ω_1, ξ_1, and a. $r(t)$ and $\bar{r}(t;\bar{p})$ are the roof response of the structure for recorded and estimated time response respectively. Summation is done with respect to the discrete value of time increment (from initial time t_i to the end of vibration t_f). When error is zero, the exact modal parameters (ξ_1, ω_1 and a) can be identified. It is clear that the least square method can have an exact estimation if $\ddot{y}(t)$ and $(\ddot{x}_g+\ddot{x}_b)$ are measured exactly. The algorithm employed to vary the parameters in the automated procedure corresponded to a variation of the steepest descent method. It is believed that the modal minimization technique is a much more reliable technique than the transfer function approach for estimating the values of the periods, damping factors and participation factors of the first few modes of vibration of an engineering building.

(2) Extended Kalman Filtering Technique :

The algorithm of the extended Kalman filtering technique is a recurrsive process for estimating the optimal state of a nonlinear system based on observed data for the input (excitation) and output (response). It is believed that under strong shaking the isolation system may have nonlinear behavior. This technique to the identification of the nonlinear parameters of the isolation system is discussed in this study.

Consider an isolation system generated by Equations (2b) and (2c). The response of the system to an input strong motion earthquake record ($\ddot{x}_g$) has been recorded. Define a state vector $\{X\}$ as

$$\{X\}=\langle u_b,\ \dot{u}_b,\ Z,\ A,\ \beta,\ \gamma,\ \alpha,\ d\mu,\ \xi_b,\ \omega_b\rangle^T =\langle x_1, x_2, x_3, \cdots, x_{10}\rangle^T \cdots\cdots\cdots(5)$$

The set of state vector equations, Eq.(2b), at time t representing an identification problem can be formulated as

$$\frac{dX_t}{dt}=f(X_t,\ t_k) \cdots\cdots\cdots\cdots(6)$$

where

$$f(X_t,\ t_k)=\{\dot{X}\}=\begin{Bmatrix} x_2 \\ \ddot{u}_g-2x_9x_{10}x_2-x_7x^2x_1-(1-x_7)x_{10}^2x_3 \\ +2\xi_1\omega_1^2x_8\dot{y}+\omega_1^2x_8y \\ x_4x_2-(x_3|x_2||x_3|^{n-1}x_3+x_6x_2|x_3|^n) \\ 0 \\ \vdots \\ 0 \end{Bmatrix} \cdots(7)$$

ξ_1, ω_1 and $\ddot{u}_g(t)$ are assumed as known parameters and excitations, respectively. The observation vector $\{Z\}$ is expressed as

$$\begin{Bmatrix} Z_1 \\ Z_2 \end{Bmatrix}=\begin{bmatrix} 1 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & 0 & \cdots & 0 \end{bmatrix}\{X\}+\{V\} \cdots(8)$$

where $\{V\}$ is the measurement noise vector. The identification by the Extended Kalman filter with Global Iteration (EK-WGI)[9] method is developed from Eqs.(6) and (7). The brief outline of the EK-WGI method is that if the initial state vector $\hat{X}(t_0|t_0)$ and error covariance matrix $P(t_0|t_0)$ are given, then the observation data $Z(t)$ are processed. It is possible to estimate the state vector

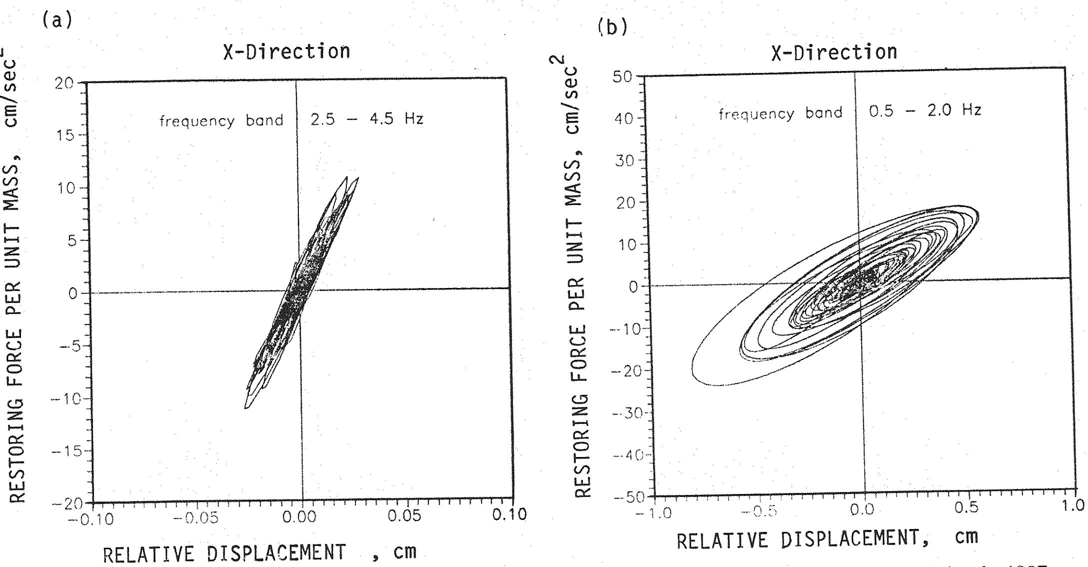


Fig.4 Plot of restoring force diagram for the test building of Tohoku University during Feb. 6, 1987 earthquake, (a) between roof and basement ; (b) between basement and foundation.

Table 1 Identified modal parameters of the test building at Tohoku University for Feb. 6, 1987 earthquake.

Test Building of Tohoku University		Superstructure			Isolation System							
		f_1 (Hz)	ξ_1	a	f_b (Hz)	ξ_b	$d\mu$	A	β	γ	α	Error
Linear Model	X-direction	3.83	0.026	1.25	0.81	0.247	0.032	—	—	—	—	1.06 %
	Y-direction	4.82	0.043	1.26	0.80	0.208	0.006	—	—	—	—	1.47 %
Nonlinear Model	X-direction	3.83	0.026	1.25	0.97	0.187	0.035	0.4240	0.9250	0.4945	0.5507	0.89 %
	Y-direction	4.81	0.043	1.26	1.02	0.146	0.008	0.4334	0.5717	-.0132	0.3573	1.52 %

Test Building of Tohoku University		*Superstructure*			*Isolation System*	
		f1(Hz)	ξ_1	a	*fb(Hz)*	ξ_b
Results of Forced Vibration*	X – *direction*	3.63	0.016	-	0.72	0.16
	Y – *direction*	4.39	0.014	-	0.73	0.15

"*" : Results from referece 15

$\hat{X}(t_k|t_k)$ and the error covariance $P(t_k|t_k)$ by the iterative calculation of the Extended Kalman filter. The associated error covariance matrix is defined as $P(t_k|t_k)=E[e(t_k|t_k)e^T(t_k|t_k)]$ and e is the estimation error.

Identification on the Test Building of Tohoku University : The data recorded from the earthquake on Feb. 6, 1987 was used to identify the dynamic properties of the building[13]. In the beginning the restoring force diagram of the system was plotted, as shown in **Fig.4**. Large relative displacement between basement and foundation was observed. It is clear from this picture that the isolation system is very effective to reduce the structure responses during earthquake excitations.

For conceptual purposes the "equivalent linear stiffness and damping" of a given hysteresis loop are assumed in the isolation system as well as in the super-structure during earthquake excitation. In the beginning, modal minimization technique was applied from frequency domain analysis to identify the modal parameters of the super-structure. With the identified modal parameter of super-structure, Kalman filter technique was applied to identify the equivalent viscous damping and stiffness of isolator from time domain. **Table 1** shows the results of the estimated modal parameters. For linear model the estimated equivalent viscous damping for isolation system is 24.7 % and 20.8 % in x-direction and y-direction respectively. During strong earthquake

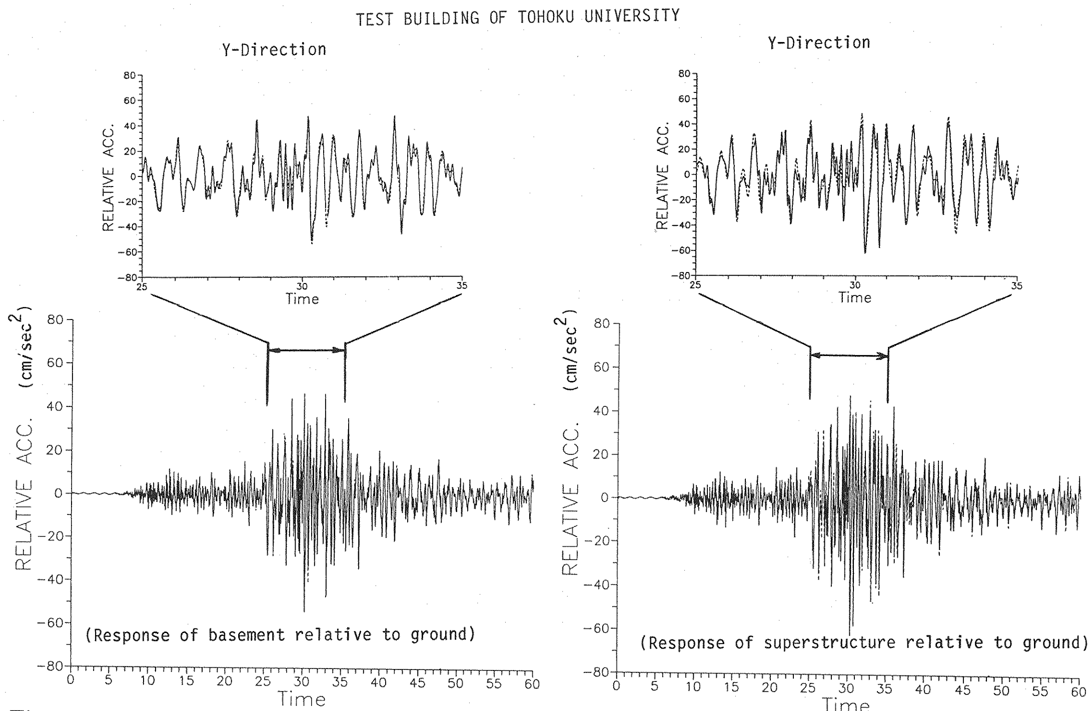


Fig.5 Comparison between the predict and recorded time history of the test building at Tohoku University (Y-direction), (a) response of basement relative to ground ; (b) response of super-structure relative to ground.

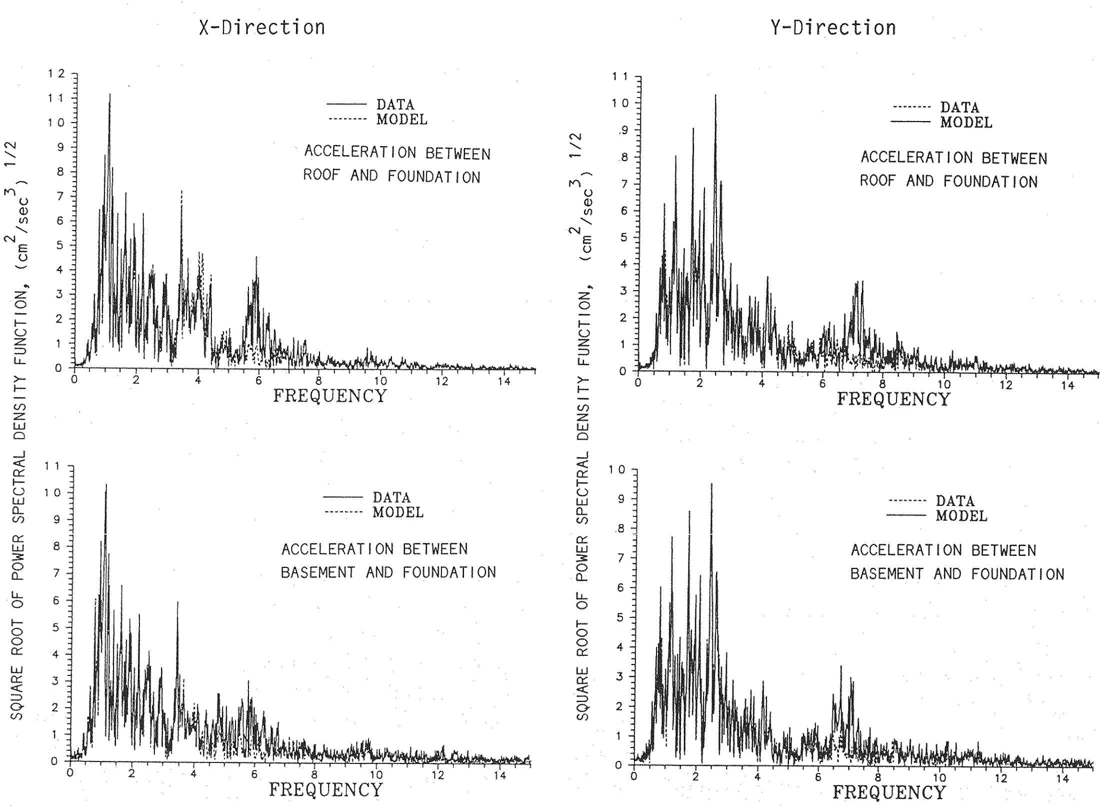


Fig.6 Comparison on the square root of power spectral density function between predicted and recorded motion of the test buildings at Tohoku University during Feb. 6, 1987 earthquake.

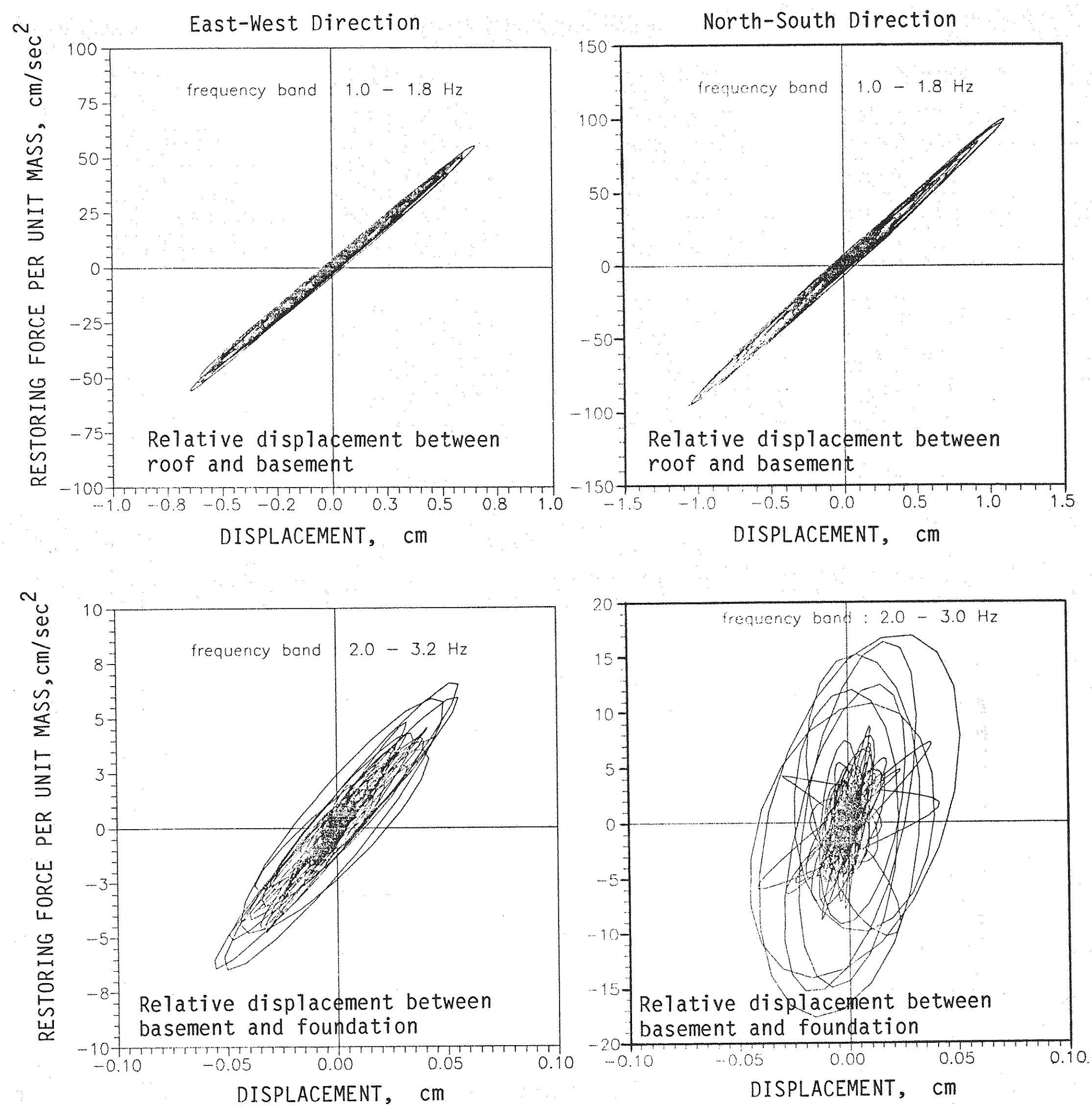


Fig.7 Plot of restoring force diagram for Feb. 28, 1990 Upland earthquake at Law and Justice Center of San Bernardina County.

excitation energy dissipation through the isolator is developed not only by viscous damping but also by hysteretic damping of material. To represent the damping characteristics, the nonlinear hysteretic model, as shown in Eq.(2), was adopted. The extended Kalman filtering technique was used to identify the modal parameters of isolation system. **Table 1** also shows the identified results of this nonlinear model. The viscous damping ratio in both x- and y-directions were reduced to 18.7 % and 14.6 % respectively. Part of the energy were dissipated through the hysteresis behavior of the isolators. **Fig.5** shows the comparison between the predicted and recorded time history in y-direction. **Fig.6** shows the comparison in square root of power spectral density of recorded and calculated motion. The root-mean-square error of the velocity and displacement between actual response and the prediction is also shown in **Table 1**. The results of forced vibration test for this building is also shown in **Table 1**. It has to point out that the estimated natural frequency of the isolator is smaller for equivalent linear model (about 0.8 Hz) and greater for nonlinear model (about 1.00 Hz). As expected the estimated equivalent linear stiffness will also have a smaller value for linear model than for nonlinear model because the identified f_b from linear model represents the overall stiffness instead

Table 2 Identified modal parameters of Law and Justice Center for Feb. 28, 1990 Upland earthquake.

Test Building of Law and Justice Center		Superstructure			Isolation System							
		f_1 (Hz)	ξ_1	a	f_b (Hz)	ξ_b	$d\mu$	A	β	γ	α	Error
Linear Model	NS-direction	1.56	0.035	1.26	2.31	0.246	0.589	—	—	—	—	6.06 %
	EW-direction	1.52	0.040	1.42	2.48	0.127	0.573	—	—	—	—	9.63 %
Nonlinear Model	NS-direction	1.56	0.035	1.26	2.49	0.231	0.642	0.6968	0.1195	0.0413	0.6875	6.24 %
	EW-direction	1.52	0.040	1.42	2.88	0.098	0.560	0.6384	0.7270	0.6352	0.3811	9.51 %

Test Building of Law & Justice Center		Superstructure			Isolation System	
		f1(Hz)	ξ_1	a	fb(Hz)	ξ_b
* Linear Model	NS-direction	1.96	0.044	1.417	3.70	0.240
	EW-direction	1.96	0.061	1.672	3.70	0.157

" * " : Results from reference 12 .

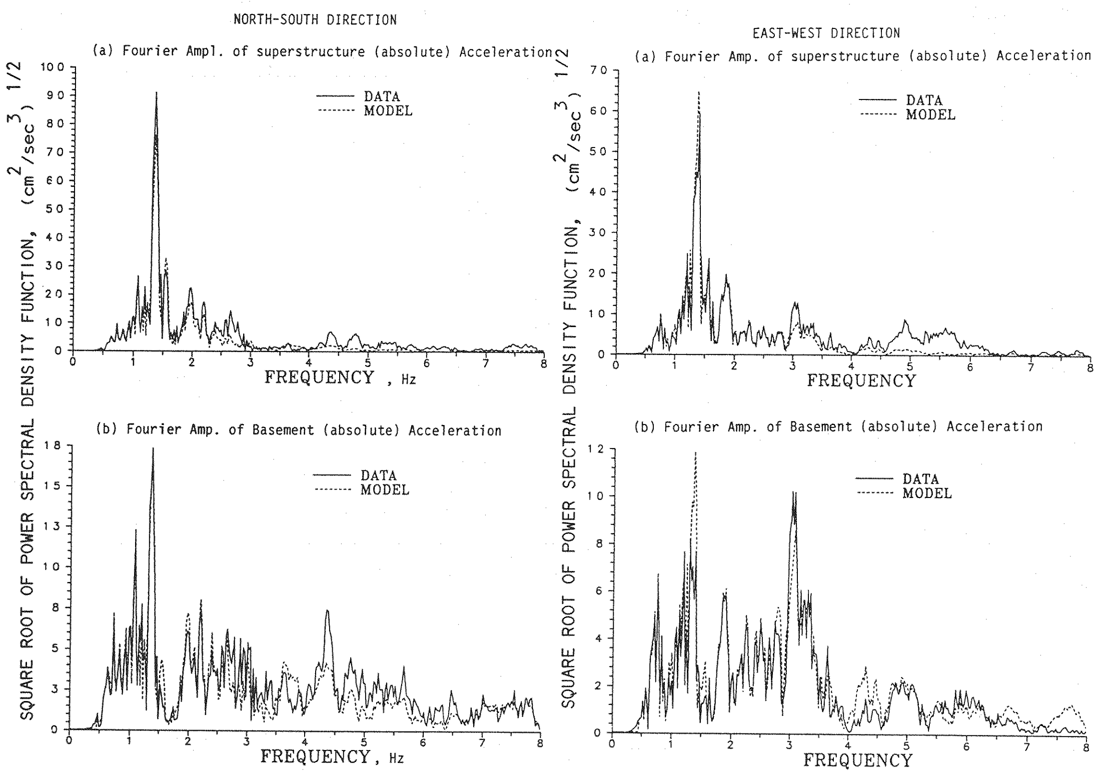


Fig.8 Comparison in Fourier amplitude spectrum of recorded and predicted basement motion and roof motion (Law & Justice center of San Bernardino County).

of the initial stiffness which was identified from nonlinear model.

Identification on the Law and Justice Center of San Bernardino County : The restoring force diagram of the building for the Feb. 28, 1990 Upland earthquake were plotted, as shown in **Fig.7**. It was found that the response between roof and basement is much greater than the response between basement and foundation. The vibration properties of the building for each of the two orthogonal directions (transverse and longitudinal) were first estimated by fitting the linear time-invariant models shown in Eq.(1). By applying the modal minimization method to identify the system, the modal parameters of Eqs.(1a) and (1b) are identified. **Table 2** shows the results of identified

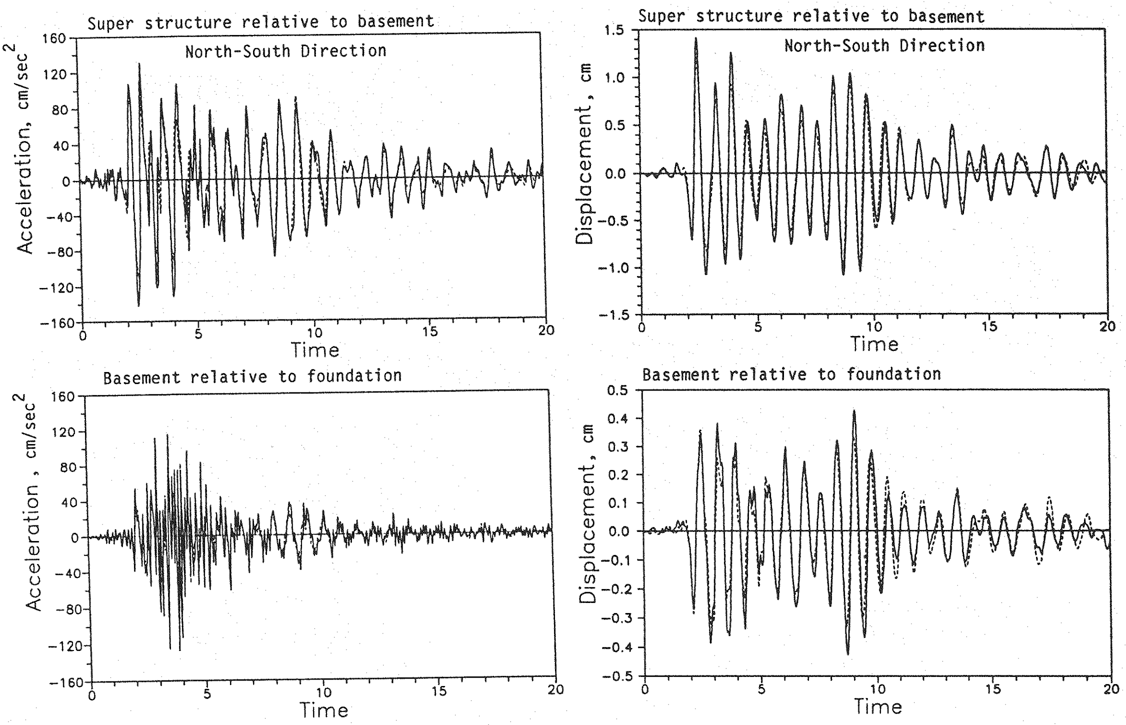


Fig.9 Comparison on time history between calculated and predicted responses (North-South direction of Law & Justice Center of San Bernardino County).

parameters. **Figs.8a** and **8b** show the comparison in square root of power spectral density of recorded and predicted basement motion and roof motion respectively. The identified equivalent modal damping ratio of isolator for North-South direction is 24.6 % and for East-West direction is 12.7 %. The comparison between predicted and recorded time history is shown in **Fig.9**. It is pointed out that the identified viscous damping ratio of the isolation system from both linear and nonlinear model is almost the same which means that the assumption of the equivalent linear model of isolation system for this building is quite correct. It has to point out that the relative motion between super-structure and the basement is much larger than the relative motion between basement and foundation at this building for this particular earthquake. This response characteristic is different from the test building of Tohoku University.

5. DISCUSSION ON THE RESULTS OF ANALYSIS

From the results of analytical study and system identification of these two isolated buildings, the following two effects are discussed.

(1) Effects of Higher Mode in Modelling the Isolator

In the analysis of Tohoku University test building, **Fig.6** shows the comparison between the recorded and predicted square root of power spectral density function of relative motion. It is observed that at frequency near 6.0 Hz in x-direction or at frequency near 7.0 Hz in y-direction the predicted model can not match the recorded data very well. Because of the symmetry of the building structure and the location of isolator and oil dampers, the mode at this frequency can not be the effect of rocking motion or the torsional motion. The peak at 6.0 Hz (x-direction) or 7.0 Hz (y-direction) in the spectrum can be explained as the effect of higher mode (possible second mode) in the isolation system. To compensate this phenomenon, the linear stiffness K_b and viscous damping C_b of the isolator are modified as frequency dependent, as shown in the following from :

$$\left.\begin{aligned} K(\omega)&=K_b[1+a_1(\omega/\omega_b)^2 \\ &\quad -a_2(\omega/\omega_b)^3+a_3(\omega/\omega_b)^4] \\ C(\omega)&=C_b[1-b_1(\omega/\omega_b)^2] \end{aligned}\right\}\cdots\cdots(9)$$

where K_b and C_b are linear stiffness and viscous damping of the isolation system, and the parameters in higher order frequency terms are obtained through identification analysis in which $a_1=0.2$, $a_2=0.1883$, $a_3=0.039$ and $b_1=0.1545$ in the present study. **Fig.10** shows the comparison in

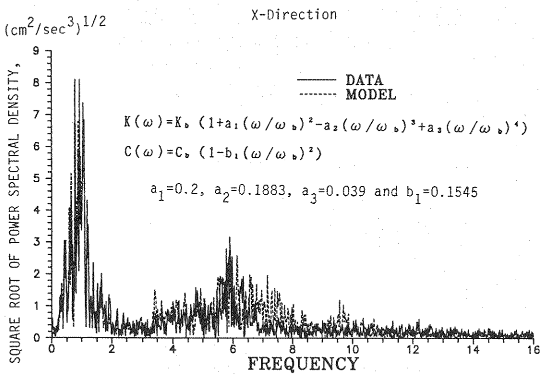


Fig.10 Comparison in square root of power spectral density function between recorded and estimated (consider frequency dependent stiffness and damping of isolator) basement acceleration —Test building at Tohoku University,

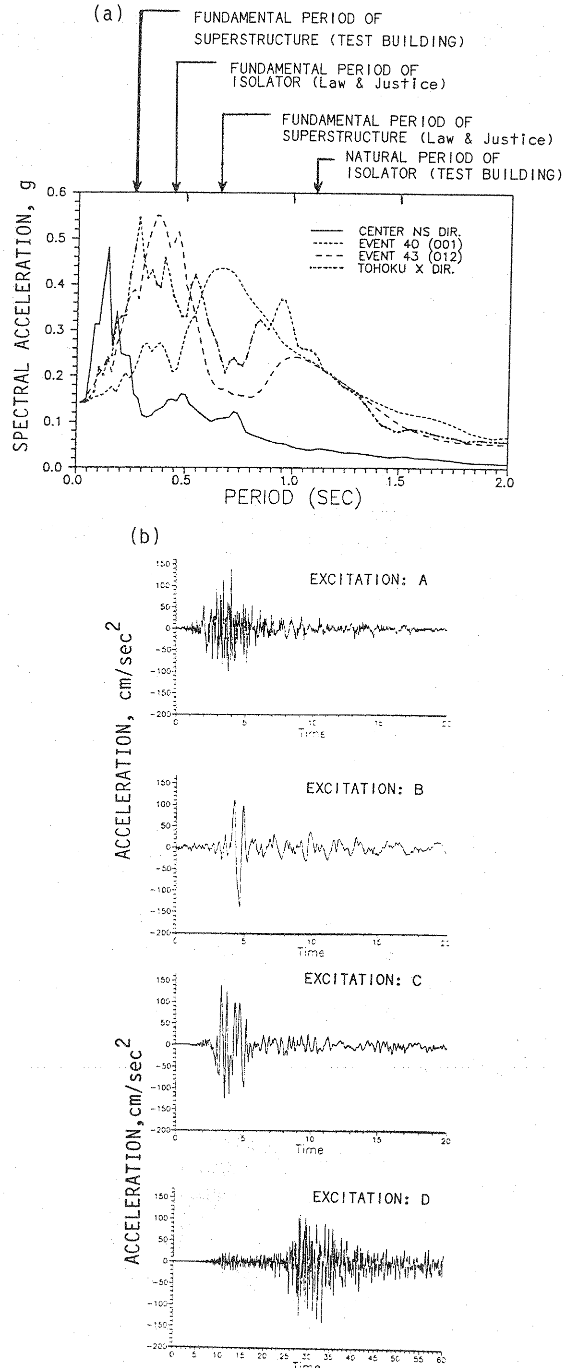
square root of power spectral density function with or without considering the frequency dependent terms. It is clear that the effect of higher mode can be considered by introducing the frequency dependent stiffness and damping of the isolation system.

(2) Effects of Long Period Waves on Isolation Structure

To study the effects of long period waves on the isolated structure, another two seismic excitations from other events with different dominant frequencies were selected to examine the dynamic response of these two buildings. The comparison on spectral accelerations of these earthquake ground excitations is shown in **Fig.11**. Longer period wave was observed in the data of Excitation B as compare to other excitations. **Fig.12** shows the acceleration response at basement and super-structure of Law and Justice Center for these four types of excitations. Since the fundamental natural frequency of the super-structure and the isolator are quite close, it is clear that only for excitation (excitation A) with dominant frequency away from these frequency range the effect of isolation can be observed. Same analysis was done on the test building of Tohoku University. Because the fundamental frequency of the isolator of this building is designed with longer period (1.1 sec). The ability of eneregy absorbtion in the isolator is much better.

6. CONCLUSION

The use of system identification techniques to study the earthquake response of two isolated buildings provide valuable informations on the dynamic characteristics of base isolation system. For the Law and Justice Center Building, the



EXCITATION A: Foundation motion of Law & Justice Center of Feb. 28, 1990 earthquake (NS Direction)
EXCITATION B: SMART-1 Station 001 ground motion of May 20, 1986 earthquake (Epicenter Dir.)
EXCITATION C: SMART-1 Station 012 ground motion of July 30, 1986 earthquake (Epicenter Dir.)
EXCITATION D: Foundation motion of the Test Building at Tohoku University for Feb. 6, 1987 earthquake.

Fig.11 (a) Spectral accleration of four ground accelerations ; (b) the time histories of these four ground acceleration.

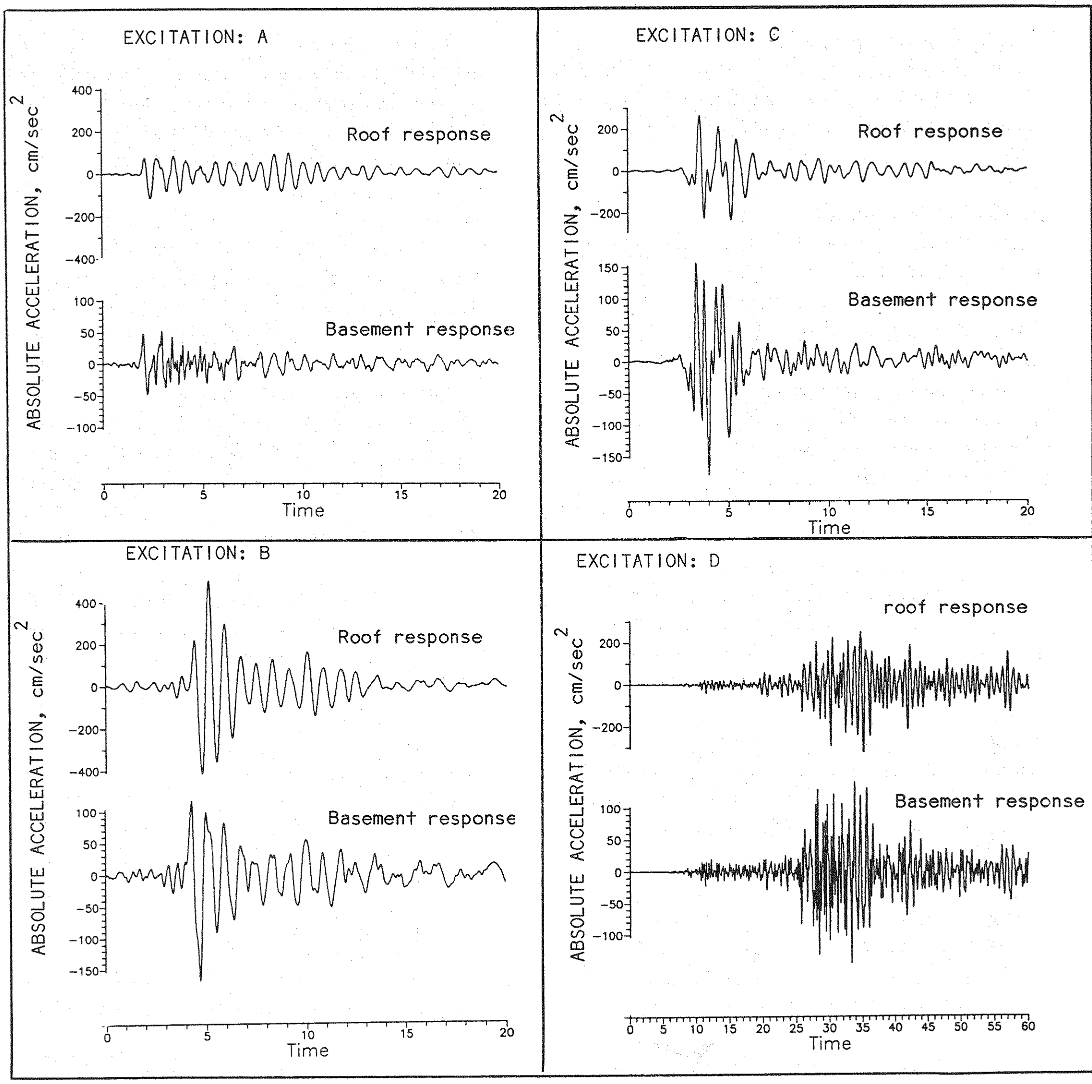


Fig.12 Seismic response analysis of the Law & Justice Center building subjected to four types of ground motion.

natural frequency of the isolators are designed with frequency greater than the natural frequency of the building. But for the test building at Tohoku University, the natural frequency of the isolation system is smaller than the super-structure itself. This design philosophy is related to the local seismic characteristics and the utilization purpose of the building. In this study, both linear and nonlinear model of the isolation system were assumed. The response of super-structure of isolated building generally behave as linear response. The dynamic characteristics of isolation system can be represented either as linear or nonlinear model that depends on the amplitude of excitation as well as the different isolation system. To examine the nonlinear behavior of isolator, time domain system identification (Extend Kalman Filtering technique) was adopted to identify the hystersis damping of the isolator.

ACKNOWLEDGEMENT

The study was supported by a grant from the National Science Council of ROC (Grant No. NSC-80-0414-P002-16B). This support is gratefully acknowledged. The authors wish to express their thanks to Shimizu Corp. and Ohsaki Research Institute for providing earthquake data of the test building of Tohoku University through Dr. Mita.

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(Received September 30. 1991)