Experimental Study on the Dynamic Characteristics of Isolated Structures

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Abstract

This paper deals with an experimental investigation on the dynamic behavior of single-story and single-bay steel frame structures with or without sliding system at the base by using an electro-magnetic type shaking table. The model structures are composed of four columns which are rigidly connected to the roof and base plates and the sliding mechanism. From the results of the preliminary frictional tests of steel plates as well as the results of the dynamic main tests of isolated structures, it is concluded that the aseismic safety of the upper main structure considerably increases by introducing a sliding mechanism at the base. The response analysis of a system with two degrees of freedom, in which the rigid-plastic hysteresis and the negative damping in the restoring force characteristics of the frictional force are incorporated, satisfactorily duplicates the dynamic behavior of isolated structures.

1. Introduction

Investigations on the prediction of future earthquakes have been considerably developed during this decade and it seems now to be able to roughly predict where, when and how a severe earthquake will happen. However, it may be imposible to decrease seismic energy itself, so reasonable design of building structures is needed to prevent the catastrophic damage of main members of structures during severe earthquakes. From this point of view, two ideas have been proposed in order to dissipate or to decrease the transmitted energy into main structures by ground motions: One approach is the method of increasing the deformation capacity of the structures, that is to say, increasing the elasto-plastic potential energy stored before catastrophic failure of the whole structure[1]. The other approach is the method of decreasing the transmitted energy to the upper main structure, namely, designing a kind of isolated structure.

In this paper, an experimental study is presented relating to the latter appraoch. There are many investigations on such isolated structures in seismic countries, especially in New Zealand and in Japan[2,3], though experimental reports of such isolated structures are very few[4,5]. An actual structure of a large coke oven was recently tested by the staff of Nippon Kokan K.K and Ohbayashi-gumi LTD in Japan[6], where the effectiveness of a vibration isolated system was discussed.

In order to obtain the dynamic properties of the frictional force, preliminary tests were scheduled. Static and dynamic frictional coefficients between two pieces of steel plates subjected to velocity controlled excitation were obtained. In the next step, dynamic tests of isolated structures were carried out by using the shaking table belonging to the Disaster Prevention Research Institute of Kyoto University. Three types of experimental models are prepared here, for comparison of the test results of isolated structures with the results of ordinary fixed structures: single-story, single-bay steel frame structure with fixed base, the same structure with sliding mechanism and the rigid body with sliding mechanism which makes clear the fundamental characteristics of the isolated system. From the experimental results of such structures subjected to a sinusoidal pulse or El Centro 1940 NS excitation ,interesting remarks are obtained on the effectiveness of isolated systems for the aseismic safety of upper structure. Systems with two degrees of freedom were analyzed to compare with the experimental results and to generalize the frictional characteristics of the isolated structure, where rigid-plastic hysteresis and negative damping are introduced in the dynamic characteristics of the friction of steel plates.

2. Preliminary Tests of the Frictional Coefficient of Steel to Steel Plate

In order to make clear the effect of the sliding velocity on the frictional coefficient of steel to steel plate, preliminary frictional tests were scheduled under the similar conditions of sliding surface to the main tests. As shown in **Fig. 1**, frictional surfaces between test specimen A and B, are horizontally compressed by the steel spring C and the specimen A is vertically enforced by the hydraulic actuator D. Spring E is designed so as to transfer the vertical (axial) force without bending. **Photo. 1** shows the view of the preliminary frictional test.

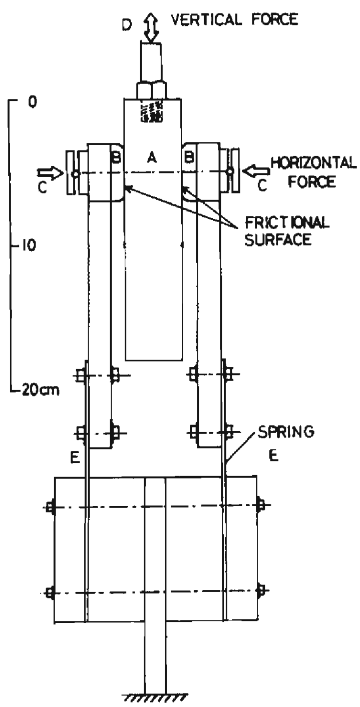


Fig. 1 View of preliminary test.

Fig. 2 shows time histories of relative displacements and vertical forces under constant horizontal force subjected to two types of external forces which are the triangular wave form with constant velocities, 0.1, 1.0, 10.0, 41.7 mm/sec. and the continuous sinusoidal wave form with the frequency 1 Hz. The relative displacement between two plates A and B was measured by a linear differential transformer and the frictional force was measured by the load cell. Horizontal force acting perpendicularly on the frictional surface by the steel spring C, which corresponds to

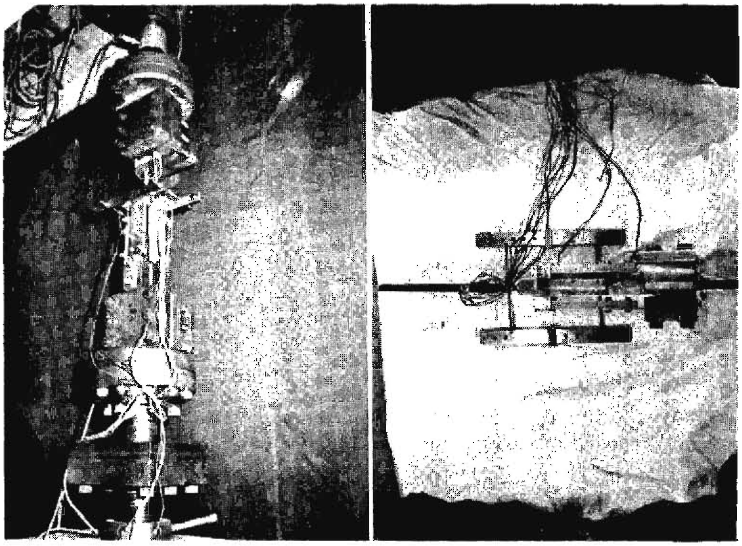


Photo. 1 View of preliminary frictional test.

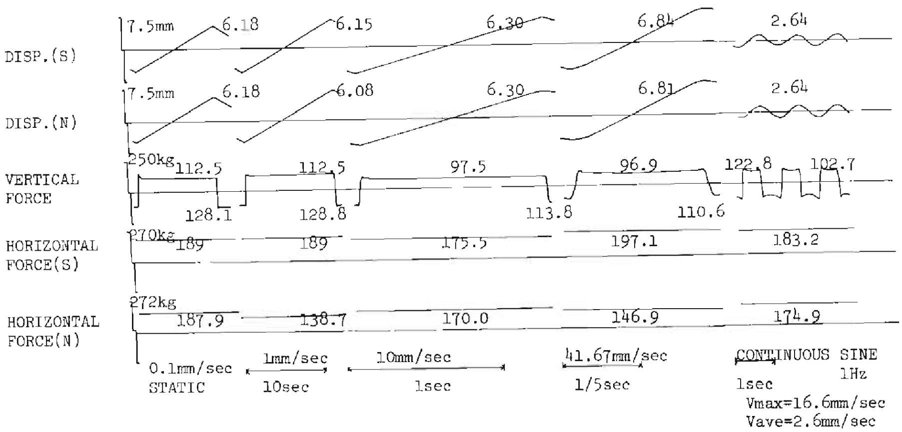


Fig. 2 Results of frictional test.

the gravity force, was measured by the strain gage. Static and dynamic frictional force obtained from the results of the peak value and smooth portion of the frictional force responses of **Fig. 2** are shown in **Table 1**, including the corresponding frictional coefficients. The last row of this table shows the result obtained from the shaking table test of the rigid body will be mentioned in the following chapter.

From this test, the following remarks are obtained:

(1) The ratio of the dynamic frictional coefficient to the static value is about 0.87.

(2) Dynamic frictional coefficient tends to decrease slightly when the sliding velocity increases except for the case (b) of **Table 1**.

Table 1 Frictional coefficient of steel plate.

Case	Velocity	Axial Force (Horizontal)	Frictional Force (Vertical)		Frictional Coef.		Ratio of Dynamic to Static Coef.
			Static	Dynamic	Static	Dynamic	
a	0.1 mm/sec	376.9kg	64.1kg	56.2kg	0.170	0.149	0.876
b	1.0	327.7	64.4	56.2	0.196	0.172	0.878
c	10.0	345.5	56.9	48.7	0.164	0.141	0.860
d	41.7	344.0	55.3	48.4	0.160	0.140	0.875
e*1	16.6max	358.1	61.4	51.3	0.172	0.143	0.831
f*2	—	475.0	83.9	65.4	0.176	0.138	0.866
AVE.					0.172	0.149	0.866

*1 The result obtained from the test due to sinusoidal excitation with 1 Hz frequency.
*2 The result obtained from the rigid body test due to sinusoidal excitation with 8 Hz frequency.

(3) Static frictional coefficient of steel to steel plate is about 0.17.

3. Shaking Table Tests of Isolated Structures

3.1 Model Structures

Three types of model structures are examined here, in order to clarify the difference of transmitted energy among the models: the rigid body with sliding base

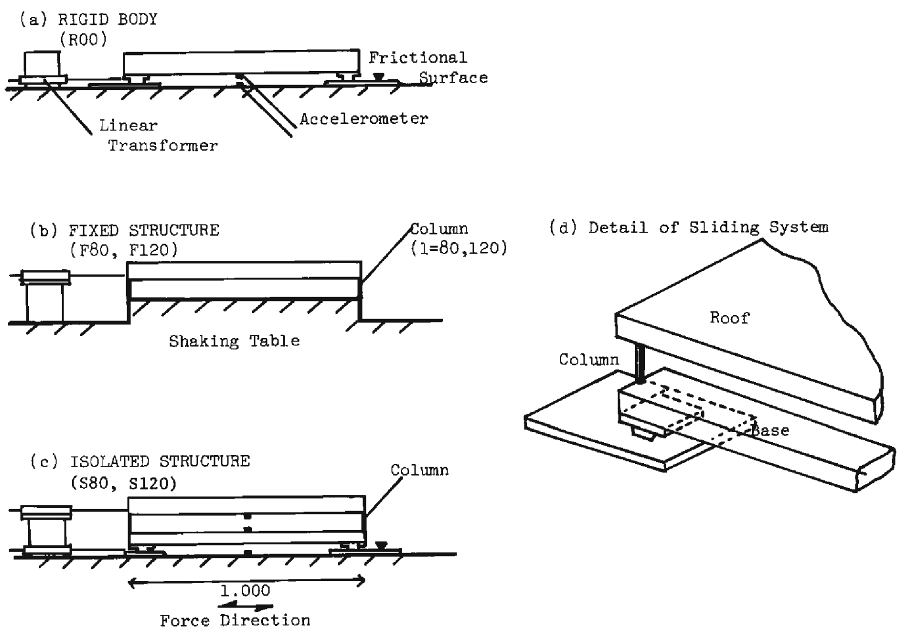
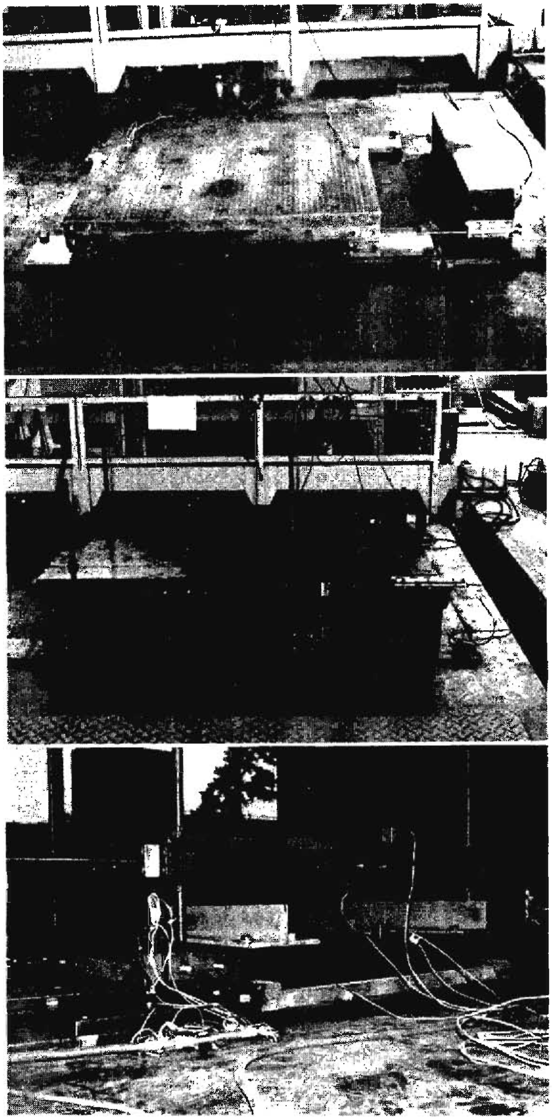


Fig. 3 Model structures of shaking table test.



(a) rigid body

(b) fixed structure

(c) isolated structure

Photo. 2 View of shaking table test.

named R00, single-storied steel frame structures with fixed base, F80 and F120, and the same structures with sliding base, S80 and S120 as shown in **Fig. 3** and **Photo. 2**. **Fig. 3**(d) shows a detail of the isolated system, where four pieces of the sliding plate with 5cm length and 10cm width are set on the other steel plates after dusting off the oil spocks. Both ends of columns of the structure are rigidly connected to the floor plate and roof plate, the length of which is adopted to be 8 cm or 12 cm, considering the effect of the fundamental frequency on the dynamic responses of the model structures. This structural model is similar to the model in the previous

Table 2 Measured Dimensions of Columns

Structure	Name of Model	Weight (ton) Roof	Base	Column Dimension (mm) Depth	Width	Height
Rigid Body	R00	0.475	—	—	—	—
Fixed Structure	F80E*	0.548	—	6.03	10.02	80.00
	F80S	0.548	—	6.03	10.04	80.00
	F120E	0.548	—	7.27	10.01	120.00
	F120S	0.548	—	7.31	10.02	120.00
Isolated Structure	S80	0.548	0.116	6.05	10.03	80.00
	S120	0.548	0.116	7.25	10.08	120.00

* E (S) means the model subjected to El Centro wave form (sinusoidal wave form)

Table 3 Mechanical Properties of Materials

Specimen		Area(cm^2)	T_y(ton)	T_u(ton)	σ_y (ton/cm^2)	σ_u (ton/cm^2)	ε_{st}	ε_u
Standard	No. A	3.60	9.37	14,75	2.60	4.10	—	0.305
	B	3.58	9.31	14.75	2.60	4.12	0.018	0.297
	C	3.59	9.38	14.82	2.61	4.13	0.018	0.314
Average					2.60	4.12	0.018	0.305
Used Column	No. A	0.72	1.95	3.00	2.70	4.16	0.017	0.220
	B	0.72	1.98	3.03	2.73	4.19	—	0.278
	C	0.73	2.02	3.05	2.77	4.18	—	0.226
Average					2.73	4.18	0.017	0.241

paper[7] except for the isolated mechanism. **Table 2** shows the weights of roof (base) and measured dimensions of the columns which are made of the identical plate of SS41 grade steel with 9 mm thickness by machine cutting and finishing. Mechanical properties obtained from the tension tests of the standard specimen and the same specimen as the column used here, are listed in **Table 3**.

3. 2 Test Procedure

A model structure was set on the electro-magnetic type shaking table belonging to the Disaster Prevention Research Institute of Kyoto University, the basic characteristics of which are listed in **Table 4**. Horizontal accelerations of shaking table and base and roof of the model structure were measured by strain gage type accelerometers and horizontal relative displacements of base and roof of the model to the shaking table were measured by linear differential transformers. Horizontal shear force was calculated from the elastic strains at the middle portions of columns where perfectly elastic response would be expected.

Three types of external wave forms are used as the input ground motion: NS

Table 4 Basic Characteristics of Shaking Table

Shaker	Electro-Magnetic Type
Table Size	$2.5 \times 2.5\ m^2$
Allowable Load	5 ton (+Table weight)
Frequency Range	0.2–200 Hz
Exciting Force	4 ton (Sinusoidal, random)
Allowable Stroke Length	150 mm

component of the 1940 El Centro Earthquake, which is compressed by the time factor 2.0, sinusoidal pulse and continuous sine wave. The frequencies of the excitations are selected by considering the fundamental frequency of the model structure.

3. 3 Behavior of Rigid Body

The rigid body is one of the simplest models to test in order to clarify the relation between frictional force and displacement or velocity. **Figs. 4** through **6** show

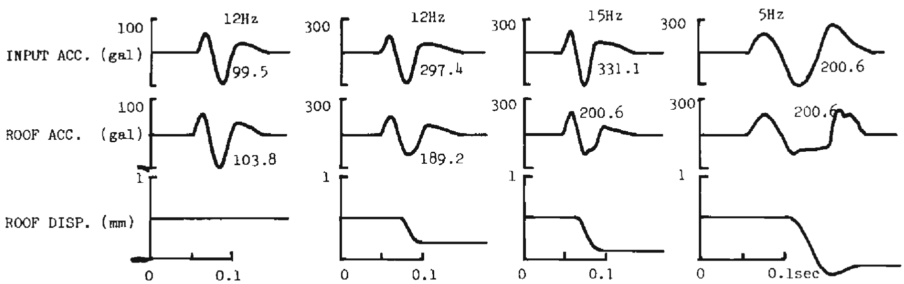


Fig. 4 Time history of rigid body due to sine pulse.

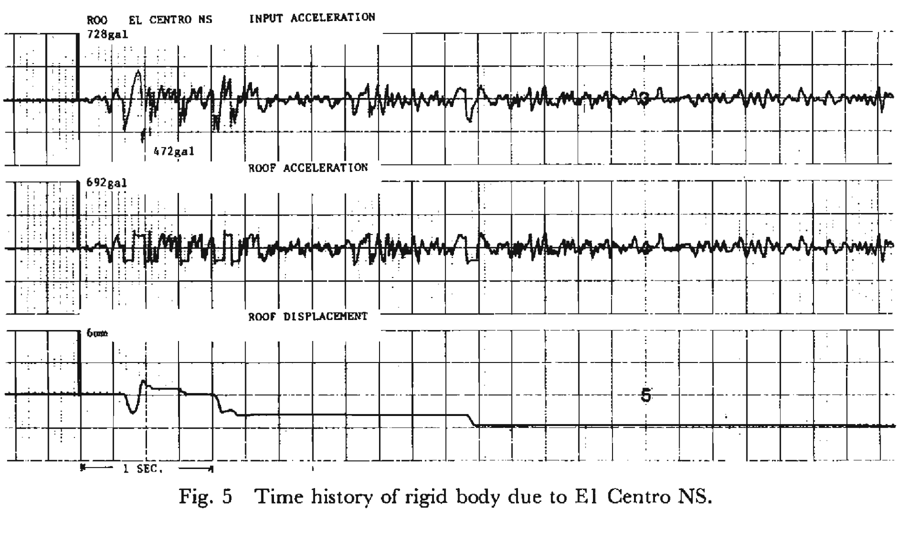


Fig. 5 Time history of rigid body due to El Centro NS.

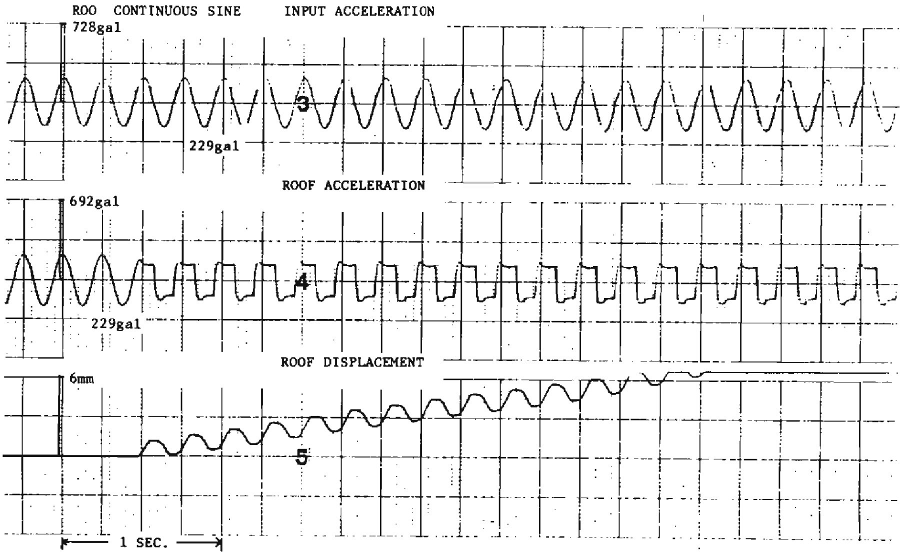


Fig. 6 Time history of rigid body due to continuous sine.

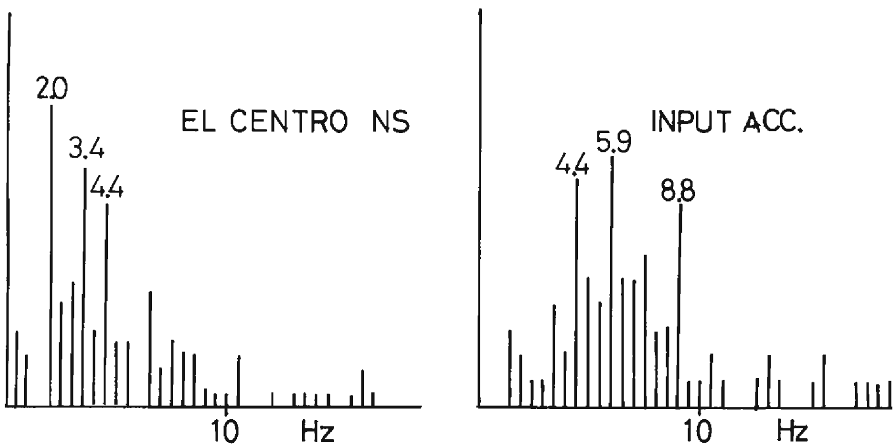


Fig. 7 Power spectrum of input acceleration

time histories of the rigid body subjected to three types of input accelerations. **Fig. 7** shows two power spectra derived from El Centro NS acceleration. The left spectrum is from the original record, while the right from the input wave-form used in the experiment. Restoring force hysteresis of the absolute acceleration of rigid body to the relative displacement, namely, sliding displacement is shown in **Fig. 8**, corresponding to three types of input waveforms.

From the comparison of input and response accelerations, it is clear that the acceleration responses are considerably restricted for the sake of the sliding mechanism. Neglecting the effect of the damping force ,the frictional force is approximately obtained from the absolute roof acceleration multiplied by the mass of the body. The average value of the static frictional coefficient is about 0.17 and the dynamic frictional coefficient decreases to about 3/4 of the static value. In **Fig. 9**, the relationship, between input and response accelerations is shown for all cases of rigid body tests. The solid line represents a non-sliding state.

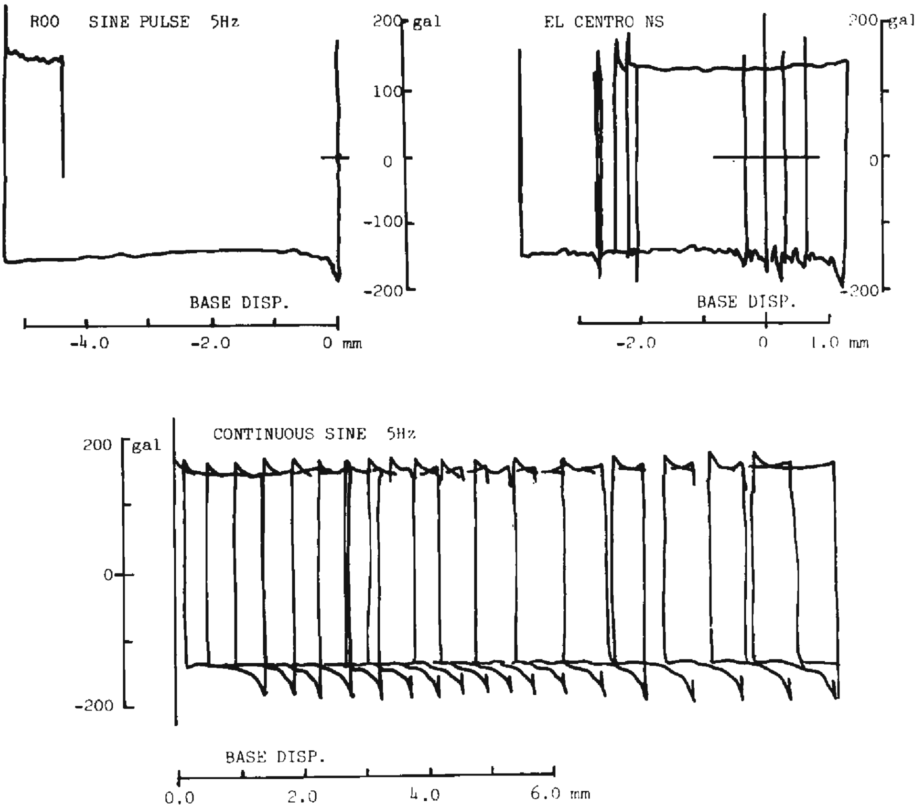


Fig. 8 Frictional hysteresis of rigid body.

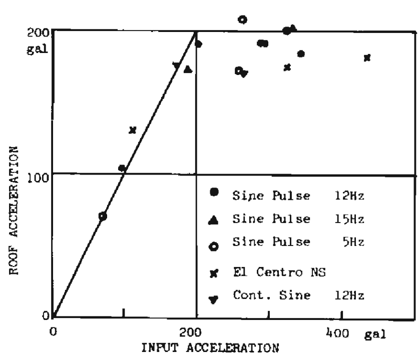


Fig. 9 Relation between input and output accelerations

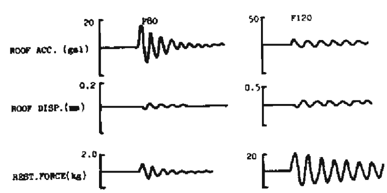


Fig. 10 Results of free vibration test due to small shock.

3. 4 Dynamic Characteristics of Fixed Structures

In order to obtain the fundamental frequency and the critical damping ratio, both the free vibration test after small shock and forced vibration test under steady state sinusoidal excitation with small amplitude are carried out. **Fig. 10** shows time histories of roof acceleration, roof displacement and restoring force characteristics due to small shock and **Fig. 11** shows the magnification factor of roof acceleration due to forced vibration. Fundamental frequencies and critical damping ratios of fixed structures obtained from these tests are listed in **Table 5**: Q_y and Δ_y denote the ultimate shear strength and corresponding relative displacement; $s=Q_y/W$ and $n=N/N_y$ mean the base shear coefficient and the ratio of the axial force due to gravity force to allowable axial force; and f_0 represents the frequency of the structure calculated from the mechanical properties of material. Above-mentioned dynamic characteristics are used in the following dynamic analysis.

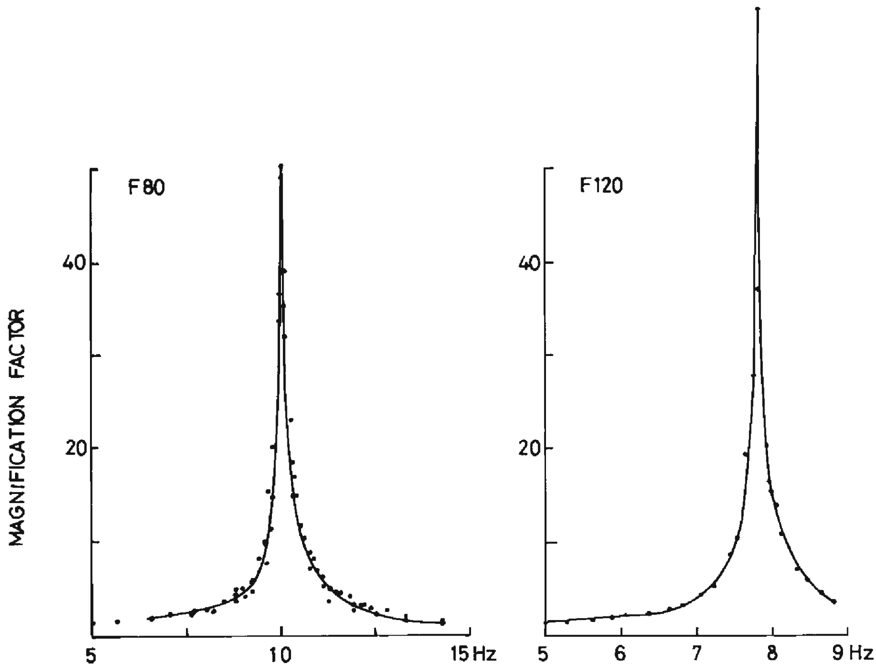


Fig. 11 Resonance curve of fixed structure.

Table 5 Fundamental Properties of Model Structure

Model Name	Δ_y(mm)	Q_y(ton)	s	n	f_0	f_1(Hz)	h_1(%)*	f_2(Hz)	h_2(%)**
F80	0.727	0.172	0.470	0.080	12.670	11.6	2.0	10.00	0.5
F120	1.345	0.254	0.464	0.066	9.255	7.9	0.4	7.82	0.3

* f_1, h_1 : due to free vibration test
** f_2, h_2 : due to forced vibration test

3. 5 Dynamic Behavior of Single-Story Model Structure

Experimental results with isolated structures are compared with the results

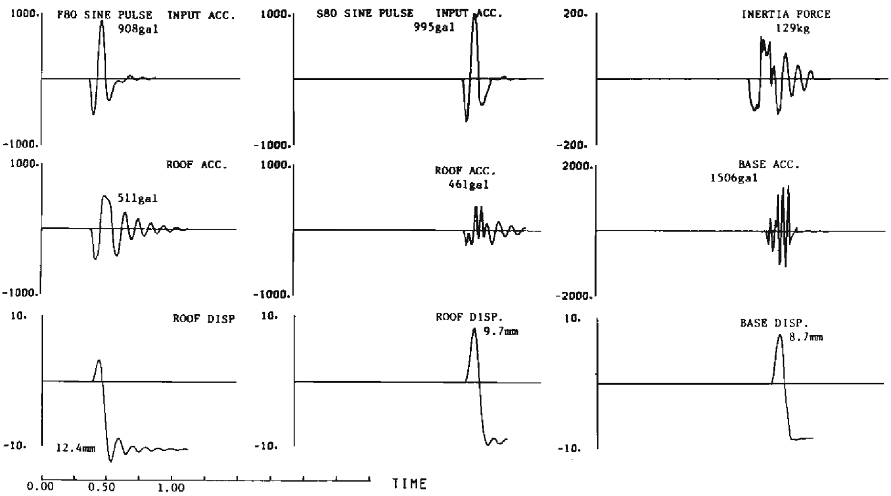


Fig. 12 Experimental time history due to sine pulse.

from fixed structures in this section to clarify the effect of frictional damping on the dynamic behavior of the upper structure. **Fig. 12** shows time history responses of fixed and isolated structures with 8 cm column heights. These were subjected to a sinusoidal pulse, which looks like differnt input acceleration, because of the effect of the frequency characteristics of the shaking table. Restoring force characteristics of the upper structure and the relation between frictional force and base displacement of the isolated structure computed from the summation of the base and the roof accelerations multiplied by corresponding masses are shown in **Fig. 13**.

As shown in these figures, the upper structure behaves in elastic-plastic range in the case of fixed model, while the isolated structure behaves elastically in spite of increase of the input acceleration amplitude. Almost all of the transmitted energy is dissipated as the frictional energy and the roof

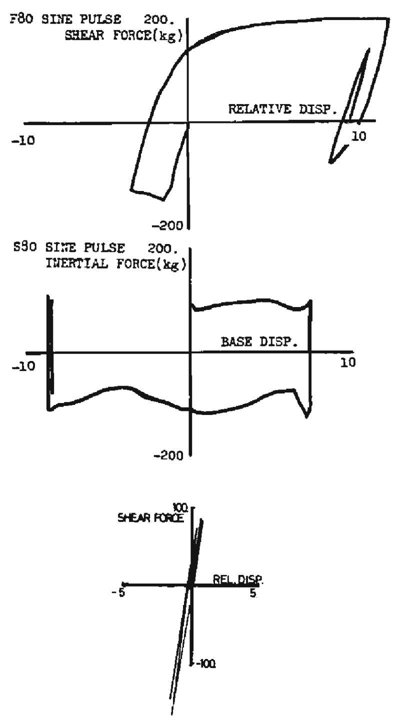


Fig. 13 Experimental hysteresis due to sine pulse.

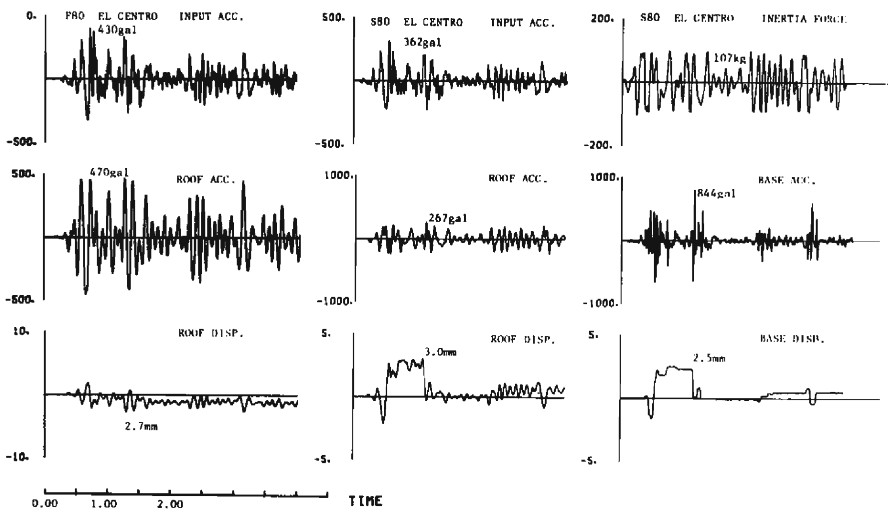


Fig. 14 Experimental time history due to El Centro NS.

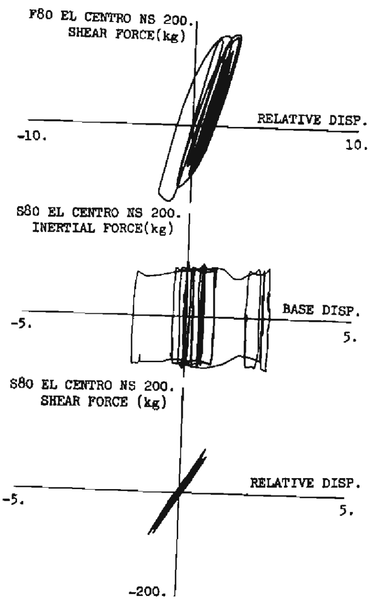


Fig. 15 Experimental hysteresis due to El Centro NS.

displacement fluctuates on the base displacement in the case of the isolated structure. Though the base acceleration of the isolated system is greater than that of the rigid body, frictional force becomes nearly the same order as the rigid body. The reason is considered to be the interaction effect of the behavior of the upper structure. Typical responses due to NS component of El Centro Earthquake are shown in **Figs. 14** and **15**, The time scale of the excitation is selected as a half of original record, considering the fundamental frequency of the real structure. The roof acceleration response of the isolated structure considerably decreases due to frictional damping. From these experimental results, the following tendencies can be pointed out:

(1) The relation between the frictional force and the base displacement is represented as the restoring force characteristics of perfectly rigid-plastic model, whose maximum frictional force is the same as results of the preliminary test and rigid body test.

(2) In the case of the isolated structure almost all of the trasnmitted energy due to external force is dissipated as frictional energy and the upper structure behaves elastically while in the case of the fixed model, the upper structure should have sufficient ductility for consuming the transmitted energy.

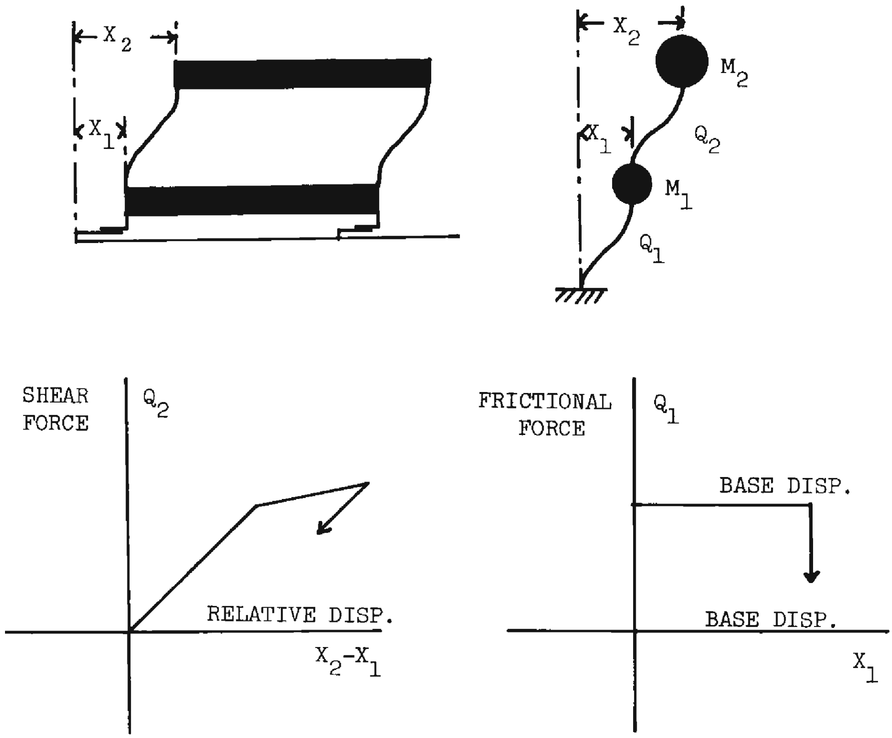


Fig. 16 Analytical model of isolated structure.

4. Dynamic Analysis of Isolated Structures

Two degrees of freedom system were adopted in order to compare the results of the dynamic response analysis to the results obtained from the shaking table tests. Equations of motion of the analytical model are

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} c_1+c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} q_1(x_1) \\ q_2(x_2-x_1) \end{Bmatrix} = -\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \ddot{y}, \tag{1}$$

where x_1, x_2 and y represent the base and the roof displacements of the structure and ground displacement, m_1 and m_2 are corresponding masses, c_1 and c_2 are damping coefficients and q_1 and q_2 represent restoring forces as shown in **Fig. 16.** Equations of energy balance are obtained by integrating the equations of motion multiplied by the absolute velocity.

$$E_k+E_d+E_p=E_t \tag{2}$$

where,

$$E_k=\int_0^t \{\dot{x}_1+\dot{y},\ \dot{x}_2+\dot{y}\}^T\begin{bmatrix} m_1 & \\ & m_2\end{bmatrix}\begin{Bmatrix}\ddot{x}_1+\ddot{y}_1\\ \ddot{x}_2+\ddot{y}_2\end{Bmatrix}dt=\frac{1}{2}\Sigma m_j(\dot{x}_j+\dot{y})^2$$

$$E_d=\int_0^t \{\dot{x}_1,\ \dot{x}_2\}^T\begin{bmatrix} c_1+c_2, & -c_2\\ -c_2, & c_2\end{bmatrix}\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\end{Bmatrix}dt=\int_0^t \{\dot{x}_1{}^2c_1+c_2(\dot{x}_2-\dot{x}_1)^2\}\,dt$$

$$E_p=\int_0^t \{\dot{x}_1,\ \dot{x}_2\}^T\begin{bmatrix} 1, & -1\\ 0, & 1\end{bmatrix}\begin{Bmatrix}q_1\\ q_2\end{Bmatrix}dt=\int_0^t \{\dot{x}_1q_1+(\dot{x}_2-\dot{x}_1)q_2\}\,dt$$

$$E_t=-\int_0^t \dot{y}c_1\,\dot{x}_1\cdot dt-\int_0^t \dot{y}q_1\,dt$$

Dynamic properties of the model structure are calculated from the material properties as shown in **Table 5**. In the following analysis, the stiffness and critical damping ratio of the upper structure are determined so as to coincide with the experimental frequency and damping ratio.

The restoring force characteristics of the main structure are supposed to be bi-linear hysteretic type, where the stiffness ratio of 2nd branch to initial stiffness is 0.05. The restoring force characteristics of the first floor, which means the relation between the frictional force and the sliding displacement of the base is

Table 6 Dynamic properties of analytical model

	Mass kg·sec²/cm	Initial Stiffness ton/cm	2nd Stiffness	Strength ton	Damping Ratio %
Base	0. 118	22075. 0	0	0. 1141	0. 03
Roof	0. 559	2207. 5	0. 05	0. 1638	0. 005

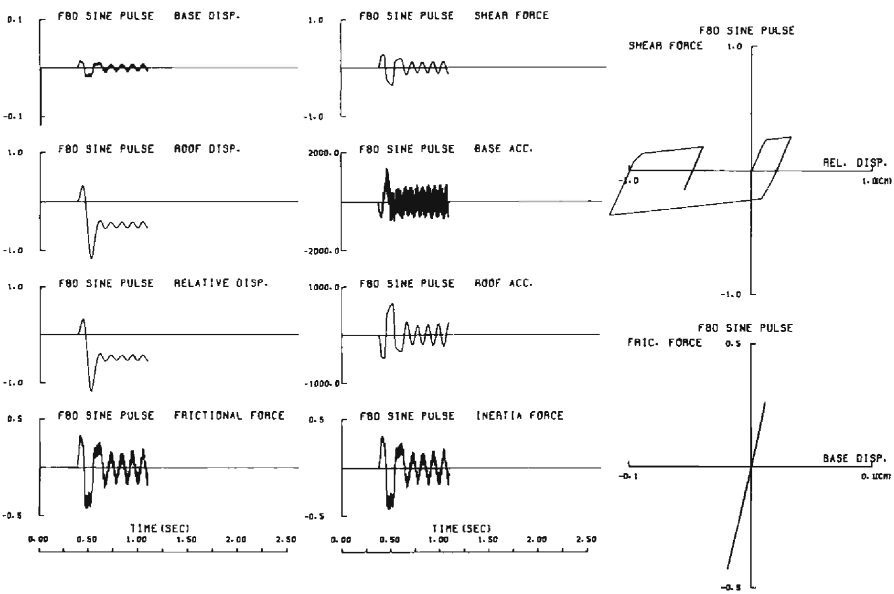


Fig. 17 Analytical response of fixed model due to sine pulse.

supposed to be rigidly plastic, the strength of which is determined from the static frictional force obtained from preliminary tests and rigid body tests. Some results of the dynamic analysis of such a structure subjected to the same excitation as the acceleration records of shaking table tests are shown in the following figures. **Fig. 17** shows time histories of displacements, accelerations and shear force of fixed structure due to sinusoidal pulse, the wave form of which is converted from analog to digital record obtained from the test acceleration. **Fig. 18** shows the similar responses of the isolated structure. Wave forms of these analytical responses look like the experimental results shown in **Fig. 12**. However, as shown in **Fig. 18**, restoring force characteristics of the base of the isolated structure are a little different from the test results in the state of non-zero velocity. In the next step, negative damping is introduced in the restoring force characteristics of the sliding mechanism in order to estimate that the dynamic frictional coefficient decreases about 20% from the static value. Supposing the maximum value of the velocity response of the sliding base, critical damping ratio is calculated from the following equation:

$$h = \frac{c}{2\omega_0 m} = \frac{(\mu_s - \mu_d)mg}{2\omega_0 mv} = 0.02 \qquad (3)$$

where $\mu_s = 0.176$, $\mu_d = 0.138$ are static and dynamic frictional coefficients; $v = 15$ kine is supposing maximum velocity; $\omega_0 = 2\pi \times 10$ is the fundamental circular frequency and g is the acceleration of gravity. **Fig. 19** shows the computed responses of the structure subjected to the sinusoidal pulse and **Figs. 20** and **21** represent the responses due to El Centro Earthquake, considering negative damping. Time

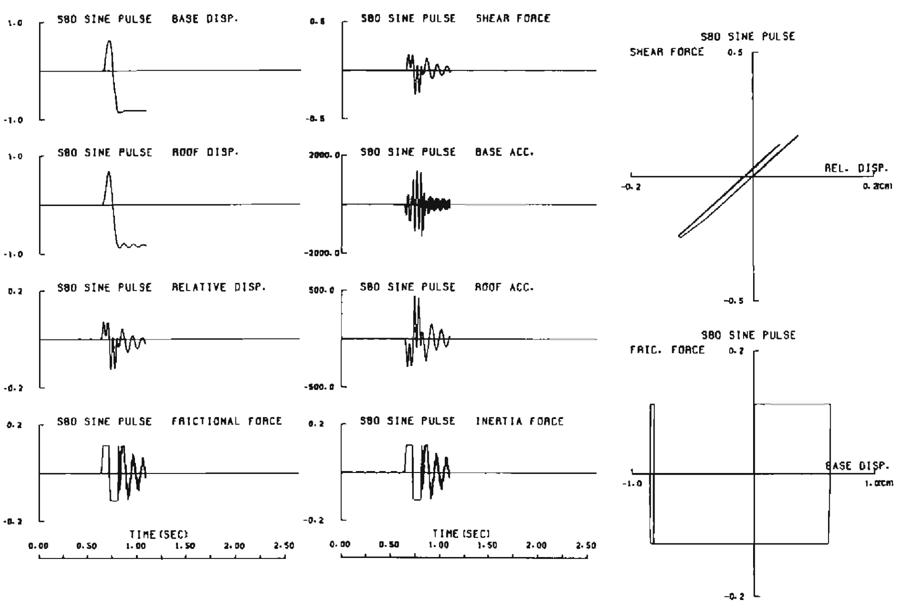


Fig. 18 Analytical response of isolated model due to sine pulse.

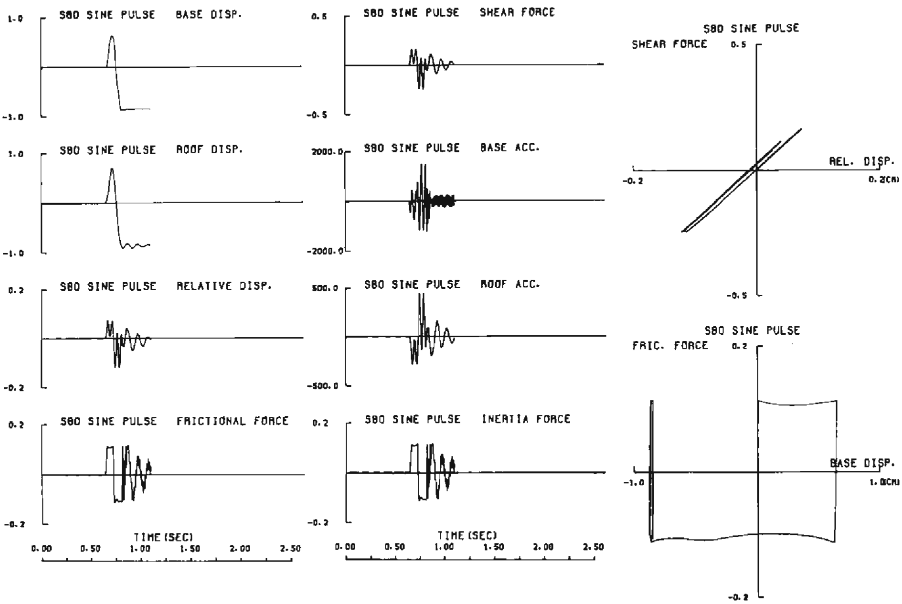


Fig. 19 Analytical response of isolated model with negative damping due to sine pulse.

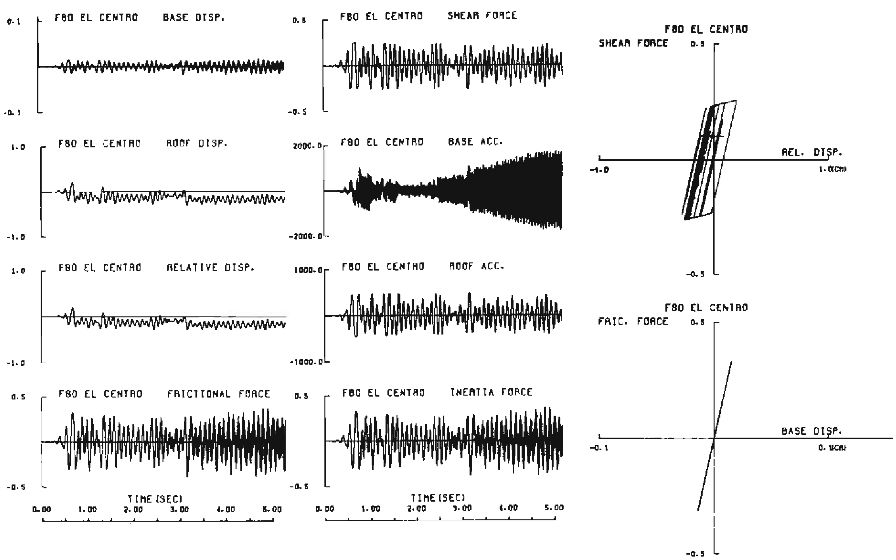


Fig. 20 Analytical response of fixed model due to El Centro NS.

history responses of the structure with or without negative damping seem to be almost similar, while the restoring force characteristics of the sliding base with negative damping are different from the responses without damping and are very similar to the experimental results. **Fig. 22** shows the effects of the frictional

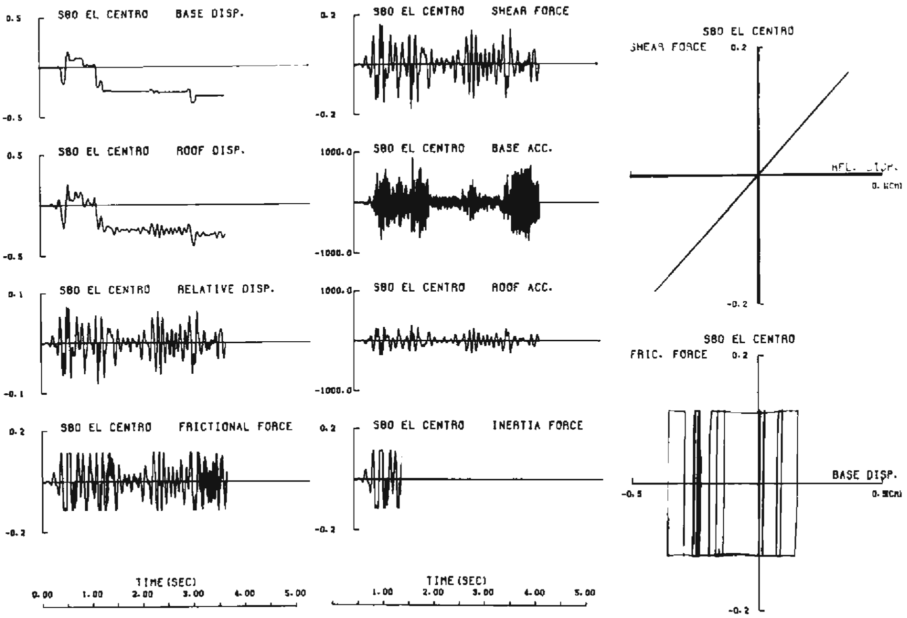


Fig. 21 Analytical response of isolated model with negative damping due to El Centro NS.

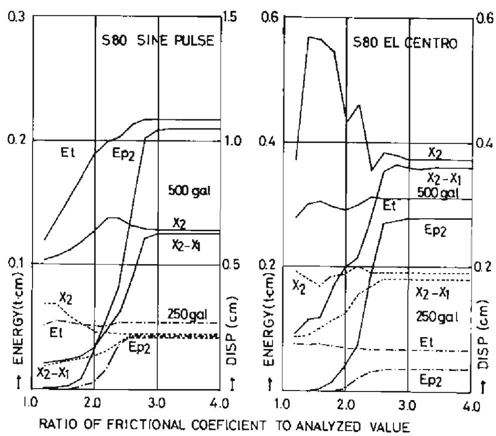


Fig. 22 Transmitted energy and displacement versus frictional coefficient ratio.

coefficient on the dynamic behavior of the same structure as above-mentioned model except for the frictional coefficient, where the abscissa of this figure is the ratio of the static frictional coefficient to the value used in the above analysis. Almost all of the transmitted energy, E_t, is consumed as the hysteretic energy of the upper structure and the sliding mechanism. Energy dissipation of the upper structure, Ep_2, has a tendency to increase, while the total displacement, X_2, does not always increase corresponding to increase of the frictional force. However, it must be noted that the sliding displacement becomes rather larger in the case of large amplitude of input acceleration. The following remarks are obtained from the afore-mentioned dynamic analyses:

(1) Dynamic response of an isolated structure can be computed by adding another spring-mass system between the base of the upper structure and foundation, to the upper structural model.

(2) Dynamic frictional force is represented by the model of static frictional force by introducing the negative damping characteristics computed from the difference of static and dynamic frictional coefficient.

(3) Isolated structures can keep the response of the upper main structure in almost elastic range and most parts of transmitted energy is dissipated in the hysteresis of frictional force. However the effectiveness of isolated mechanism depends on the relation between frictional force and elastic limit shear force of the upper structure.

5. Conclusions

In order to make clear the effects of the isolated system on the aseismic safety of upper structures, preliminary frictional tests between steel plates and dynamic tests of single-story steel structures with or without sliding mechanism at the base by using the electro-magnetic shaker were performed. Two degrees of freedom system subjected to the same input motion as the shaking table tests were analysed by considering the negative damping as the additive dynamic frictional force, for the purpose of comparing the experimental results and making clear the general tendency of an isolated system.

The following conclusions were obtained from the restricted experiments and response analysis of such a steel frame structure.

(1) Aseismic safety of the main structure considerably increases by introducing the isolated mechanism at the base, because most parts of the transmitted energy are dissipated in the frictional hysteresis. In spite of the above results, the relative displacement of the isolated system against the ground motion does not always increase in comparison with the response of the fixed structure.

(2) Dynamic frictional force has a tendency to decrease from the static value. Therefore, the restoring force characteristics of the frictional force can be represented as the conbined relation of the rigid plastic hysteresis, whose yield strength is determined from the static frictional coefficient, and the negative damping proportional to the velocity response, corresponding to the difference of the static and dynamic frictional coefficients.

Recently, recommendations for the design of isolated structures have been presented in New Zealand[8], where it has been pointed out that the frequency characteristics of the excitation affect on the effectiveness of the isolated systems, that is to say, the responses do not always decrease when the predominant frequency of the motion is smaller than the fundamental frequency of the main structure. Furthermore the isolated system is not effective to reduce the overturning moment of high rise buildings or the vertical excitation.

On the real structure, some more problems to be solved concerning the large amount of the base displacement will be left, for instance, the connection of the water supplements or gas lines buried under the ground. However, there are several isolated buildings under construction in New Zealand and in Yugoslavia, and the improvement for the method of construction of isolated structures may be expected in near future.

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