FLUID VISCOUS DAMPERS IN APPLICATIONS OF SEISMIC ENERGY DISSIPATION AND SEISMIC ISOLATION

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Abstract

Fluid dampers which operate on the principle of fluid flow through orifices have found numerous applications in the shock and vibration isolation of military and aerospace hardware and in wind vibration suppression of missile launching platforms. Characteristics of these devices which are of interest in applications of seismic energy dissipation are linear viscous behavior, insensitivity to temperature changes, very small size in comparison to stroke and output force, reliability and longevity.

The application of these devices as part of seismic energy dissipating systems for buildings and bridges has been experimentally and analytically studied. This paper presents a summary of these studies.

Introduction

Various energy dissipating devices have been proposed as add-on devices to buildings for improving seismic resistance. Most notable of these devices are mild steel dampers, frictional dampers and constrained-layer viscoelastic shear dampers (Whittaker 1989, Aiken 1990, Chang 1991). Experimental studies demonstrated that these dampers are effective in reducing drifts while maintaining shear forces at the same level or, under certain conditions, less than those of structures without dampers. However, due to their hysteretic or strong viscoelastic behavior, these devices introduce a substantial axial force component which is in phase with the maximum bending moment in columns.

Fluid viscous dampers may be designed to behave as linear viscous devices and, thus, they introduce damping forces which are out-of-phase with drifts and column bending moments. Accordingly, they can be very effective in reducing both drifts and shear forces without introducing axial column forces which are in-phase with column bending moments. These significant properties of fluid viscous dampers have been confirmed in shake table testing of a series of 1-story and 3-story model structures (Constantinou 1992a). The experimental results demonstrated reductions of drifts and shear forces of the order of 2 to 3 in comparison to the response of the models without dampers for a wide range of earthquake input motions.

Furthermore, fluid dampers may be used as elements of seismic isolation systems for enhancing their energy dissipation capability. Tests have been conducted on a seismic isolated bridge model with and without fluid viscous dampers (Constantinou 1992b). The experimental results demonstrated a simultaneous reduction of isolation bearing displacement and force transmitted to the bridge superstructure. Moreover, the experiments showed that the isolated bridge with fluid dampers had a marked insensitivity to the frequency content of input motions.

This paper presents a description of these experimental studies, sample experimental results and comparisons of experimental and analytical results.

Construction and Properties of Fluid Dampers

The construction of a fluid damper is shown in Figure 1. It consists of a stainless steel piston with bronze orifice head and an accumulator. It is filled with silicon oil. The piston head utilizes specially shaped passages which alter the flow characteristics with fluid speed so that the force output is proportional to $|\dot{u}|^{\alpha}$, where $\dot{u}$ = piston rod velocity and α = predetermined coefficient in the range of 0.5 to 2. A design with $\alpha = 1$ results in a linear viscous damper.

This behavior dominates for frequencies of motion below a predetermined cutoff frequency (related to the characteristics of the accumulator valves). Beyond this frequency, the fluid dampers exhibit strong stiffness in addition to substantial ability to dissipate energy. The existence of the cutoff frequency is desirable, since the lower modes of vibration are only damped while the higher ones are both damped and stiffened so that their contribution is completely suppressed.

The orifice flow may be compensated by a passive bi-metallic thermostat which allows operation of the device over a temperature range of -40°C to 70°C. The performance characteristics of the device are considered state-of-the-art. The described device with fluidic control orifices, bi-metallic thermostat and special silicon oil originated within products used in classified applications of the U.S. Air Force. Over 13,000 of these devices are currently in service in the United States.

The tested fluid dampers had all of the aforementioned characteristics and they were designed to behave as linear viscous dampers. Each had stroke of ± 51 mm, length of 280 mm and weighed 10 N. They were used in the tested building and bridge models described in the sequel.

Figure 2 shows recorded loops of force vs displacement of one damper at temperature of 23°C. The purely viscous nature of the device is apparent. For frequencies above about 4 Hz, the dampers exhibited stiffness. Figure 3 shows recorded data on the peak output force vs peak velocity of input at temperatures of 0°, 25°, and 50°C. It may seem that the experimental results may be fitted with straight lines of slope C_o which represents the damping constant. The behavior of the device was completely unaffected by the amplitude of motion. The values of C_o in Figure 3 demonstrate the small dependency of the characteristics of the device on temperature.

Experimental Models

The experimental models included the 3-story steel structure of Figure 4 and the bridge structure of Figure 5. At quarter length scale, the models had weights of 28.5 kN (equally distributed to the three floors) and 161 kN, respectively. The 3-story model was tested without dampers and with dampers installed as braces at an angle of about 35°. Tests were conducted with four dampers installed at the first story and with six dampers installed in pairs at each story. The dynamic characteristics of the structure were determined in small vibration amplitude tests and are listed in Table 1. Evidently, the addition of fluid dampers substantially increased the damping ratio of the structure and also stiffened the higher modes (damper cutoff frequency about 4 Hz).

The bridge model had the following characteristics: period of free vibration when the deck was pinned to both piers (non-isolated) = 0.25 secs and period of free vibration of each pier in cantilever position = 0.1 secs. The isolation system consisted of four sliding (Teflon - polished stainless steel) bearings with coefficient of friction at high velocity of sliding equal to 0.14 and two rubber restoring force devices. The restoring force devices provided an isolation period of 1.4 secs in the scale of the model. Furthermore, four fluid dampers were included in the isolation system.

The design of the isolation system was based on the seismic input specified for design of bridges in Japan. Figure 6 shows Japanese Level 2 bridge design spectra for Ground Conditions 1 (stiff soil) to 3 (deep alluvium). One should note the substantial spectral acceleration values in the period range of 2 to 5 secs. Compounding to the difficulties caused by these severe motions, the isolation system design called for a limit of 0.4 W on the shear force transmitted to the substructure (W = deck weight) with isolation bearing displacement less than 50 mm (or 200 mm in prototype scale). These strict requirements could only be met with the inclusion of fluid dampers in the isolation system.

Results for Building Model

Table 2 presents a sample of recorded peak response values of the tested 3-story structure. The excitation consisted of recorded earthquakes which were time compressed by a factor of 2 and scaled in peak acceleration by the shown percentage figure. An examination of the results in Table 2 reveals that the addition of fluid dampers resulted in a two-fold to three-fold reduction of the peak response of the bare frame. Particularly interesting is the reduction in story shear forces. It should be noted that the shear forces in Table 2 include the contribution from the damper forces.

Figure 7 compares the response of the bare frame without dampers under El Centro 50% to the response of the frame with 6 dampers under El Centro 150%. Apparently, the addition of dampers increased the ability of the structure to resist this earthquake by a three-fold. Furthermore, the results of Figure 7 demonstrate that the addition of dampers had no effect on the stiffness of the structure. Rather, they only increased its energy dissipation capacity.

Figure 7 includes analytical results on the response of the damped structure. The analytical results were obtained by the use of the Maxwell model for the constitutive relation of the dampers. In this model

$$P + \lambda \dot{P} = C_o \dot{u} \tag{1}$$

where P = damper force, $\dot{u}$ = damper piston velocity, C_o = damping constant (see Fig. 3) and λ = relaxation time. The term $\lambda \dot{P}$ accounts for the stiffening effect at frequencies above the cutoff limit. In the tested dampers, λ was very small (0.006 secs) and the cutoff frequency was larger than the fundamental frequency of the model so that the term $\lambda \dot{P}$ could be neglected. This simpler viscous model produced nearly identical results to those of the Maxwell model. Both models predicted the recorded response with good accuracy as demonstrated in the comparison of responses in Figure 7. Furthermore, a simplified procedure for predicting the peak response through the use of response spectra has been developed and verified (Constantinou 1992a).

Results for Isolated Bridge Model

Testing of the bridge model was conducted with fifteen different isolation system configurations as part of the University at Buffalo - Taisei Corporation bridge isolation project (Constantinou 1992b). Of these configurations, one consisted of flat sliding bearings with coefficient of friction at high velocity equal to 0.14 and arc-shaped rubber restoring force devices. Period in the isolated mode was 1.4 secs.

The most severe excitations with which the bridge model was excited were simulated motions compatible with the Level 2 Japanese bridge design spectra (Fig. 6). None of the tested isolation system configurations could sustain these motions and simultaneously satisfy the requirements of bearing displacement being less than 50 mm and pier shear force being less than 0.4 times the pier axial load (W) under elastic conditions. For example, Figure 8a shows the recorded isolation system hysteresis loop of the system in the Ground Condition 1 (stiff soil) motion. Bearing displacement reach the limit of 50 mm with pier shear force equal to 0.5 W (see Table 3).

Subsequently, four fluid dampers identical to those used in the testing of the 3-story model structure were added to the isolation system. They provided viscous damping of the order of 50% of critical. The test results are presented in Table 3 and in Figure 8. Evidently, the use of fluid dampers caused a marked reduction of the isolation system force and pier shear force and reduced bearing displacement.

The response of the isolated bridge with fluid dampers is only marginally affected by the characteristics of the excitation. In the three types of ground conditions in Table 3, the bearing displacement varies between 37 and 40 mm, while the pier shear force varies between 0.33 and 0.36 W. It is important to note that a marked improvement in the behavior of isolation system (in terms of reduction of response and increase of insensitivity) was achieved by the inclusion in the system of fluid dampers with a total weight equal to 1/4000 of the weight of the bridge model.

Conclusions

Experimental results have been presented which demonstrate that fluid dampers are very effective in reducing the seismic response of structures to which they are attached. These dampers may be designed to exhibit essentially linear viscous behavior and insensitivity to significant temperature changes.

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Table 1. Properties of Tested Structure under Elastic Conditions

Frequency and Damping Ratio Mode 1	Without Dampers	With 4 Dampers	With 6 Dampers
	2.00 Hz, 0.018	2.11 Hz, 0.177	2.03 Hz, 0.194
Mode 2	6.60 Hz, 0.008	7.52 Hz, 0.319	7.64 Hz, 0.447
Mode 3	12.20 Hz, 0.003	12.16 Hz, 0.113	16.99 Hz, 0.380

Table 2. Peak Response of Tested Structure (Number in Parenthesis is Floor or Story at Which Peak was Recorded).

Excitation	No. Dampers	Acceleration (g)	$\frac{\text{Shear Force}}{\text{Total Weight}}$	$\frac{\text{Story Drift}}{\text{Height}}$ (%)
El Centro 33%	0	0.417 (3)	0.220 (1)	1.069 (2)
El Centro 50%	0	0.585 (3)	0.295 (1)	1.498 (2)
Taft 100%	0	0.555 (3)	0.255 (1)	1.161 (1)
El Centro 50%	4	0.282 (3)	0.159 (1)	0.660 (2)
El Centro 100%	4	0.591 (3)	0.314 (1)	1.279 (2)
Taft 100%	4	0.246 (3)	0.130 (1)	0.638 (2)
El Centro 50%	6	0.205 (3)	0.138 (1)	0.510 (2)
El Centro 100%	6	0.368 (3)	0.261 (1)	0.998 (2)
El Centro 150%	6	0.534 (3)	0.368 (1)	1.492 (2)
Taft 100%	6	0.178 (3)	0.120 (1)	0.463 (2)
Taft 200%	6	0.348 (3)	0.235 (1)	0.921 (2)
Pacoima Dam 50%	6	0.376 (3)	0.275 (1)	1.003 (1)
Hachinohe 100%	6	0.334 (3)	0.256 (1)	0.963 (2)
Miyagiken 200%	6	0.342 (3)	0.254 (1)	0.963 (2)

Table 3 Recorded Response of Isolated Bridge for Japanese Level 2 Excitation (Length Scale = 4).

System	Excitation	Peak Bearing Displ. (mm)	Base Shear/Weight	Pier Shear/Weight	Pier Displ. (mm)
Rubber Device	Japanese, Level 2 G.C. 1	49.3	0.46	0.50	7.2
Rubber Device, Fluid Damper	Japanese, Level 2 G.C. 1	40.0	0.28	0.33	5.5
Rubber Device, Fluid Damper	Japanese, Level 2 G.C 2	38.1	0.31	0.36	5.8
Rubber Device, Fluid Damper	Japanese, Level 2 G.C. 3	36.9	0.30	0.35	5.6

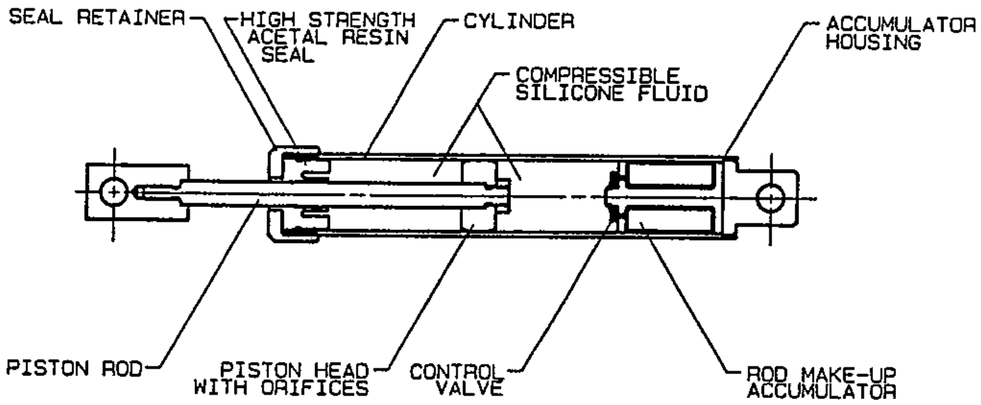

Figure 1 Construction of Fluid Damper.

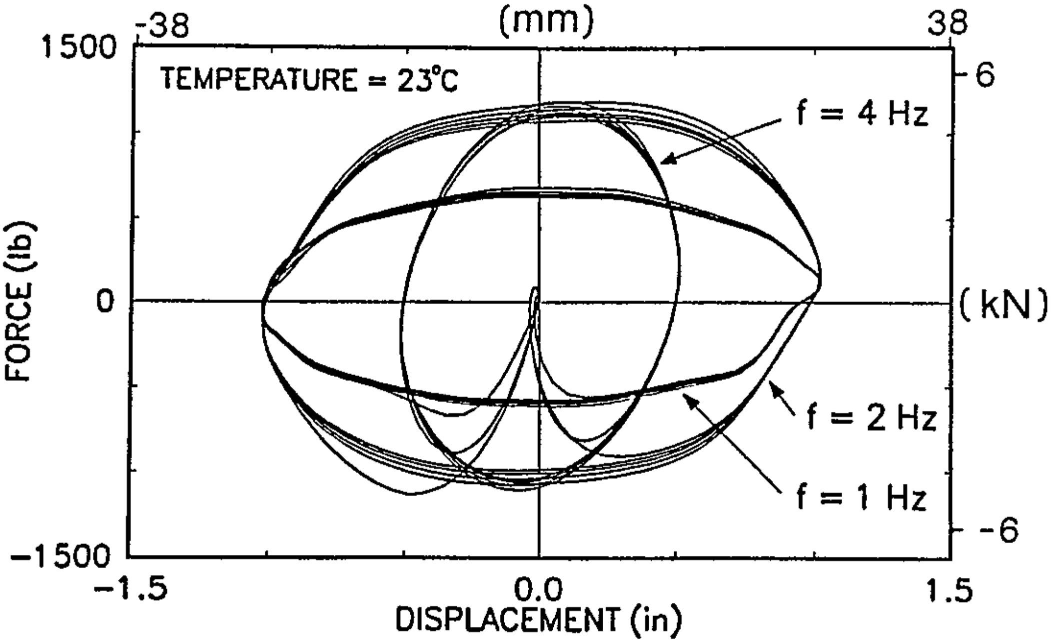

Figure 2 Loops of Force vs Displacement of Fluid Damper.

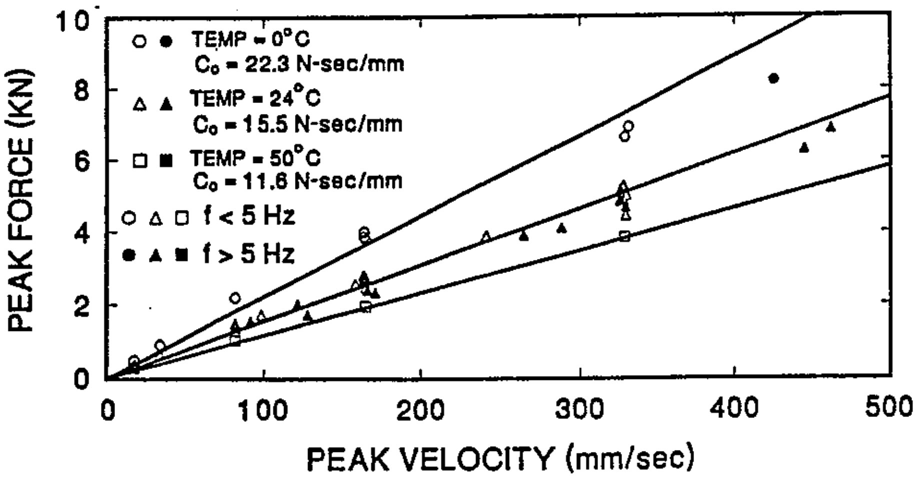

Figure 3 Mechanical Properties of Tested Fluid Dampers.

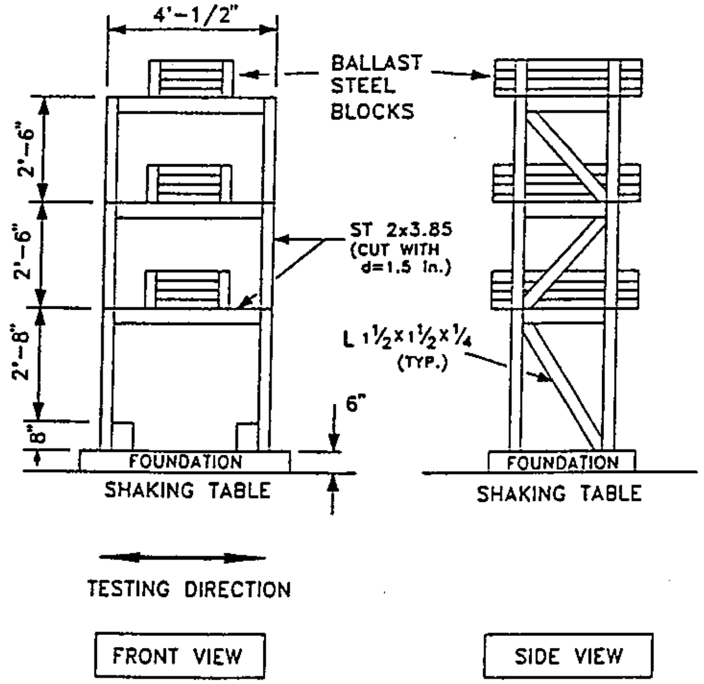

Figure 4 Tested 3-story Model Structure.

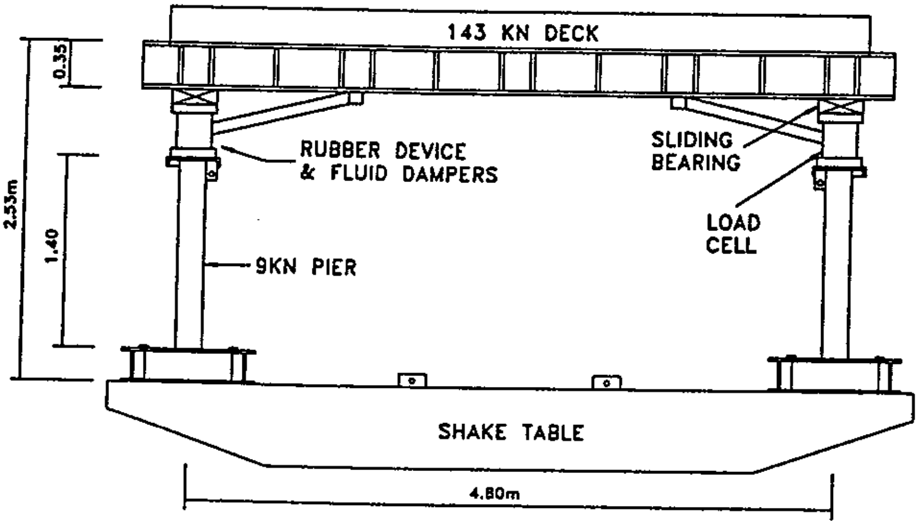

Figure 5 Tested Isolated Bridge Structure.

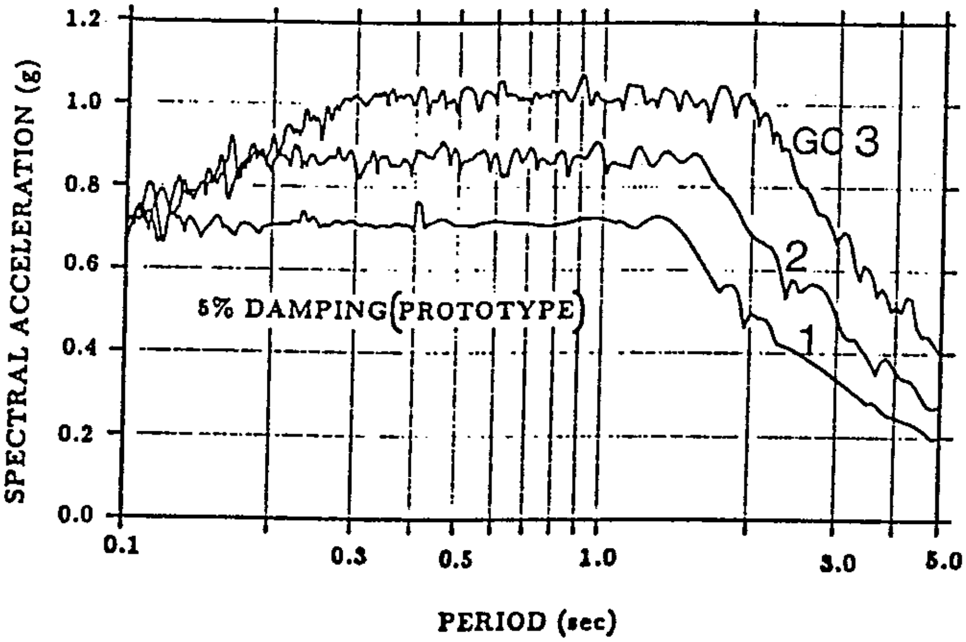

Figure 6 Japanese Level 2 Bridge Design Spectra.

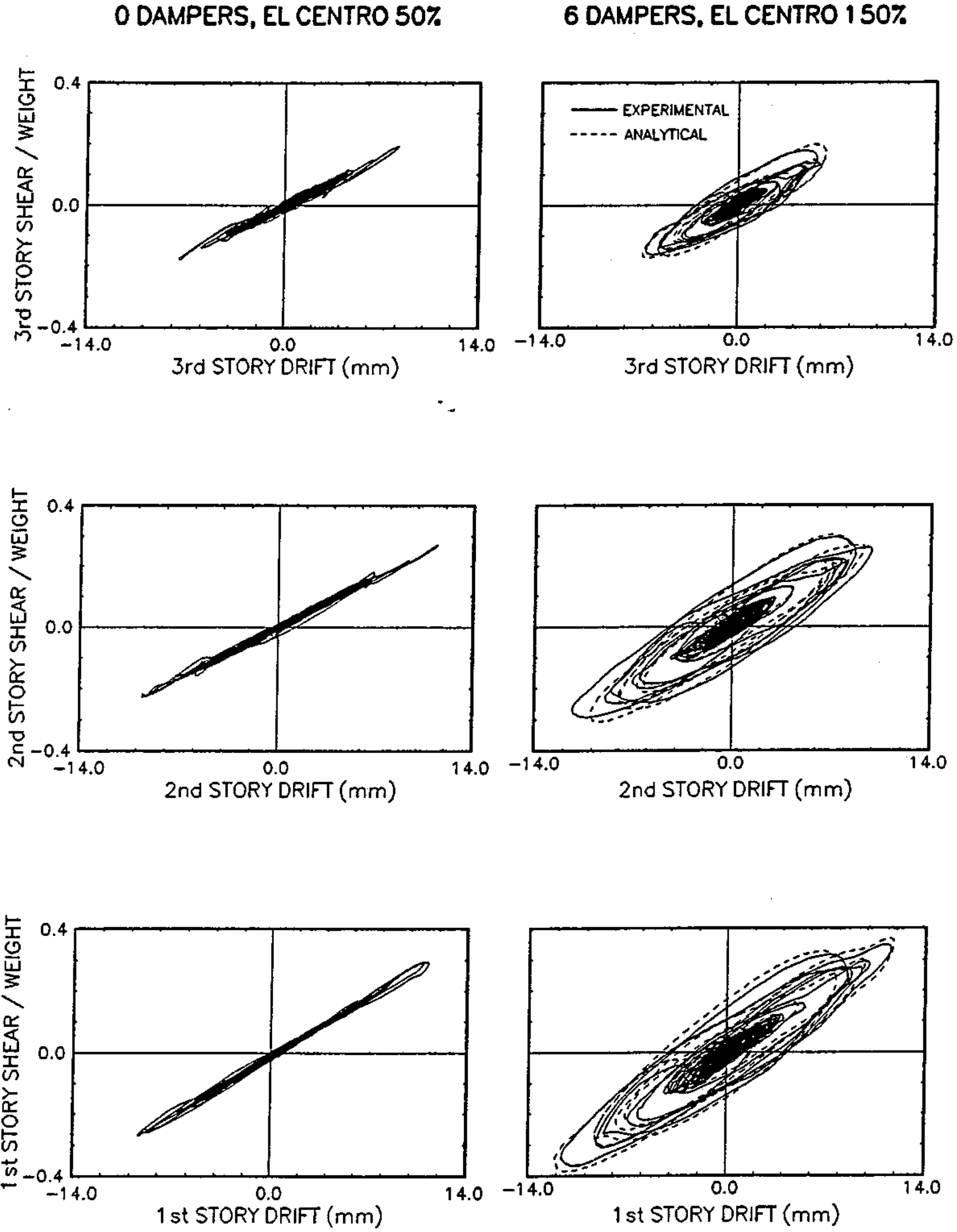

Figure 7 Response of 3-story Model With and Without Fluid Dampers.

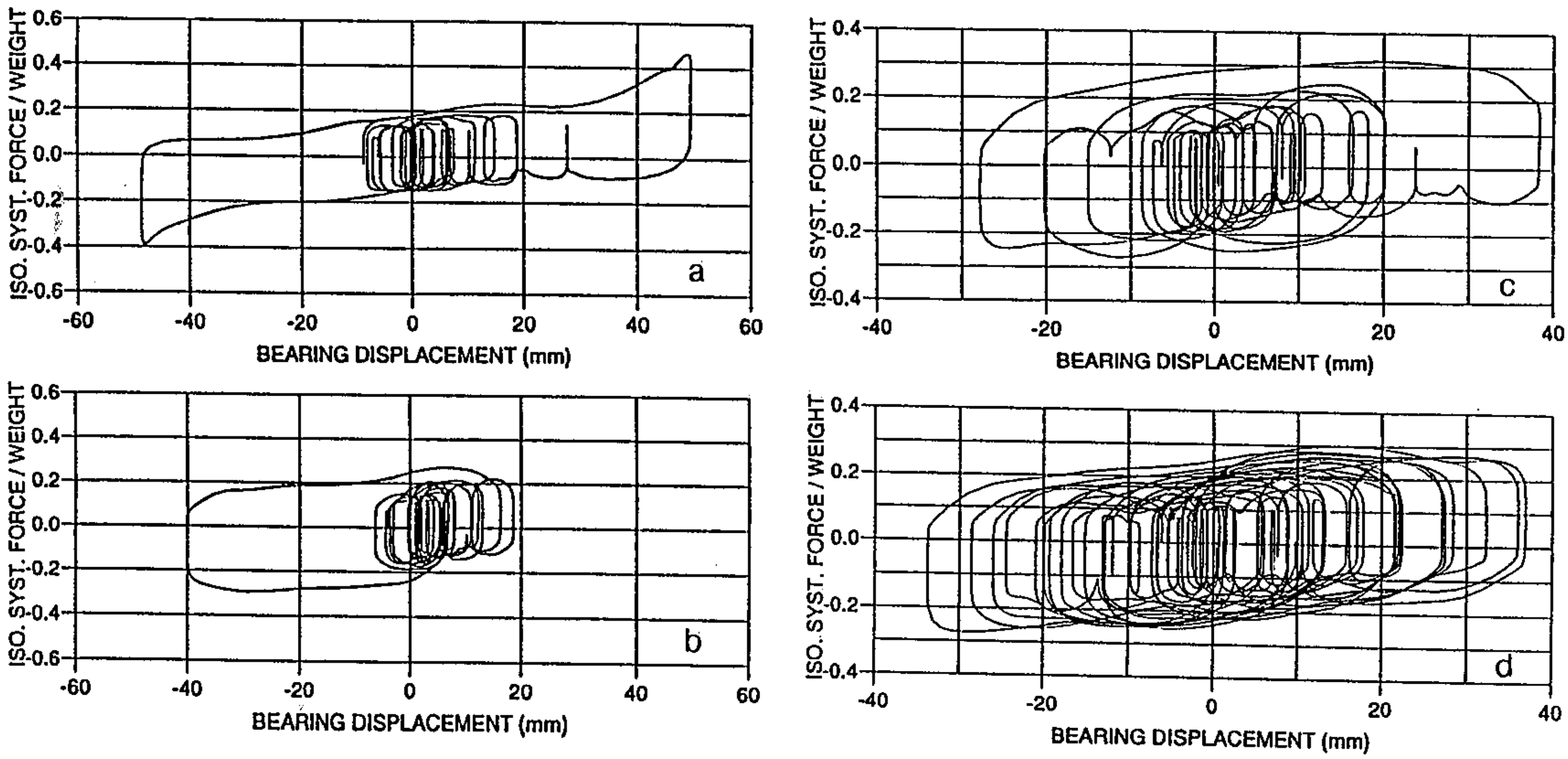

Figure 8 Isolation System Hysteresis Loops of Bridge Structure for Japanese Level 2 Excitation. (a) Without Fluid Dampers, G.C.1; (b) With Fluid Dampers, G.C.1; (c) With Fluid Dampers, G.C.2; (d) With Fluid Dampers, G.C.3.