# EARTHQUAKE SIMULATOR TESTING OF TWO DAMPING SYSTEMS FOR MULTISTORY STRUCTURES

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## ABSTRACT

The use of two different types of damping devices to improve the earthquake resistance of buildings is investigated in a program of earthquake simulator testing of a 1/4-scale, nine-story, steel frame model. The devices studied are a constrained-layer viscoelastic shear damper designed using an energy approach, and a friction damper with almost perfectly rectangular hysteresis behavior, for which an iterative nonlinear analysis design method was adopted.

The model was tested with both types of energy absorbers installed and also in moment-resisting and concentrically-braced configurations. Numerous diagnostic and earthquake tests were performed. The large number of tests performed permitted numerous different comparisons of the four structural systems. Responses are compared in terms of accelerations, displacements, interstory drifts, and story shears. Floor response spectra are also evaluated for the moment-resisting frame and the two damped systems.

The damped structures were found to behave similarly to the concentrically-braced frame in terms of displacements, while having accelerations similar to those of the moment-resisting frame. Story and base shears of the damped structures were of the order of those of the moment-resisting frame, and less than those of the concentrically-braced frame. The response of the two damped systems was very similar for nearly all of the earthquake motions used.

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# INTRODUCTION

Conventional seismic design practice permits the reduction of forces for design below the elastic level on the premise that inelastic action in a suitably designed structure will provide that structure with significant energy dissipation potential and enable it to survive a severe earthquake without collapse. This inelastic action is typically intended to occur in especially detailed critical regions of the structure, usually in the beams near or adjacent to the beam-column joints. Inelastic behavior in these regions, while able to dissipate substantial energy, also often results in significant damage to the structural member, and although the regions may be well detailed, their hysteretic behavior will degrade with repeated inelastic cycling. The interstory drifts required to achieve significant hysteretic energy dissipation in critical regions are large and would usually result in substantial damage to non-structural elements such as in-fill walls, partitions, doorways, and ceilings. As a response to the shortcomings inherent in the philosophy of conventional seismic design a number of innovative approaches have been developed (Fig. 1).

One of these approaches involves adding energy absorbers to a structure. The use of energy absorbers to improve the dynamic behavior of structural systems is well established. There are many applications to tall buildings to reduce wind-induced vibrations. The possibility of using energy-dissipating devices to improve the earthquake resistance of buildings and other structures is a more recent development. The aim of including energy absorbers in a structure for earthquake resistance is to concentrate hysteretic behavior in especially designed and detailed regions of the structure and to avoid inelastic behavior in primary structural elements (except perhaps under the most severe conditions). Numerous different types of energy-absorbing devices have been proposed for this purpose. Devices based on the plastic deformation of mild steel were developed and extensively tested a number of years ago [1]. Friction devices of several types have been the subject of a number of test programs, and one type was recently installed in a library building in Montreal [2]. By the end of 1990, the Sumitomo-type friction dampers studied here had been incorporated in 31- and 22-story buildings, both in Japan. Viscoelastic dampers have been used in several tall buildings as wind vibration absorbers [3]. The dampers use a highly-dissipative polymeric material which has well-defined material properties and behavioral characteristics [4]. The most notable applications are the twin 110-story towers of the World Trade Center in New York City, in which the dampers have been installed for twenty years.

# DESCRIPTION OF DAMPERS

The two types of devices studied were a sliding friction damper and a viscoelastic (VE) shear damper. Both types of device have already been used in a number of structural or mechanical engineering applications, however, this experimental study represented the first use of the dampers for earthquake loading conditions.

The friction damper was designed and developed by Sumitomo Metal Industries, Ltd., Japan. It is a cylindrical device, with friction pads that slide directly on the inner surface of the steel casing of the device (Fig. 2). The device was originally used for shock absorption applications in railway rolling stock. Each of the friction devices manufactured for the test program was subjected to proof tests prior to the earthquake tests. These tests were intended to confirm the correct setting of the slip load and to identify any dependence of the force-displacement behavior on the variables of loading frequency, amplitude, temperature, or the number of loading cycles. All of the dampers performed as intended, and the effect of these factors was found to be negligible. The very good behavior of the devices has been observed in many previous tests performed by Sumitomo.

The VE damper comprises two layers of material, and was introduced in single-diagonal bracing in the test structure (Fig. 3). The VE material was manufactured by 3M Co., USA. The detailed nature of the VE material and its physical properties have been described elsewhere [4,5] and are summarized in the next section.

## VISCOELASTIC MATERIAL

The VE dampers used in the earthquake simulator test program were based on a class of viscoelastic materials with certain specific characteristics. The acrylic copolymer materials are known to be very stable with good aging properties, are chemically inert and are resistant to environmental pollutants. When used as the energy absorbing components in dampers, they are normally used in the form of shear layers and the exposed surface area is very small relative to the volume of material. Thus any chemical processes that depend on diffusion, for example, moisture absorption or penetration, will be very slow.

The viscoelastic properties of these materials when used in shear are characterized by: (i) the loss modulus $G''$, (ii) the storage modulus $G'$, and (iii) their ratio, the loss factor $\tan\delta = G''/G'$. The loss modulus controls the specific energy dissipation capacity of the material. This is the most important characteristic of the material for damping applications. High values of $G''$ mean high energy dissipation per unit volume of the material. The storage modulus $G'$ is also important in that it will influence the change in stiffness (frequency) of the structural system to which the damper is added. The ratio $\tan\delta$ is a measure of the suitability of the material as a damping medium. The materials used in this research program have peak values of $\tan\delta$ in the range of 1 to 1.4.

These three material properties are sensitive to temperature, frequency and strain. The materials can be produced with the desired properties over a wide range of temperature and frequency. Four types of material are currently available, and of these, the material designated ISD 110 by 3M was used in the test program. The manner in which the loss modulus $G''$ depends on temperature, frequency, and strain is the same for all of the ISD copolymers. Thus the behavior characteristics of one material can be used to predict that of the others, provided that data points at a certain temperature, frequency and strain are available.

Tests of the materials were carried out using a standard MTS closed-loop hydraulic test machine. The primary purpose of the tests was to determine the strain sensitivity of the material properties. Material properties provided by the manufacturer in the form of data tables are based on standard tests at low levels of shear strain (< 10%) which are appropriate for vibration damping applications. For seismic applications, however, strains in the range of 10—100% or greater are needed, and tests were performed to provide performance data in this strain range.

The material tests were performed on the dampers used in the earthquake simulator test program (Fig. 3). The dampers were subjected to sinusoidal displacement signals at a range of frequencies. The test results showed that (for a given frequency) while there is a very large difference between moduli at small strains (< 10%) and those at large strains (20—150%) the sensitivity of the moduli to strain within this range is not great. This has advantages for seismic design since over the range of seismic response the damping system can be considered as linear. In contrast, a conventional structural system with equivalent damping greater than 10% must be considered to be nonlinear, and nonlinear dynamic analysis is not convenient for routine seismic design.

## DESIGN OF DAMPING SYSTEMS FOR THE MODEL

### (a) FRICTION DAMPERS

The size (slip force) of the friction dampers and their layout in the test structure was determined using a nonlinear time-history analysis approach. An initial slip load distribution was chosen, based closely on the results of a previous shake table study of the test structure containing another type of friction damper [6], and a series of analyses were performed for a number of different earthquakes at various input levels. The final slip load distribution was chosen as that which provided the best (lowest) structural response for all of the inputs.

### (b) VISCOELASTIC DAMPERS

The method used for the design of the VE dampers for the test structure was a simplified first-mode procedure aimed at providing the structure with a specified level of damping (10%) at a nominal maximum displacement. This was done using an energy approach. A complete description of the procedure used is given in [5].

## DESCRIPTION OF TEST FACILITY AND MODEL STRUCTURE

The experimental program was carried out using the earthquake simulator of the Earthquake Engineering Research Center of the University of California at Berkeley. The earthquake simulator (or shake table) measures 20 ft x 20 ft in plan and can support test specimens weighing up to 130 kips. Simulated seismic motions can be applied vertically and in one horizontal direction, with maximum accelerations of 1.0g and 1.5g, respectively.

The basic test structure was a 9-story, moment-resisting steel frame representing a section of a typical steel building at 1/4-scale. The structure was tested as a moment-resisting frame (MRF), a concentrically-braced frame (CBF), and in friction-damped (FD) and viscoelastically-damped (VD) configurations (Fig. 4). The VE dampers were added to the MRF in single-diagonal bracing, and the friction dampers were added as part of a modified chevron bracing system.

Constant stress scaling, such that model and prototype accelerations are equal, was used for the shake table tests. This required that approximately 90 kips of mass be added to the model in the form of concrete blocks and lead billets. The total test weight of the model was 100 kips. Response quantities measured during the shake table tests included floor displacements and accelerations, bracing forces and damper displacements, base shear and base overturning moment, and shake table accelerations and displacements.

## DESCRIPTION OF EXPERIMENTS

The four configurations of the model structure (Fig. 4) were subjected to a number of different dynamic tests. These were free vibration (pull-back), pulse, random noise, and earthquake tests. Fundamental frequencies for the MRF and CBF of 1.95 Hz and 2.95 Hz, respectively, were identified. The dynamic characteristics of the VD and FD models were a function of the level and type of excitation, and were largely a result of whether or not the dampers were activated during the motion. From the results of the pulse tests, the fundamental frequencies of the VD (dampers activated) and the FD (dampers not activated) models were 2.30 Hz and 2.60 Hz, respectively. A more detailed presentation of the diagnostic test results is given in [5]. The remaining discussion of results is devoted to those from some of the earthquake tests.

Fourteen different earthquake motions were used in the shake table tests of the MRF, CBF, FD, and VD structures. The most extensive sequences of tests were performed for these motions:

(i) El Centro, Imperial Valley, May 18, 1940
(ii) Miyagi-Ken-Oki, Tohoku University, Sendai, June 12, 1978
(iii) Taft, Kern County, July 21, 1952
(iv) Llolleo, Chile, March 3, 1985
(v) La Union, Michoacan, September 19, 1985
(vi) Zacatula, Michoacan, September 19, 1985.

This paper discusses some of the results for the El Centro and Miyagi tests.

## EARTHQUAKE TEST RESULTS

Typical hysteresis loops for the two types of dampers are shown in Fig. 5. The friction dampers exhibited outstanding behavior. The hysteretic behavior is extremely regular and repeatable. The devices showed almost no variation in slip load during earthquake motions, and from previous tests of individual dampers, their force-displacement response was known to be basically independent of loading frequency, amplitude, number of loading cycles, and temperature. In contrast to the VE dampers, the friction dampers are not activated during small excitations. Under such circumstances, the FD model behaved more as though it were a CBF.

The VE dampers exhibit elliptical hysteresis loops, typical of materials with velocity-dependent properties. The loops are regular in shape and show stable behavior. Throughout the VD model tests the maximum VE damper shear strain was 208 %. Viscoelastic dampers have no threshold or activation force level, and thus they dissipate energy for all levels of earthquake excitation. This contrasts with the behavior of the friction dampers, which for forces less than the slip force, do not slip and do not dissipate energy. The stiffness characteristics of the VE dampers are dependent on a number of factors, notably strain amplitude, frequency, and temperature. The variation of VE damper stiffness with shear strain for all of the Miyagi tests is shown in Fig. 6. Between strains of about 0 and 50 %, there is a large decrease in stiffness, but for strains in the range of about 50 to 200 %, the stiffness can be regarded as approximately constant.

Because of the variation in VE damper stiffness with strain amplitude, the fundamental frequency of the VD model also varied with excitation level, from 2.43 Hz down to 2.00 Hz, compared with 1.95 Hz for the MRF. Low-level earthquake tests of the FD model revealed a fundamental frequency of 2.67 Hz (compared with 2.95 Hz for the CBF), while for large excitations a variation of 2.47 to 2.35 Hz was observed.

Temperature increases in the VE material during earthquake shaking were small and did not significantly affect the behavior of the VE dampers.

Shake table response comparisons of the various systems were made wherever possible. For a sequence of El Centro and Miyagi tests, the VD model generally behaved in the same way as the CBF with regard to displacements, and in the same way as the MRF with regard to accelerations. The same general trends were also seen for the FD model compared with the CBF and MRF models. FD, MRF, and CBF acceleration and displacement response profiles for the El Centro-400 tests are compared in Fig. 7. The FD floor accelerations are considerably lower than those of the CBF, and about the same as those of the MRF, while the peak floor displacements of all three structural systems are approximately the same. VD, MRF, and CBF acceleration and displacement response profiles for the El Centro-400 tests are compared in Fig. 8. For this input the VD model has peak accelerations *and* displacements less than those of the MRF and CBF. The FD and VD models responded very similarly for a large number of signals and a wide range of input levels. The FD and VD response profiles for the Miyagi-350 tests shown in Fig. 9 are typical of this close comparison.

Peak base shears of the FD, VD, and MRF models for a series of El Centro and Miyagi tests are compared in Fig. 10, where the FD and VD values are seen to be less than those of the MRF. This result, coupled with the reduced drift levels achieved by the dampers represents a significant overall improvement in response. A large number of equivalent tests were performed on the MRF, FD, and VD models. From response comparisons for the El Centro, Taft, and Miyagi sequences of inputs, drifts in both the FD and VD models were reduced by 10 to 60 % over those of the MRF, while story accelerations were reduced by 25 to 60 %. In all cases, the FD and VD responses were reduced.

Floor response spectra were also used to compare the MRF, FD, and VD models. Two percent-damped spectra for the 3rd floor of each of the models are presented in Fig. 11 for the El Centro-400 and Miyagi-400 tests. The damped structures both offer significant reductions in spectral acceleration, particularly over the range of 5 to 10 Hz. Above 10 Hz, the VD spectrum is about half that of the MRF, while the FD spectrum is less than or about the same as that of the MRF. These results, and those for many other earthquake inputs, indicate that these two types of energy absorbers do not pose problems for internal equipment in structures, and in most cases actually provide improvements over the equivalent MRF.

A comprehensive presentation of the results of the shake table tests is given in [5].

## CONCLUSIONS

This experimental study has demonstrated the response improvements possible in earthquake-resistant structures through the use of energy absorbers. Separate comparisons of the FD and VD systems with the "undamped" MRF and CBF structures showed that both damped systems behaved similarly to the CBF in terms of story drifts and similarly to the MRF in terms of story accelerations and story shears. The FD and VD systems were remarkably similar with regard to acceleration and displacement responses for a wide selection of earthquake inputs. Peak base shears of the FD and VD models were similar for a range of input levels of the El Centro, Miyagi and Taft signals. They were approximately the same as, or less than, the MRF maximum base shears. These results were achieved while simultaneously reducing the drifts to as little as one half of those of the MRF. The VE dampers supplemented the structure damping at all levels of excitation, in contrast to the friction dampers which do not operate below a threshold level of excitation. This means that VE dampers are particularly effective for low to moderate levels of seismic loading.

Floor response spectra showed spectral accelerations of both damped systems to be less than those of the MRF. Neither type of energy absorber caused undesirable high frequency response amplifications in the frequency ranges important for internal equipment or nonstructural components.

## ACKNOWLEDGEMENTS

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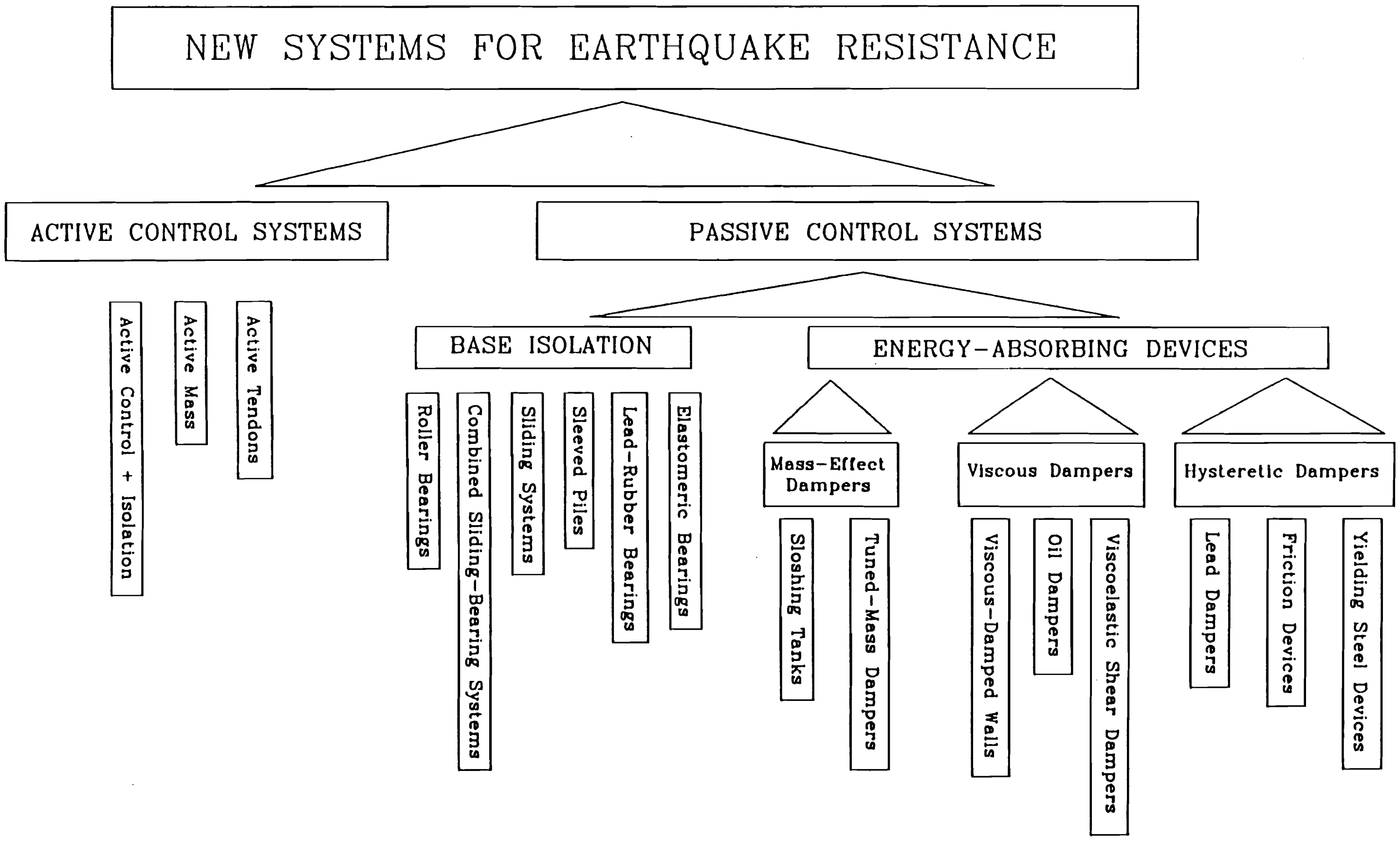
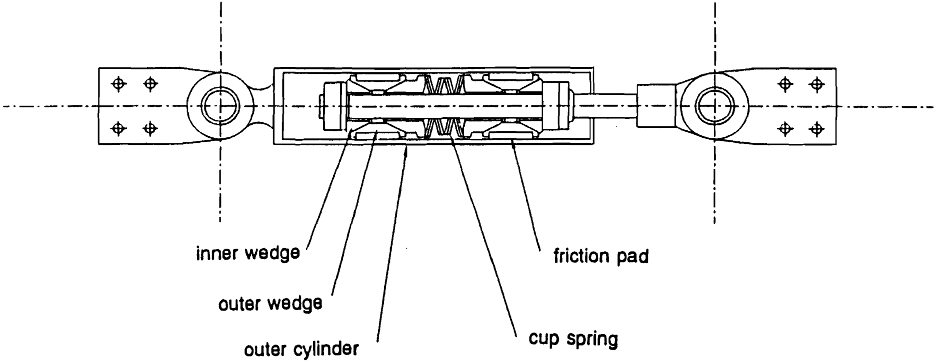


Fig. 1 New Systems for Improved Earthquake Resistance of Structures

(a) Longitudinal Section



(b) Cross Section

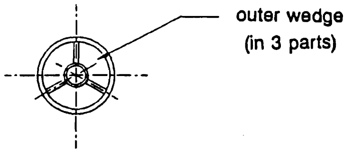


Fig. 2 Sectional Views of Friction Damper

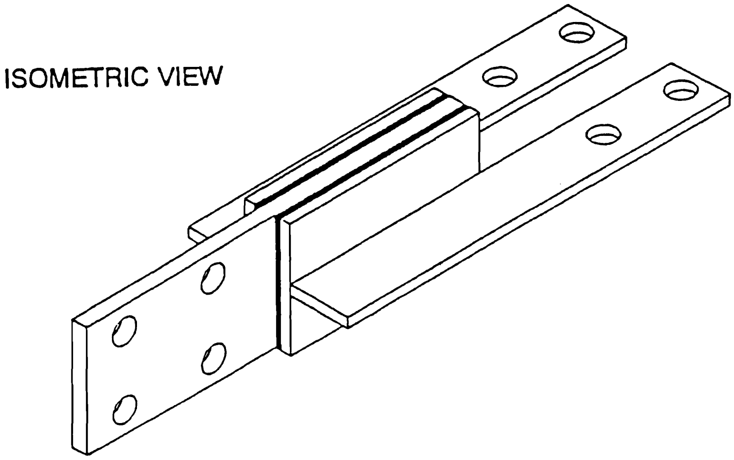
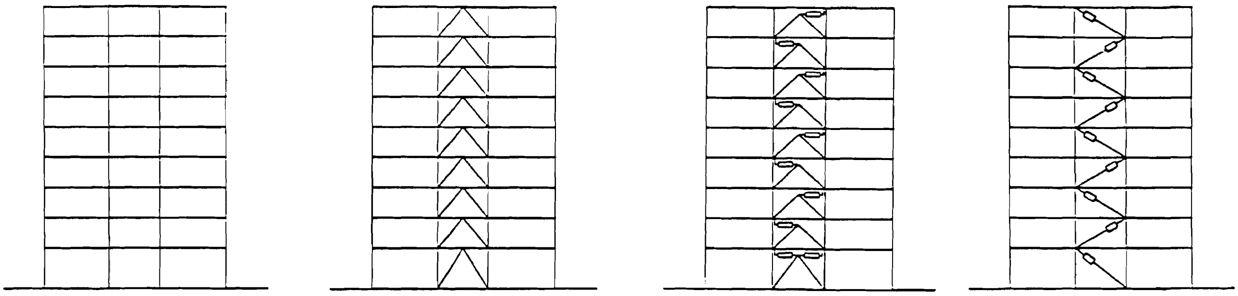
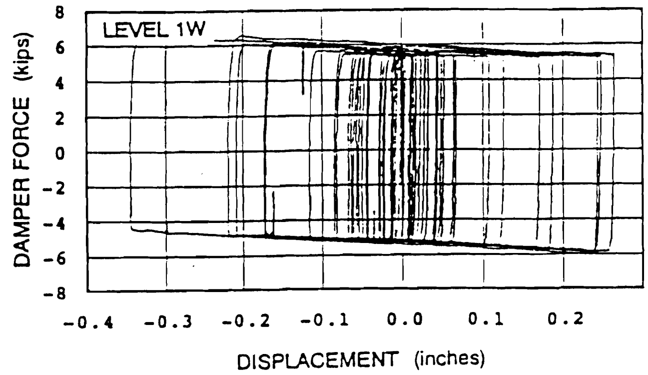


Fig. 3 Constrained-Layer Viscoelastic Shear Damper

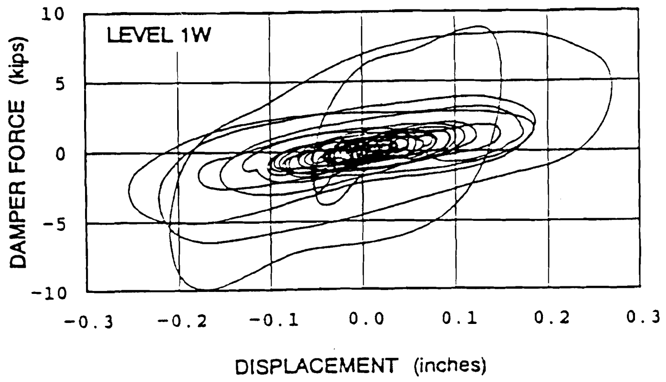


(a) MRF (b) CBF (c) FD (d) VD

Fig. 4 Test Configurations of Model Structure



(a) Friction Damper



(b) VE Damper

Fig. 5 Typical Damper Hysteresis Loops — El Centro-400 Tests

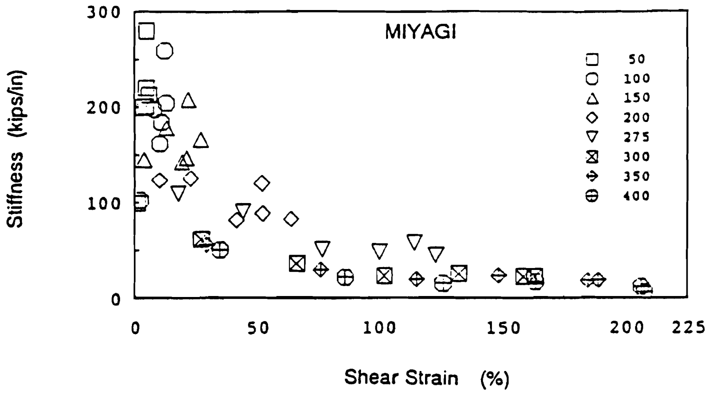


Fig. 6 VE Damper Stiffness versus Shear Strain

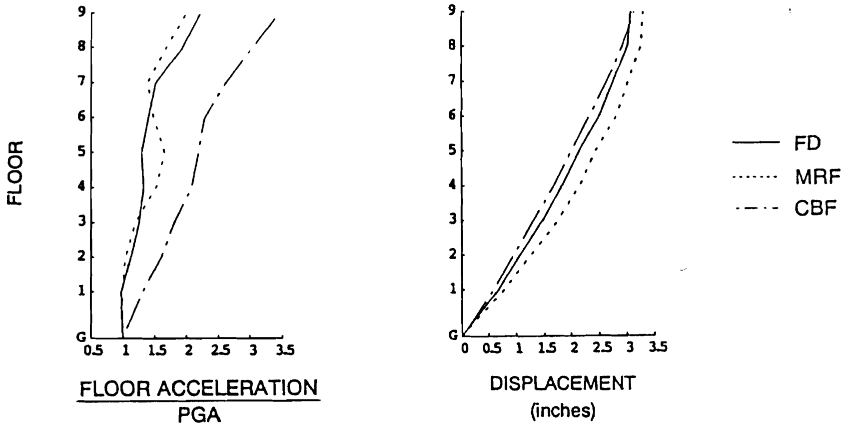


Fig. 7 FD, MRF, and CBF Acceleration and Displacement Response Profiles for El Centro-400 Tests

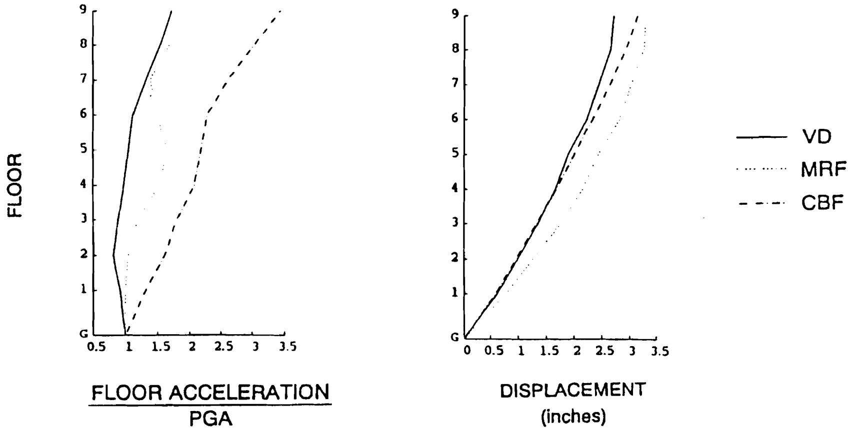


Fig. 8 VD, MRF, and CBF Acceleration and Displacement Response Profiles for El Centro-400 Tests

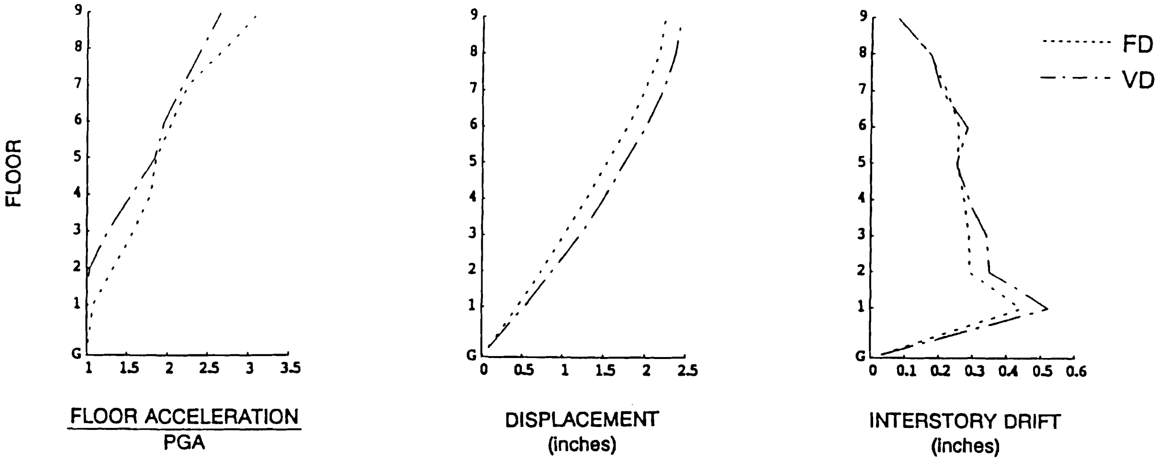


Fig. 9 FD and VD Acceleration and Displacement Response Profiles for Miyagi-350 Tests

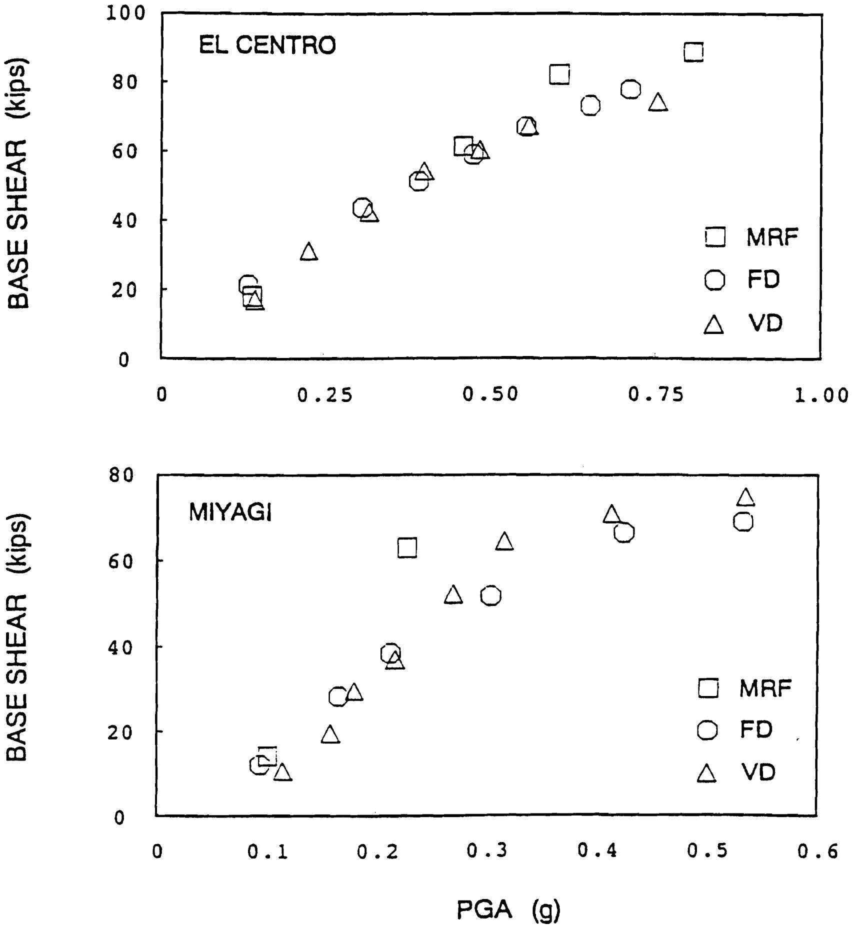
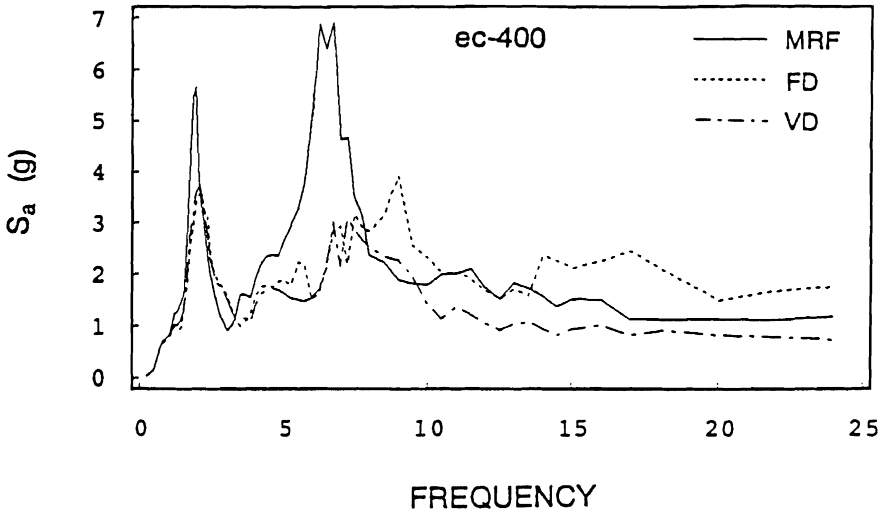
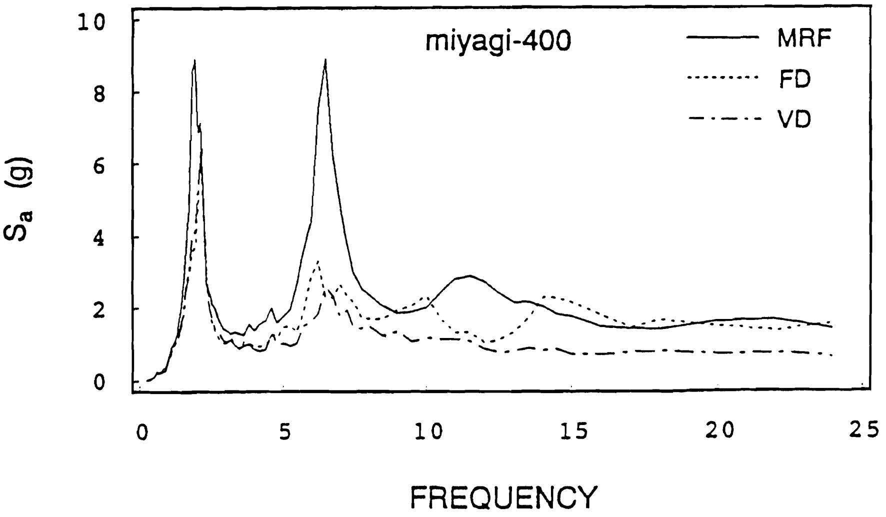


Fig. 10 FD, VD, and MRF Peak Base Shear vs. PGA for El Centro and Miyagi Tests



(a) El Centro-400



(b) Miyagi-400

Fig. 11 FD, VD, and MRF Level 3 Two Percent-Damped Floor Response Spectra, El Centro-400 and Miyagi-400 Tests