# Experimental and Analytical Studies of Two Energy-Absorbing Systems for Multistory Structures

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## ABSTRACT

The use of two different types of energy-absorbing devices to improve the earthquake resistance of buildings is investigated in a series of earthquake simulator tests and analytical studies of a nine-story, moment-resisting steel frame model. The devices studied are a constrained-layer viscoelastic shear damper and a friction damper. 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. Floor response spectra are evaluated for the moment-resisting frame and the two damped systems. Analytical methods for predicting the response of the two damped structures are studied. Linear time-history analyses and response spectrum analyses were used for the viscoelastically-damped system and nonlinear time-history analyses for the friction-damped system.

## 1 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.

One of these approaches involves adding energy absorbers to a structure. 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. 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. 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. The dampers use a highly dissipative polymeric material which has well-defined material properties and behavioral characteristics (Mahmoodi, 1972). 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.

### 1.1 Description of dampers

The two types of devices studied were a viscoelastic (VE) shear damper and a sliding friction damper. The VE damper comprises two layers of material, and was introduced in single-diagonal bracing in the test structure (Fig. 1). The VE material was manufactured by 3M Co., USA. The detailed nature of the VE material and its physical properties have been described elsewhere (Mahmoodi, 1972; Aiken, 1990) and are not discussed further here. 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. The mechanical characteristics of both types of dampers were well-known from previous studies, and both have already been used in a number of structural or mechanical engineering applications. This experimental study represented the first use of the dampers for earthquake loading conditions.

### 1.2 Design of damping systems for the model

#### 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 (Aiken et al., 1988) containing another type of friction damper, 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.

#### 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 (Aiken, 1990).

## 2 EARTHQUAKE SIMULATOR STUDY

### 2.1 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 × 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. 3). 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.

## 2.2 Description of experiments

The four configurations of the model structure (Fig. 3) 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 (Aiken, 1990). 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. This paper discusses some of the results for the following earthquakes:

(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.

## 2.3 Earthquake test results

Typical hysteresis loops for the two types of dampers are shown in Fig. 4. 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. 5. 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. This assumption was utilized in the use of "effective" damper stiffnesses in the numerical analyses described in section 3. Temperature increases in the VE material during earthquake shaking were small and did not significantly affect the behavior of the VE dampers.

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.

Because of the variation in VE damper stiffness with strain amplitude, the fundamental frequency of the VD structure 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.

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. Peak base shears of the FD, VD, and MRF models for a series of Miyagi tests are compared in Fig. 6, where the FD and VD values are seen to be less than those of the MRF. This, 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. 7 for the 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 (Aiken, 1990).

## 3 ANALYTICAL STUDY

### 3.1 Friction-damped structure

An inelastic time-history analysis program was used for the numerical study of the FD structure. The structural frame was modelled using bilinear beam-column elements, and the friction dampers were modelled using yielding truss elements having equal tension and compression yield forces. A number of large input motions were chosen from the shake table test program, and these were used as inputs to the numerical model of the FD structure. Roof displacement time-histories, peak floor drifts, and story shears were compared to the experimentally observed responses. In general, agreement was good. In both the shake table tests and the computer analyses, no yielding of the FD primary structural members (beams and columns) was observed.

The MRF and CBF configurations of the test structure were not subjected to large intensity inputs such as those used on the FD structure. To provide a basis for response comparisons, analyses of the MRF and CBF structures were performed for the large inputs used in the FD shake table tests. Results of the MRF and CBF El Centro-400 and Chile-750 analyses are shown in Fig. 8. Significant yielding of the MRF was observed for all inputs. The CBF response was better than that of the MRF, with reduced yielding and some brace buckling for most inputs. For several analyses, however, the CBF response was poor.

### 3.2 Viscoelastic-damped structure

A linear-elastic finite element structural analysis program was used for the numerical study of the VD structure. The diagonal brace-damper assemblage was represented by an element with an "effective" axial stiffness that corresponded to the shear stiffness of the VE dampers. The effective stiffness of a damper is shown by the dotted line superimposed on the hysteresis loop of Fig. 4(a). The damping provided by the dampers to the structure was included in the analysis by increasing the modal damping. This increase was determined from the shake table test results, and a first-mode damping ratio of 10 % was used for all of the analyses. Time-history analyses were performed for the El Centro, Miyagi, and Taft motions, at several different input intensities. Very good agreement with the shake table test results was obtained. Experimental and analytical roof displacement time-histories for the El Centro-250 input are compared in Fig. 9.

A series of analyses were performed to decompose the separate effects on response of adding damping and adding stiffness to the MRF. A computer model was developed with frequency characteristics equivalent to the VD test structure, but with 2% first-mode damping. The response of this model to the El Centro-250 input is compared to the VD test structure in Fig. 10. The reduction in response due to the increase in damping is clear. Analysis results were found not to be sensitive to the damping values assigned to the higher modes.

Response spectrum analyses of the VD structure were performed for each of the input signals used in the shake table test program. A linear-elastic response spectrum (LERS) was calculated for each input, and then peak spectral displacement and base shear were determined. The results obtained from these analyses compared well with the experimental results.

## 4 CONCLUSIONS

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.

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 non-structural components.

The FD model was analyzed using a nonlinear analysis program. Good agreement with experimental results was obtained. The stable hysteretic behavior of the friction devices makes them particularly amenable to accurate modelling. A linear elastic analysis approach was used for the VD model. The analyses captured both the damping and stiffness characteristics of the VE dampers accurately. Very good results were obtained. Response spectrum analyses of the VD model were also performed, with good results.

This combined experimental and analytical study has demonstrated the response improvements possible through the use of energy absorbers. Existing analysis programs have been shown to be suitable for modelling structures equipped with energy absorbers, and this should provide the basis for more-detailed parametric analyses in the future.

## REFERENCES


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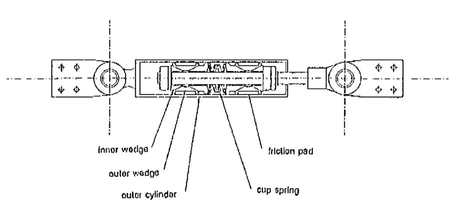



Fig. 1 Cross-Section of Friction Damper

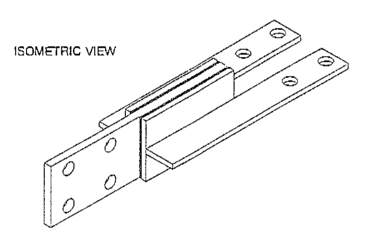



Fig. 2 Constrained Layer Viscoelastic Shear Damper

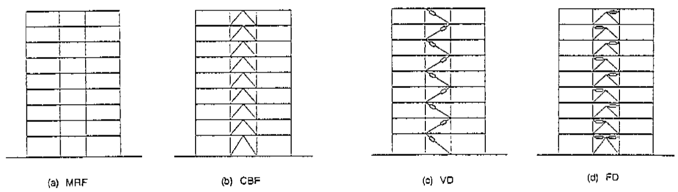
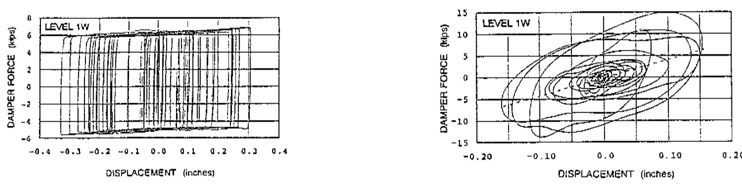



Fig. 3 Test Configurations of Model Structure




(a) Friction Damper — Chile-750 Test

(b) VE Damper — El Centro-250 Test

Fig. 4 Typical Damper Hysteresis Loops

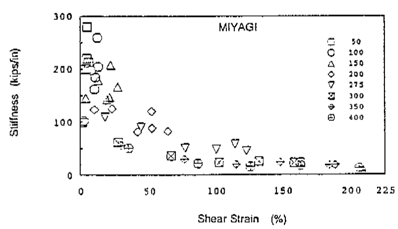



Fig. 5 VE Damper Stiffness vs. Shear Strain for Miyagi Tests

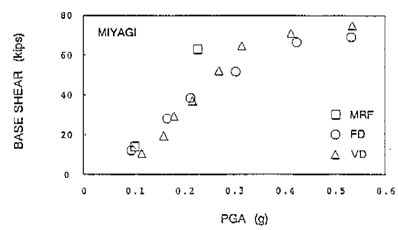



Fig. 6 MRF, FD, and VD Peak Base Shear vs. PGA for Miyagi Tests

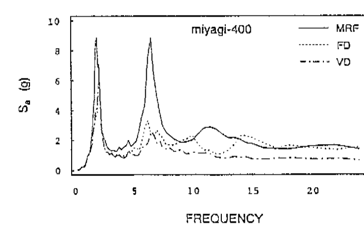
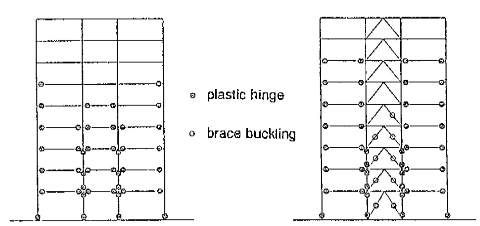



Fig. 7 MRF, FD, and VD Level 3 2%-Damped Floor Response Spectra, Miyagi-400 Tests




(a) MRF

(b) CBF

Fig. 8 Analytical Inelastic Demands, Chile-750 Input

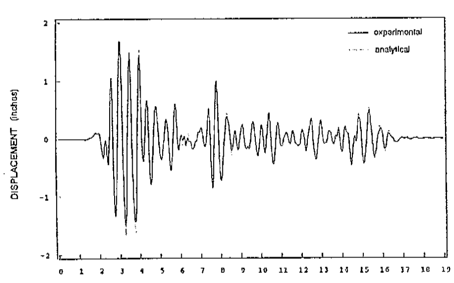



Fig. 9 VD Experimental and Analytical Roof Time Histories, El Centro-250 Input

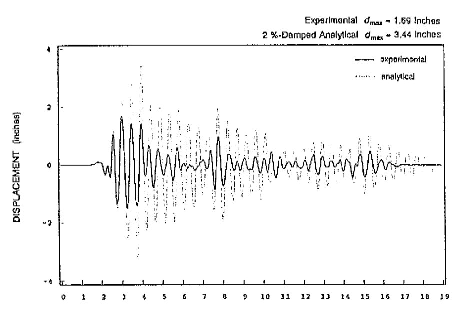



Fig. 10 VD Experimental and 2%-Damped Analytical Roof Time Histories, El Centro-250 Input