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# 점탄성 감쇠기를 설치한 2/5 축척 강구조물의 지진하중에 의한 거동연구
# Seismic Behavior of A 2/5-Scale Steel Structure with Added Viscoelastic Dampers

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## ABSTRACT

This paper summarizes an experimental and analytical study on the application of viscoelastic dampers as energy dissipation devices in structural applications. Shaking table tests are carried out on the viscoelastically damped structure and the obtained structural responses are compared to those of the inelastic analysis results for the same test structure with no dampers added. It can be concluded the viscoelastic dampers are effective in reducing excessive vibrations of structures under strong earthquake ground motions. It is also observed that the increase in structure's stiffness by the addition of dampers can not contribute to improving the seismic response of a structure. In general, the reduction of the seismic response by adding the dampers to the structure is mostly resulted from the increased damping effect. It is found that the modal strain energy method can be used to reliably predict the equivalent structural damping, and the seismic response of a viscoelastically damped structure can be accurately estimated by conventional modal analysis techniques.

## 요 지

본 논문은 에너지 분산 장치의 일종인 점탄성 감쇠기를 설치한 건물의 거동에 관한 실험 및 해석적 연구를 다루고자 한다. 지진 모형 실험 장치를 이용하여 감쇠기를 설치한 건물의 구조응답을 구하고, 이를 감쇠기를 설

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치하지 않은 건물에 대하여 행해진 비탄성 해석 결과와 비교한다. 결론적으로 말하면, 점탄성 감쇠기는 강지진 하중에 의하여 건물에 발생한 과도한 진동을 감소시키는데 효과적이다. 일반적으로 점탄성 감쇠기를 건물에 설치함으로써 감쇠비와 함께 강성도가 증가하여 지진 응답을 감소시키는데 기여하나, 대부분은 감쇠기의 역할에 의해 증가된 감쇠비의 영향인 것으로 밝혀졌다. 모드 변형에너지법을 이용하여 감쇠기에 의해 증가된 등가구조 감쇠를 성공적으로 예측할 수 있으며, 따라서 점탄성 감쇠기를 설치한 건물의 지진 응답이 일반적인 모드 해석 기법을 이용한 수치모형해석에 의해 정확히 예측된다.

## 1. INTRODUCTION

In recent years, earthquake resistant design and retrofit of mement resisting steel frames using energy-absorbing devices have received considerable attentions[1,2,3]. Among the available devices, viscoelastic(VE) dampers have shown to be capable of providing structures with added damping to dissipate energy resulting from severe earthquake ground motions.

While aerospace systems and mechanical systems have utilized added damping provided by VE materials to control excessive vibrations since 1950's[4,5], similar efforts have not been made for the civil engineering structures until early 1970's. VE dampers have been installed in several tall buildings to reduce vibrations due to wind loading, on the basis of their ability to absorb large amounts of energy and their cost effectiveness. It has been demonstrated that wind-induced sway of high rise building can be considerably reduced by adding VE dampers to the structure[6,7].

Lin, et al.[8] studied experimentally to evaluate the feasibility of applying VE dampers to seismic response control at the State University of New York at Buffalo. In that study, a three-story steel frame equipped with VE dampers was tested under earthquake excitations. A significant increase in structural damping and correspondingly considerable decrease in seismic structural response were observed. Another experimental study aimed at evaluating the suitability of VE dampers for seismic design applications was conducted at the University of California, Berkeley[1]. For all the earthquake tests the dynamic model response was substantially reduced as compared to that of the moment resisting frame. In some cases, the reductions of the structural accelerlations and inter-story drifts are as much as one half.

Recently, an analytical and experimental study on dynamic response of VE dampers and on seismic response of viscoelastically damped structures has been carried out at the State University of New York at Buffalo. The experimental program was conducted on a 2/5 scale five-story steel frame under a variety of recorded ground motions and intensities. Based on the test results, it can be shown that the equivalent structural damping of the viscoelastically damped structures can be accurately predicted using the modal strain energy method. The seismic reponse can then be estimated using conventional dynamic linear analysis routines.

In this paper, experimental and analytical results on seismic behavior of a 2/5 scaled steel frame with and without added VE dampers under strong earthquake motions will be presented and discussed.

## 2. PROPERTIES OF VISCOELASTIC DAMPERS

Damper property tests were carried out using an MTS axial-torsional testing system. Figure 1 shows a typical design of a VE damper. The energy dissipation capacity of VE dampers are characterized by shear storage modulus, $G'$, and shear loss modulus, $G''$. $G'$ determines the stiffness of the damper, $k'$, while the ratio of $G''$. $G'$ determines the damper loss factor, $\eta$, as

$$k' = \frac{G'A}{h} \tag{1}$$

$$\eta = \frac{G''}{G'} \tag{2}$$

where $A$ is the total shear area of VE material and $h$ is the thickness of each VE slab. $k'$ and $\eta$ will later be used to calculate modal damping of the structure.

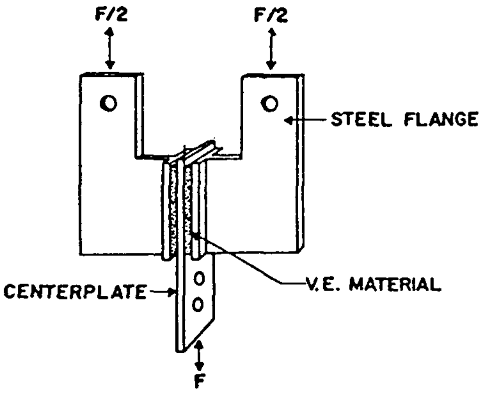


Fig. 1 Viscoelastic damper

The above VE damper properties are dependent on the vibrational frequency and environmental temperature. In general, as the vibrational frequency goes higher, the values of G′ and G″ also become larger. The opposite is ture for the effect of ambient temperature. The energy dissipation capacity of the VE damper also decreases with increasing ambient temperature. The loss factors, however, remain somewhat constant regardless of the frequencies and ambient temperatures. Test results with the average of the first twenty cycles showing the above effects from a typical VE damper are listed in Table 1. It can be seen that the damper properties remain somewhat cocnstant for each temperature and frequency for strains up to 20%.

Table 1 Damper properties

| Temp ℃ | Freq. Hz | Strain % | k′ lb/in | G′ psi | G″ psi | $\eta$ |
|---|---|---|---|---|---|---|
| 24 | 1.0 | 5 | 2124 | 142 | 193 | 1.36 |
| 24 | 1.0 | 20 | 2082 | 139 | 192 | 1.38 |
| 24 | 3.0 | 5 | 4084 | 272 | 324 | 1.29 |
| 24 | 3.0 | 20 | 3840 | 256 | 306 | 1.20 |
| 36 | 1.0 | 5 | 880 | 59 | 67 | 1.13 |
| 36 | 1.0 | 20 | 873 | 58 | 65 | 1.12 |
| 36 | 3.0 | 5 | 1626 | 108 | 119 | 1.10 |
| 36 | 3.0 | 20 | 1542 | 103 | 112 | 1.09 |

The damper properties are also, to a certain degree, dependent on the number of loading cycles and the range of deformation; especially under large strain excitations because of the temperature increase within the damper material. However, these effects have been shown to be insignificant in seismic applications [9]. This is because in an earthquake ground motion, it is typical that the peak accelerations occur in only a few cycles of excitation. The average excitation is normally far less severe than the peaks. Therefore, it is possible to analyze the seismic reponse of viscoelastically damped structures accurately based on the properties of the VE dampers corresponding to 20% strain.

In general, damper properties can be obtained through constituitive modeling to include the effects of frequency, temperature and deformation. For practical applications, they can also be obtained from regression analysis on the test data to include the effects of frequency and ambient temperature[9].

## 3. STRUCTURAL RESPONSE

### 3.1 Test structure

The test structure is a 2/5-scale five-story steel frame with overall dimensions of 52.0" x 52.0"(132cm x 132cm) in plane and 224.0"(570cm) in height. A lumped mass system simulating the dynamic properties of the prototype structure was accomplished by adding steel plates at each floor level. The weight at each floor is 1.27 kips(576 Kg) for the first four floors and 1.12 kips(508Kg) for the fifth one. All the girder-to-column joints are fully welded as rigid connections. This type of design produces a frame behaving as a lumped mass five-degree-of-freedom system when subjected to lateral loads. The ends of the first floor columns were welded to base plates which were bolted to a large concrete boat-type foundation secured to a shaking table.

The diagonal bracing members with added VE dampers are connected by bolts to the gusset plates welded to the girders. Each set of bracing is composed of two L $1^1/2$ x $1^1/2$ x $^1/8$ double angles with a VE damper connected at the upper one-third part of the bracing.

### 3.2 Test set-up and experimental program

The test set-up was designed to monitor the global structural response, local damper response, and temperature rise within the VE dampers. Two criteria were considered in order to determine an appropriate earthquake record in this test program:(1) the structure without added dampers will behave elastically without being damaged, and (2) the maximum damper strain will be less than 75% to prevent possible damage to the dampers.

### 3.3 Dynamic structural characteristics

Based on the acceleration transfer function between signals of the structural response output and the white noise input, important dynamic characteristics of the structure such as natural frequencies and damping ratios can be obtained. The natural frequency of the model structure without added dampers is 3.1Hz while the natural frequency of the viscoelastically damped model structure lies between 3.5Hz and 3.6Hz, depending on the intensities of input ground motions. The VE dampers were designed to have 15% damping ratio for the first mode of the model structure at room temperature without significantly changing the natural frequency of the structure. Fig. 2a and 2b show the scaled response spectra with damping ratios of the two earthquake ground motions used in the experimental study. It can be seen that while there are ups and downs in response spectra, they are nearly constant for 15% damping. This indicates that providing extra damping to the structure will reduce not only the seismic response but also dependency on frequency contents of earthquake motions.

Shaking table tests were carried out on the viscoelastically damped structure at room temperature(25℃) under time scaled

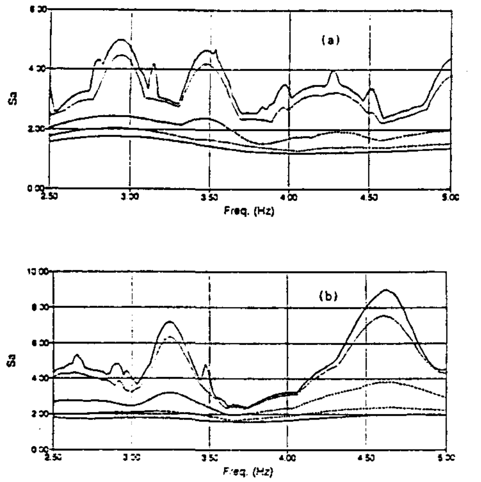


Fig. 2 Time scaled response spectra with different damping rations(0.5, 1, 5, 10, 15%)
(a)El Centro carthquake,
(b)Hachinohe earthquake

El Centro of 1940 and Hachinohe of 1968 earthquakes with scaled peak accelerations of 0.6g. Numerical studies using an inelastic analysis program DRAIN-2D[10] showed that without added VE dampers, the model structure would experience inelastic deformation under these ground motions (Fig. 3a and 3b). The inelastic analysis results are used to access the efficiency of VE dampers under strong earthquake ground motions.

Fig. 4 shows the caculated displacement time history at the roof of the model structure without added VE dampers under 0.6g El Centro earthquake ground motion. Fig. 5 shows the displacements with added dampers. It can be seen that VE dampers provide significant extra damping to the structure so that the structure behaved elastically and the seismic response greatly reduced. Similar observations were attained for story drifts and floor accelerations at all floor levels.

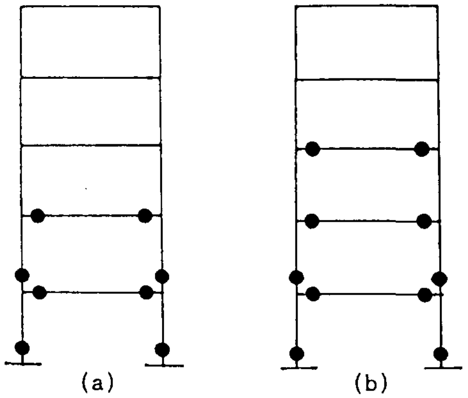


Fig. 3 Distribution of plastic hinges in model structure
(a)0.6g El Centro earthquake,
(b)0.6g Hachinohe earthquake

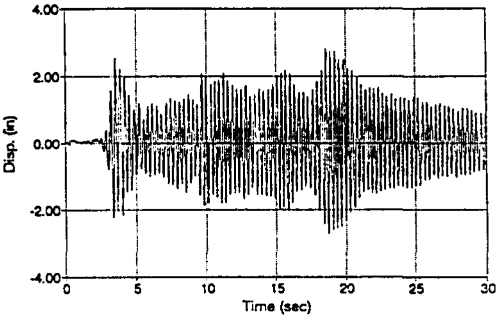


Fig. 4 Analytical displacement without dampers added(0.6g El Centro)

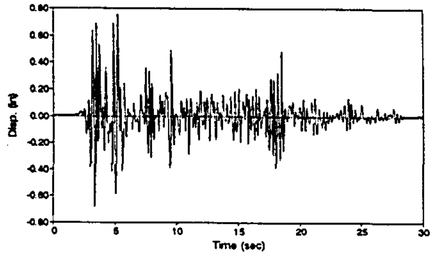
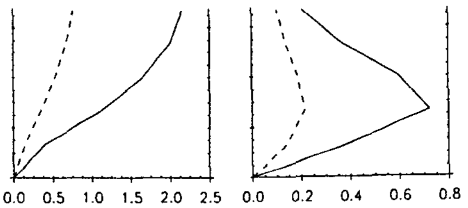
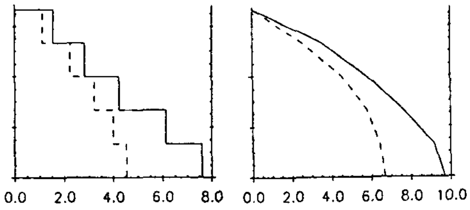


Fig. 5 Measured displacements with dampers added(0.6g El Centro)

Fig. 6a-6d show the envelop curves of the lateral displacement, inter-story drift, accumulated story shear, and overturning moment of the model structure with and without added dampers under 0.6g El Centro earthquake. It can be seen that adding VE dampers to the structure reduces not only the deformation but also the base shear and overturning moment even when the structure without the added dampers is allowed to have inelastic deformation. Therefore, the VE dampers dissipate a significant amount of seismic input energy to prevent the structure from inelastic deformation. Similar results were obtained for 0.6g Hachinohe earthquake.



(a) Lateral Disp. (in) (b) Inter-Story Drift (in)



(c) Story Shear (kips) (d) Overturning Moment (x100 kip-in)

Fig. 6 Envelop curves:
........................ With dampers
———————— Without dampers

## 4. ANALYTICAL SIMULATIONS

### 4.1 Estimation of equivalent structural damping

Voscoelastically damped structures dissipate seismic input energy through extra damping provided by the added VE dampers. In order to insure the effectiveness of these added dampers, it is very important to predict the amount of equivalent structural damping due to the added dampers. In a recent study[11], by assuming a proportionally damped system, the resultant damping ratio for the *i*th mode of vibration of the structure with added dampers can be expressed as

$$\xi_i = \frac{E^i_d}{4\pi E^i} \qquad (3)$$

where $\xi_i$=structural damping ratio for the *i*th vibration mode, $E^i_d$=energy dissipated by the dampers for the *i*th vibration mode, and $E^i$=maximum strain energy of the structure of the *i*th vibration mode.

The above equation can also be expressed in terms of modal strain energy as[9,12,13]

$$\xi = \frac{\eta}{2}\left[1-\frac{\Phi^T_s K_e \Phi_s}{\Phi^T_s K_s \Phi_s}\right] \qquad (4)$$

where $K_s$ is the stiffness matrix of the structure including added damper stiffness, $\Phi_s$ is the associated mode shape and $K_e$ is the stiffness matrix of the original structure without adding dampers. In this paper, we only calculate the structural dynamic properties associated with the first mode of vibration (n=1) since the higher modal responses are relatively insignificant for viscoelastically damped structures.

Using damper stiffness and loss factors given in Table 1 at 25℃, the modal damping ratio of the model structure with added VE dampers is calculated to be 14.5% from the modal strain energy mothod[9].

### 4.2 Simulation of structural response

The ultimate goal of calculating the damping ratio is to compute the structural response with the basic structural properties. Numerical simulations on dynamic response of the test structure under strong earthquake excitations were carried out and the damping ratios predicted by the modal strain energy method were used in the analysis. It was observed that the numerical simulation for the model structure at the roof under 0.6g El Centro earthquake, Fig. 7, agrees very well with the experimental result as shown in Figure 5. Similar correlations were obtained for other numerical simulations of the test results[9].

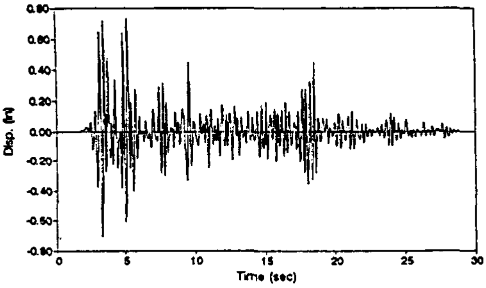


Fig. 7. Estimated displacements with dampers added(0.6g El Centro)

## 5. SUMMARY AND CONCLUSIONS

This paper summarizes an experimental and analytical study on the application of VE dampers as energy dissipation devices in structural applications. It can be concluded that VE dampers are effective in reducing excessive vibrations of structures due to earthquake ground motions. It is also found that the modal strain energy method can be used to reliably predict the equivalent structural damping. The seismic response of viscoelastically damped structures can be accurately predicted using conventional modal analysis techniques. Comparisons between numerical simulations and test results show very good agreement for the viscoelastically damped structure. The ease and reliability of analysis for the viscoelastically damped structure is an important feature in practical design applications.

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