CORRELATION OF EXPERIMENTAL RESULTS WITH PREDICTIONS OF VISCOELASTIC DAMPING FOR A MODEL STRUCTURE

T. T. Soong
Department of Civil Engineering
State University of New York at Buffalo
Buffalo, NY 14260
(716) 636-2469

and

M. L. Lai
The 3M Company
New Product Department
Building 201-1N-35, 3M Center
St. Paul, MN 55144
(716) 736-0704

ABSTRACT:

Viscoelastic dampers as supplementary damping devices have been applied to building structures under wind loads. More recently, analytical and experimental results have shown that, when properly designed, they can also be effective against earthquake and other environmental forces. One of the challenging areas in research and implementation of viscoelastic dampers is to evaluate the damping effect of the dampers on structures. In this paper, the modal strain energy method in conjunction with the finite element method is used to evaluate the damping ratio of a 1/2.5 scaled steel frame building with viscoelastic dampers installed. Computed damping ratios are found to be in very good agreement with the experimental results.

INTRODUCTION

In recent years, both researchers and practicing professionals have recognized that energy dissipation devices can provide an efficient means of mitigating the building response induced by strong motion earthquakes (ATC-17 1986 and ATC-15-3 1990). By dissipating the vibratory energy in the structure, the energy dissipation devices can reduce the risk for the building of experiencing excessive deformations or accelerations. As a result, less ductility or inelastic energy demand is required.

Since the first implementation of 10,000 viscoelastic dampers in each of the two World Trade Center buildings in New York City in early the 1970's, two more buildings, the Columbia Center and the Two Union Square building, both in Seattle, have incorporated passive viscoelastic dampers. All these applications are to increase the structural damping and eventually to reduce the building response due to ambient wind loadings. Recently, the viscoelastic dampers have also been tested in scaled models on shaking tables for seismic applications (Soong and Mahmoodi 1990 and Aiken, Kelly and Mahmoodi 1990). It has been shown that passive viscoelastic dampers can very effectively attenuate the earthquake-induced structural response. It is also noted that the viscoelastic dampers behave quite linearly. This should greatly simplify the damping analysis and design for buildings.

Literatures on the characterization of viscoelastic materials for passive building dampers are identified by Mahmoodi (for instance, Mahmoodi 1969 and Keel and Mahmoodi 1986). Recently, the analysis of the damping effect on buildings were attempted by Lin, *et al* (1991) and Zhang, *et al* (1989). However, no efforts has been made to correlate the analytical results to the experimental results.

In this paper, analytically calculated modal damping ratios and modal frequencies are compared to experimental results.

EQUATIONS OF MOTION OF A VISCOELASTICALLY DAMPED SYSTEM

Viscoelastic dampers installed in a building may behave linearly within a range of strain of the viscoelastic material (Aiken, Kelly and Mahmoodi 1990). The dampers will contribute to the viscous damping as well as the stiffness of the building. In this case, the discretized system linear equations of motion for the building subjected to an earthquake excitation $\ddot{X}_g(t)$ may be written as

$$[m]\{\ddot{X}\} + [c]\{\dot{X}\} + [k]\{X\} = -[m]\{1\}\ddot{X}_g(t) \qquad (1)$$

where $\{X\}$ is the column vector of the displacements of the nodes relative to the base; a dot represents differentiation with respect to time; $\{1\}$ is a column vector of ones; and $[m]$, $[c]$ and $[k]$ are the mass, damping and stiffness matrices, respectively, in physical coordinates.

Although the response of the building can be obtained by direct time integration of Eq. 1, it is generally more efficient to analyze the system by modal analysis techniques. The system response is then approximated by a linear combination of the lowest modes of vibration.

In conducting modal analyses, one of the main tasks is to estimate modal parameters, i.e., modal frequency, mode shape and modal damping ratio for the modes of interest. It has become a common practice to calculate the modal frequency and mode shape of buildings, for instance, using finite element methods. The modal damping ratio of a building is usually based on empirical estimates since efficient analytical predictions are hindered by the complex damping mechanisms involved in buildings. However, by taking advantage of the fact that a viscoelastically damped building responds approximately linearly to dynamic excitations, a method based on the modal strain energy method can be used to predict the modal damping ratio.

MODAL STRAIN ENERGY METHOD

The modal strain energy method has widely been used to calculate the damping ratio of viscoelastic damped systems (Ungar and Kerwin 1962 and Johnson and Kienholz 1982). In this method, the real normal mode modal analysis is used.

In real normal mode modal analyses, the modal equations of motion for Eq. 1 can be written as

$$\ddot{Z}_n + 2\zeta_n\omega_n\dot{Z}_n + \omega_n^2 Z_n = \frac{-\{\phi\}_n^T[m]\{1\}\ddot{X}_g(t)}{m_n} \qquad (2)$$

$$\{X(t)\} = \sum\{\phi_n\}Z_n(t) \qquad n = 1,2,3,\cdots \qquad (3)$$

where Z_n is the nth modal response, ζ_n is the nth modal damping ratio, ω_n is the nth modal frequency, $\{\phi_n\}^T$ is the nth mode shape vector and is the transpose of $\{\phi_n\}$, and m_n is the nth modal mass. These quantities as well as the system response, $\{X(t)\}$, can readily be evaluated if the matrices $[m]$, $[c]$ and $[k]$ and the excitation in Eq. 1 are known.

In this paper, no attempts is committed to the evaluation of the damping matrix $[c]$ of the system. Rather, from the modal strain energy method (Johnson and Kienholz 1982), the modal damping ratio of the nth mode ζ_n can be calculated as

$$\zeta_n = \frac{\eta_v}{2}\frac{E_v}{E_s} \qquad (5)$$

where η_v is the loss factor of the viscoelastic material at the modal frequency, E_s is the nth modal strain energy of the system with dampers and E_v is the energy stored in the viscoelastic dampers. These energies are calculated from

$$E_v = \{\phi_n\}^T[k_v]\{\phi_n\} \qquad \text{and} \qquad E_s = \{\phi_n\}^T[k_s]\{\phi_n\} \qquad (6)$$

where $[k_v]$ is the stiffness matrix attributed to the added dampers and $[k_s]$ is the stiffness matrix of the structure when the dampers are installed.

Eq. 5 can be rewritten as

$$2\zeta_n E_s = \eta_v E_v \qquad (7)$$

Eq. 7 states that the energy loss in the structure equals the energy dissipated in the dampers. In other words, only the viscoelastic dampers contribute to the damping of the structure. Other mechanisms of damping are neglected.

DAMPING RATIOS OF A VISCOELASTICALLY DAMPED 5-STORY MODEL

Viscoelastic dampers are installed in a 1/2.5 scaled single bay 5-story steel moment resisting frame model as shown in Figs. 1a and 1b. Six cases are used to verify the modal strain energy method for computing the modal damping ratio of the first mode. Experimental verifications were conducted on a shaking table. Detailed test procedures and results will be presented elsewhere.

Finite element methods are used to obtain the system mass and stiffness matrices. A spring element is used to represent the damper stiffness. Fig. 2 shows that the predicted first modal frequencies in all cases are in very good agreement with the measurements. It is also shown that by employing the dampers, the modal frequency of the structure is slightly increased.

Predicted damping ratios of the first mode for all cases using Eqs. 5 and 6 are shown in Fig. 3 along with experimental results. The prediction error is within ±5%. It is also shown that the damper placement greatly affects the modal damping ratio of the structure. In order to maximize the damping ratio, an optimum placement strategy may be warranted. However, as a rule of thumb, dampers should be placed at the locations that will experience large deformations.

CONCLUSIONS

The structural modal damping ratio is estimated using the modal strain energy method in conjunction with the finite element method. The estimated damping ratios of a 1/2.5 scaled model are verified by experiments. The viscoelastic dampers provide a very efficient way to increase the damping and survivability for buildings under earthquake excitations.

REFERENCES

Aiken, I. D., Kelly, J. M. and Mahmoodi, P. (1990). "The Application of Viscoelastic Dampers to Seismicity Resistant Structures." *Proc. 4th National Conf. on Earthquake Engineering,* Vol. 3, pp. 459-468, May 20-24, 1990, Palm Spring, CA.

ATC-15-3 (1990). *Four*th U.S.-Japan Workshop on the Improvement of Building Structural Design Practices, August 27-29, 1990. Kona, Hawaii.

ATC-17 (1986). Base Isolation and Passive Energy Dissipation. March 12-14, 1986. San Francisco, CA.

Johnson, C. D. and Kienholz, D. A. (1982). "Finite Element Prediction of Damping in Structures with Constrained Viscoelastic Layers." *AIAA Journal.* Vol. 20, No. 9, pp. 1284-1290.

Keel, C. J. and Mahmoodi, P. (1986). "Design of Viscoelastic Dampers for Columbia Center Building." *ASCE Structural Division, Building Motion in Wind,* Edited by N. Isyumov and T. Tschanz, pp. 66-82.

Lin, R. C., Liang, Z., Soong, T. T., and Zhang, R. H. (1991). "An Experimental Study of Seismic Structural Response with Added Viscoelastic Dampers." *Engineering Structures,* Vol. 13, No. 1, pp. 75-84.

Mahmoodi, P. (1969). "Structural Dampers." *Journal of Structural Division, ASCE,* 95, 1661-1972.

Soong, T. T. and Mahmoodi, P. (1990). "Seismic Behavior of Structures with Added Viscoelastic Dampers." *Proc. 4th National Conf. on Earthquake Engineering,* Vol. 3, pp. 499-506, May 20-24, 1990, Palm Spring, CA.

Ungar, E. E. and Kerwin, E. M., Jr. (1962). "Loss Factor of Viscoelastic Systems in Terms of Energy Concepts." *Journal of the Acoustical Society of America*, 34(7), 954-957.

Zhang, R. H., Soong, T. T. and Mahmoodi, P. (1989). "Seismic Response of Steel Frame Structures with Added Viscoelastic Dampers." *Earthquake Engineering and Structural Dynamics*, 18, 389-396.

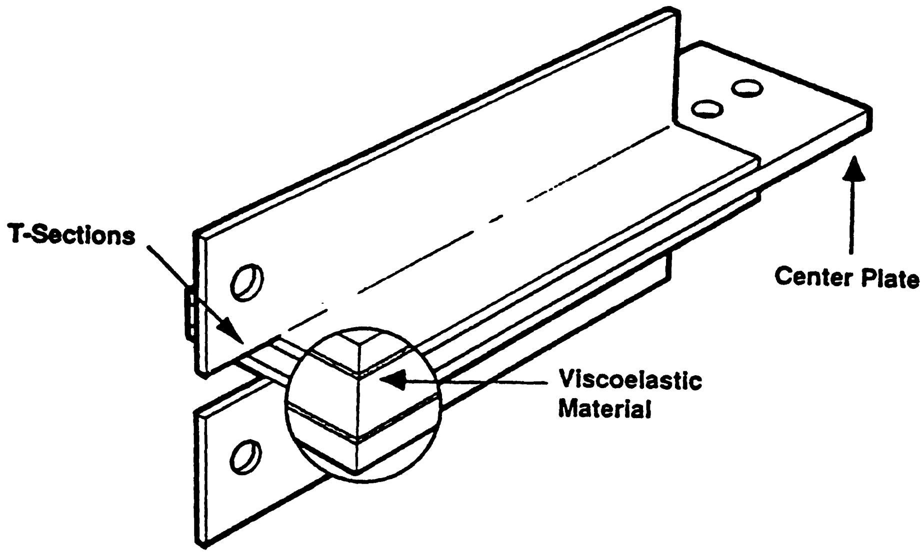

Fig. 1a A typical Viscoelastic Damper.

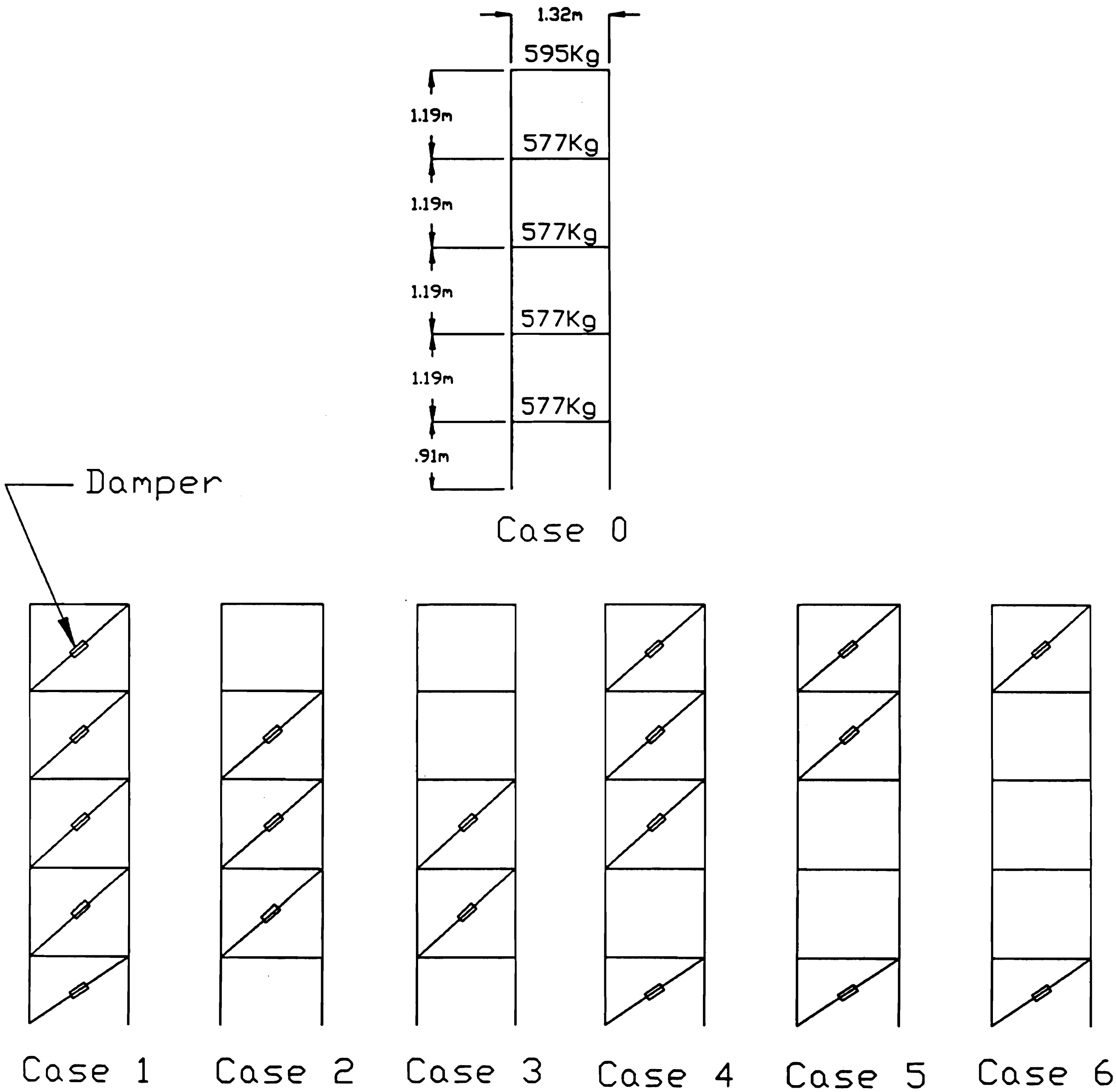

Fig. 1b **A 1/2.5 scaled structure with and without viscoelastic dampers installed.**

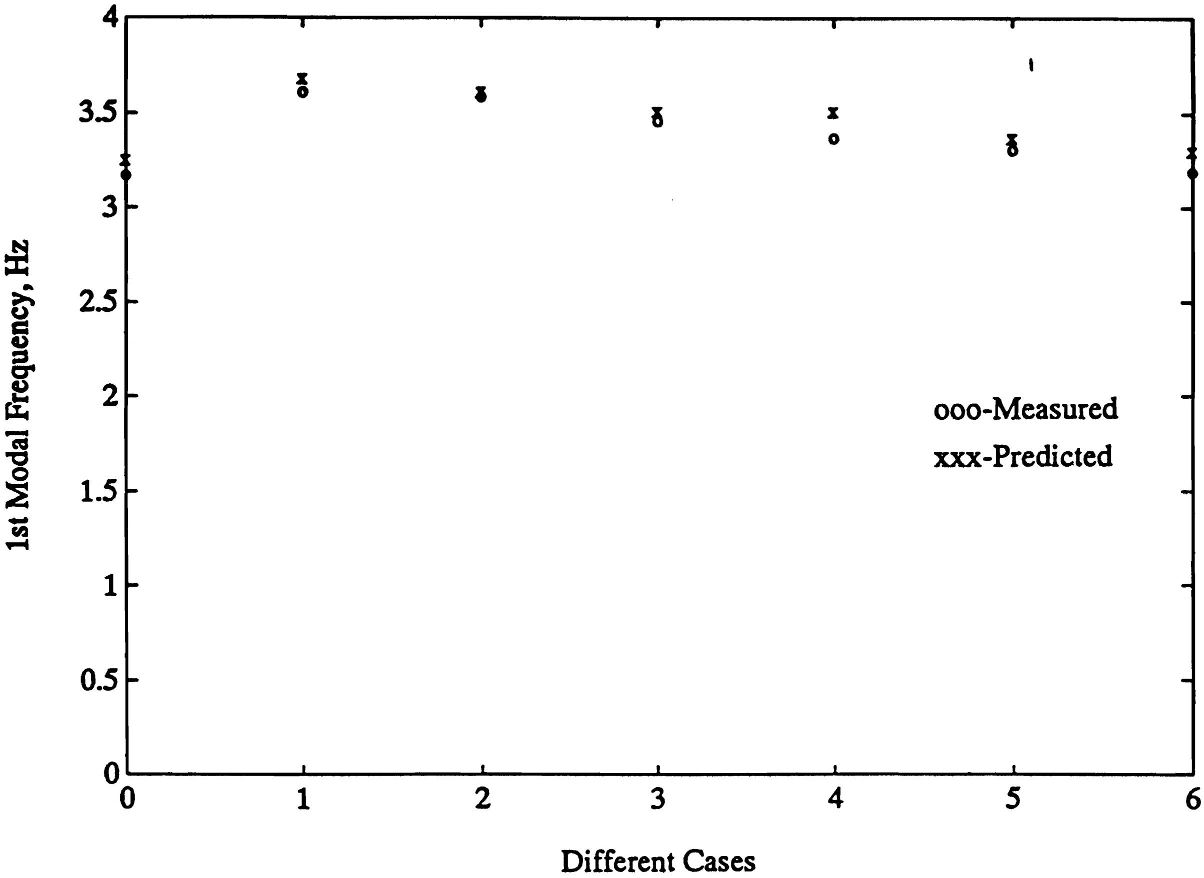

Fig. 2 Measured and Predicted 1st Modal Frequencies for All Cases.

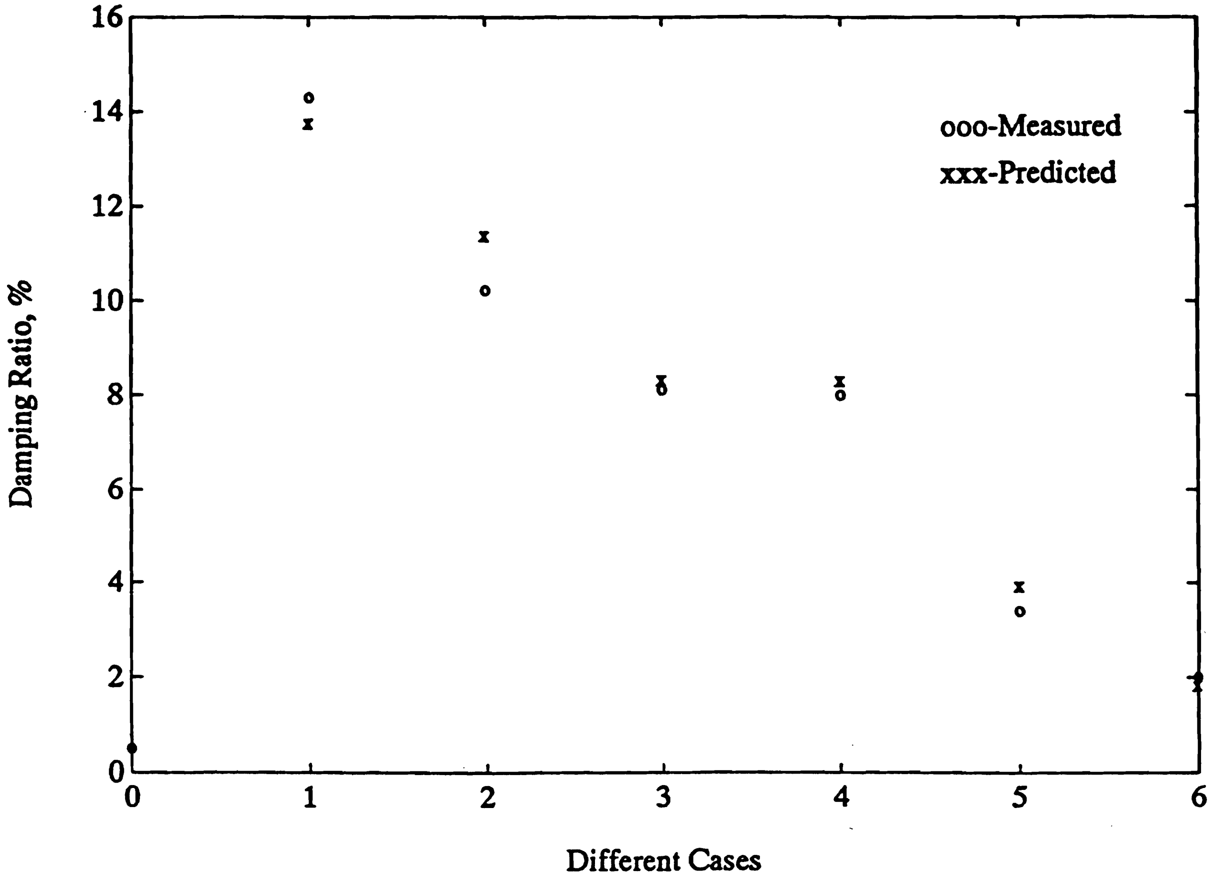

Fig. 3 Measured and Predicted 1st Modal Damping Ratios for All Cases.