Seismic Applications of Viscoelastic Dampers

by Tsu T. Soong

Abstract

The application of viscoelastic materials to vibration control can be dated back to the 1950's, when they were first used on aircrafts as a means of controlling vibration-induced fatigue in airframes. Its application to civil engineering structures appears to have begun in 1969 when 10,000 viscoelastic dampers were installed in each of the twin towers of the World Trade Center in New York to help resist wind loads The major objective of this research project was to investigate the feasibility of using viscoelastic dampers in structures to protect against seismic loads. For seismic applications, larger damping is usually required in comparison with that required for mitigation of wind-induced vibrations. Furthermore, energy input into the structure is usually spread over a wider frequency range, requiring more effective use of the viscoelastic materials

Both steel and concrete structures were considered in this program. Extensive analytical and experimental investigations have led to the development of a design strategy for incorporating viscoelastic dampers into steel-frame structures. In turn, they have led to the first seismic upgrade of an existing steel frame building using viscoelastic dampers in the United States in 1993. Significant progress has also been made in the quantification of the influence of viscous and elastic stiffness properties of dampers during the inelastic response of reinforced concrete structures. Furthermore, it has been shown that a design procedure for viscoelastic dampers as applied to concrete structures can be formulated similar to that developed for steel frame structures.

Collaboration

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Objectives and Approach

The objective of this research project was to investigate the feasibility of applying viscoelastic dampers to structures to protect against seismic loads, and to develop design guidelines for their use in both new and existing structures.

The approach to this research was to develop analytical and simulation procedures to assess the effects of adding viscoelastic dampers to steel and concrete structures under seismic loads, and institute a comprehensive experimental program involving a variety of structures ranging from simple structural models to full-scale structures.

This research task is part of NCEER's Building Project. Task numbers are 90-2107, 91-5131, 92-5202, and 93-5111.

Accomplishments

Steel-Frame Structures

Following extensive analytical studies, a comprehensive test program was designed and carried out involving experimental studies of the viscoelastic damper properties as functions of strain, excitation frequency, and ambient temperature. Structural tests with added viscoelastic dampers were conducted on a variety of structural models. They included a 1/4-scale nine-story model at the University of California at Berkeley, a 1/4-scale, three-story and 2/5-scale, five-story model at the University at Buffalo, and a full-scale version of the 2/5-scale University at Buffalo model at Beijing Polytechnic University.

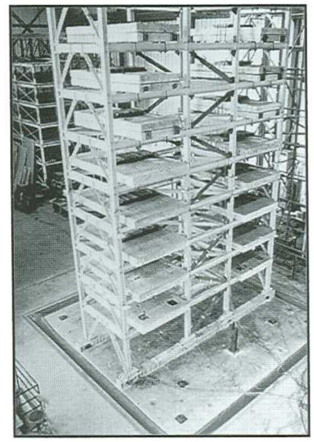


Figure 1
Nine-story 1/4-scale Model Test

Viscoelastic dampers were tested on a nine-story, three-bay, 1/4-scale model structure (figure 1) at the University of California (Aiken et al., 1990). These dampers were tested with thirty earthquake events using eight different simulated earthquake signals. For all of the earthquake tests, the structural response (both acceleration and displacement) was reduced compared to the moment-frame response. In some cases, the dampers reduced the structural accelerations by as much as one half, and simultaneously reduced the interstory drifts by a similar level. Thermocouples embedded in the viscoelastic material illustrated a temperature rise of about 10°F for the 150 El Centro earthquake event. Temperature decreased relatively rapidly after the earthquake test was completed.

The effect of ambient temperature on damper performance was evaluated on a five-story 2/5-scale model steel structure (figure 2) at the University at Buffalo (Chang et al., 1992). Structural response results as shown in figure 3 show that even at high temperatures, the viscoelastically damped structure can achieve a significant reduction of structural response as compared to the case with no added dampers. Testing at strong earthquake ground motion,

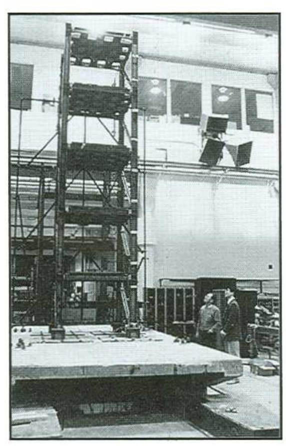
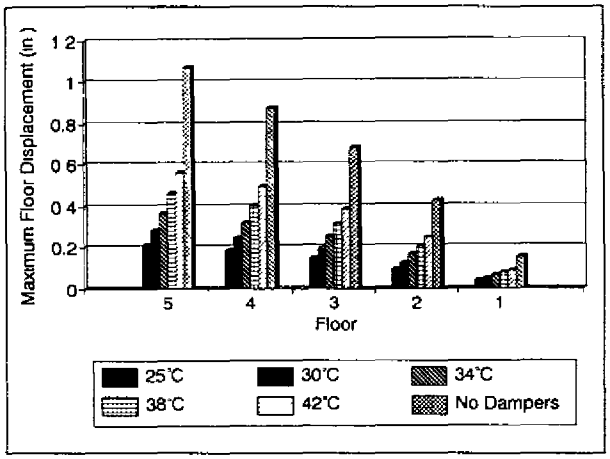
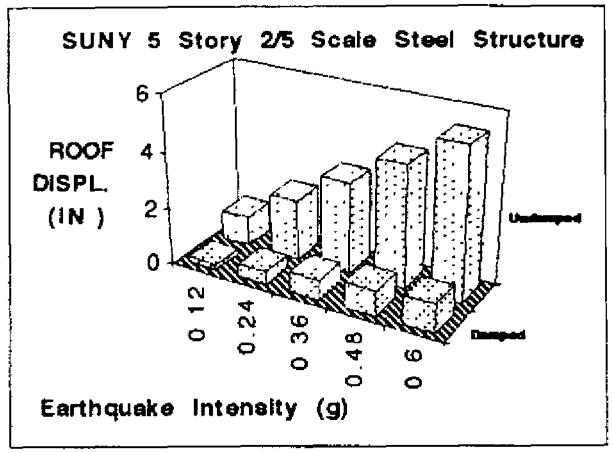


Figure 2
Five-story 2/5-scale Model Test



■ **Figure 3**
Damper Effectiveness - Maximum Floor Displacements

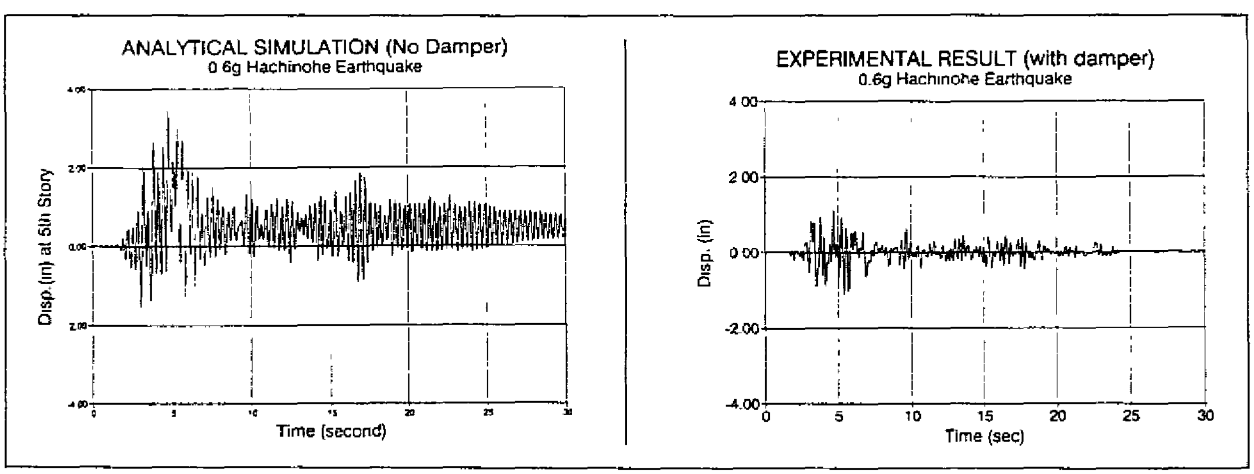


■ **Figure 5**
Relative Displacement at Roof

0.6g Hachinohe (figure 4), demonstrated that structural response is significantly reduced and remains elastic with viscoelastic dampers as compared to inelastic deformation from analytical simulation without dampers (Oh et al., 1992). Testing demonstrated that viscoelastic dampers are effective for strong, moderate and small earthquake ground motions (figure 5).The modal strain energy method for damper design was shown to be simple and reliable.The seismic response of a viscoelastically damped structure can be predicted using the conventional linear dynamic approach. On the basis of the above studies, a design procedure for viscoelastically damped structures was developed and is summarized in figure 6 in the form of a flow chart (Chang et al., 1993).

A full scale version of the 2/5 University at Buffalo model was tested in Beijing, China (figure 7) using a large vibration generator to excite the structure. The results showed the modal strain energy method provided comparable results for both the model and the full scale structures.

As mentioned earlier, a seismic upgrade project using viscoelastic dampers is currently underway for the 13-story Santa Clara County building located in San Jose, California. As shown in figure 8, it is approximately 64 meters in height and nearly square in plan, with 51m x 51m on



■ **Figure 4**
Analytical Simulation (No Damper, left)and Experimental Result (With Dampers, right)

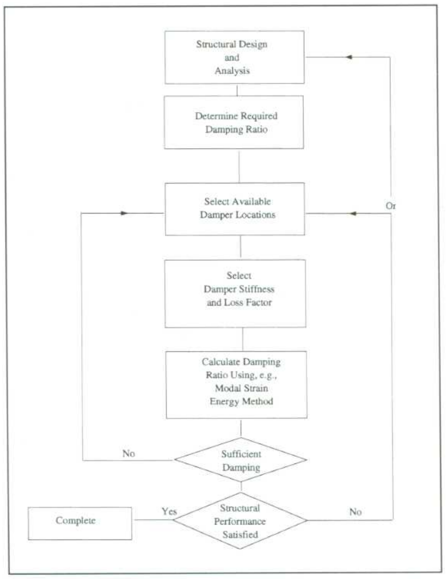


Figure 6
VE Damper Design Flow Chart

typical upper floors. The exterior cladding consists of full-height glazing on two sides and metal siding on the other two sides. The exterior cladding, however, provides little resistance to structural drift. The equivalent viscous damping in the fundamental mode is less than 1% of critical.

The building has been extensively instrumented, and useful data has been obtained during a number of recent small to moderate earthquakes. A plan for seismic upgrade of the building was developed, in part, when the response data indicated large and long-duration motion, including torsional coupling, during even moderate earthquakes.

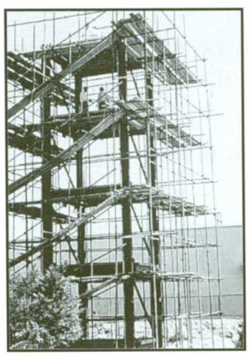


Figure 7
Full-scale Structural Test

Figure 8
Santa Clara County Building

The final design called for installation of two dampers per building face per floor level, which would increase the equivalent damping in the fundamental mode of the building to about 17% of critical, providing substantial reductions to building response under all levels of ground shaking (Crosby et al., 1994). The dampers are now being fabricated by the 3M Company.

Reinforced Concrete Structures

The seismic response of a reinforced concrete structure is by and large inelastic, which is often accompanied by permanent deformation and damage. The addition of viscoelastic dampers in this case can dissipate energy at the early stages of cracking of the concrete elements and reduce the development of damage. With proper selection of dampers, this damage can be substantially reduced or even eliminated. The quantification of the influence of viscous and elastic stiffness properties of dampers during the inelastic response of reinforced concrete structures was the subject of several analytical and experimental investigations.

A one-third scale model of a three-story lightly reinforced concrete framed building was tested under simulated base motions using a shaking table (Lobo et al., 1993; Chang et al., 1994). The structure was tested using a series of simulated

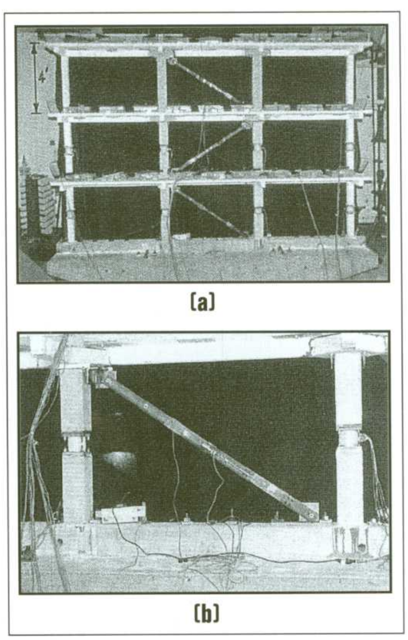


Figure 9
Details of R/C Model with VE dampers

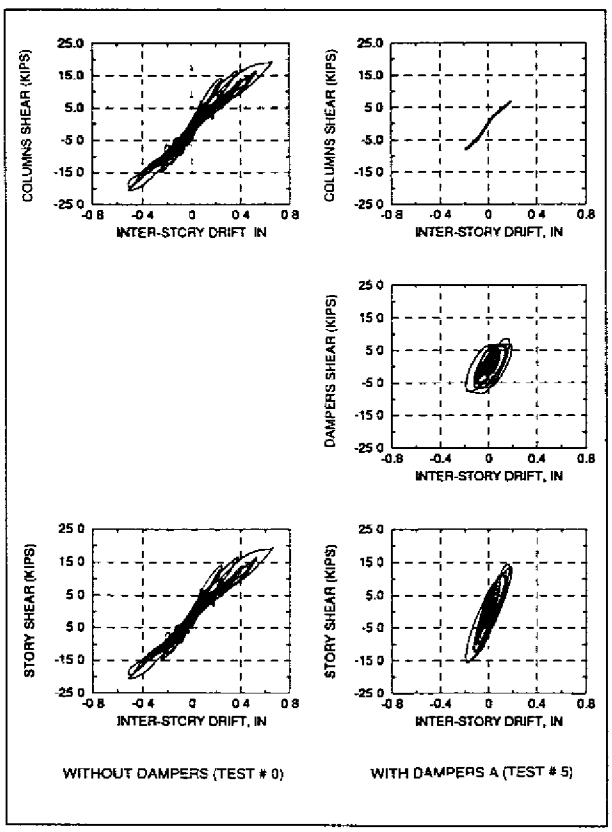
	Interstory Drifts (in)			Column Story Shears (kips)		
	First	Second	Third	First	Second	Third
Without Dampers	0.656	0.388	0.167	20.63	16.20	10.71
With Dampers	0.194	0.147	0.066	7.68	5.71	4.19

■ Table 1
Maximum Measured Story Response for 0.2g Taft Excitation

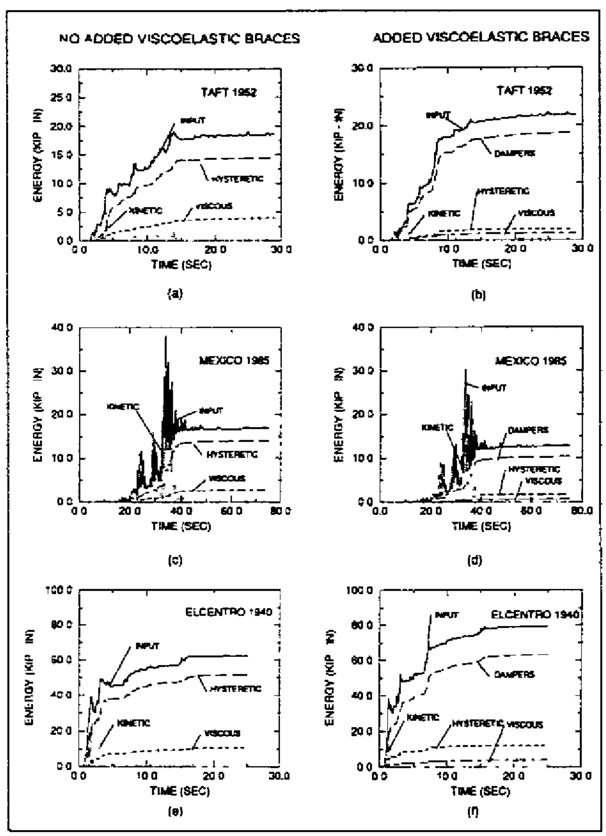
The interstory drifts and story shears in the columns are substantially reduced at all floors as indicated in table 1. The deformations are reduced approximately three times, while the shear forces are reduced twice. These forces are much smaller than the ultimate strength of the columns, moreover, they are smaller than their yielding strengths. A sample set of force-deformations at the first floor as shown in figure 10 indicates that the column forces and deformations are substantially reduced, while most of the energy dissipation (area of hysteretic loops) is transferred from the columns to the viscoelastic dampers Although some inelastic deformations are experienced by the columns in the presence of the viscoelastic braces, the column response is substantially improved.

ground motions obtained from the scaled 1952 Taft earthquake, N21E component, normalized for peak ground accelerations of 0.05g, 0.20g, and 0.30g, representing minor, moderate, and severe ground motions. The structure was strengthened by adding viscoelastic diagonal braces in the interior bay of each frame as shown in figure 9.

Some selected experimental results under the 0 2g Taft earthquake are summarized here for one type of dampers tested from the viewpoint of energy dissipation.



■ Figure 10
Force-deformation Curves Under 0.2g Taft Earthquakes



■ Figure 11
Contribution of Energy Terms

The viscoelastic dampers alter the overall energy balance as shown in figure 11. For the 0.2g Taft earthquake used in the experiment (figures 11a-11b), the added VE dampers dissipate a majority of the input energy, leaving only a small amount of hysteretic energy to be dissipated by the structural members. Similar energy calculations under some other earthquakes are also given in figure 11, showing that the overall energy input may vary depending on the match between the structural frequencies and the earthquake frequency content.

These experimental results verify analytical predictions of the performance of viscoelastic dampers installed in reinforced concrete frames and show great potential for applying this technology to seismic strengthening of reinforced concrete structures.

A multi-phase study at the University of Illinois and the Army Corp. of Engineers - Construction Engineering Research Laboratory (CERL) began on 6/10-scale lightly reinforced models simulating the construction of nonductile concrete military structures built prior to the 1970s. For Phase I, two identical simple column/beam/slab models were constructed and tested on the CERL shaking table. One of the two models was tested to failure without dampers. The second model was then tested with dampers under the same conditions as the first model. The model with dampers resisted the same load magnitudes with minor cracks as compared to the model without dampers, which experienced brittle failure (Foutch, et al , 1993). This study demonstrated the ability of dampers to absorb significant amount of energy and reduce concrete cracking. These results were further verified during Phase II testing of the three-story, three-bay, 1/3-scale nonductile concrete structure in 1994 at the Army Corp. of Engineers - Construction Engineering Research Laboratory.

Technical References

Aiken, I.D., Kelly, J.M and Mahmoodi, P., "The Application of Viscoelastic Dampers to Seismically Resistant Structures," Proceedings, Fourth U.S. National Conference on Earthquake Engineering, Palm Springs, California, 1990.

Chang, K.C., Soong, T.T, Oh, S-T and Lai, M.L. Effect of Ambient Temperature on Viscoelastically Damped Structures," ASCE Journal of Structural Engineering, Vol 118, No 7, 1992, pp. 1955-1973

Chang, K.C , Soong, T.T., Lai, M.L., and Nielsen, E J., "Development of a Design Procedure for Structures with Added Viscoelastic Dampers," Proceedings, ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control, San Francisco, California, 1993.

Chang, K.C , Lai, M L., Soong, T.T., Hao, D.S. and Yeh, Y.C., "Seismic Behavior and Design Guidelines for Steel Frame Structures with Added Viscoelastic Dampers," Technical Report NCEER-93-0009, National Center for Earthquake Engineering Research, University at Buffalo, May 1, 1993.

Chang, K C., Shen, K., Soong, T.T., and Lai, M.L., "Seismic Retrofit of a Reinforced Concrete Frame with Added Viscoelastic Dampers," Proceedings, Fifth National Conference on Earthquake Engineering, Chicago, Ilinois, 1994.

Crosby, P., Kelly, J M., and Singh, J , "Utilizing Viscoelastic Dampers in the Seismic Retrofit of a Thirteen Story Steel Framed Building," Proceedings, Structures Congress XII, Atlanta, Georgia, 1994

Foutch, D.A., Wood, S.L., and Brady, P.A., "Seismic Retrofit of Non-ductile Reinforced Concrete Frames Using Viscoelastic Dampers," Proceedings, ATC-17-1 Seminar Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control, San Francisco, California, April 5, 1993.

Lobo, R.F., Bracci, J.M , Shen, K L., Reinhorn, A.M., Soong, T.T., "Inelastic Response of R/C Structures with Viscoelastic Braces," Technical Report NCEER-93-0006, National Center for Earthquake Engineering Research, University at Buffalo, April 5, 1993.

Oh, S-T., Chang, K.C., Lai, M.L., and Nielsen, E.J., "Seismic Response of Viscoelastically Damped Structure under Strong Earthquake Ground Motions," Proceedings, 10th World Conference on Earthquake Engineering, Madrid, Spain, 1992.

Publications

Journal Papers

Zhang, R.H., Soong, T.T., and Mahmoodi, P., "Seismic Response of Steel Frame Structures with Added Viscoelastic Dampers," Journal of Earthquake Engineering Structural Dynamics, Vol. 18, No. 3, 1989, pp. 389-396.

Lin R.C , Soong, T.T., et al., "An Experimental Study of Seismic Behavior of Viscoelastically Damped Structures," Engineering Structures, Vol 13, No. 1, 1991, pp 75-84.

Zhang, R.H. and Soong, T.T., "Seismic Design of Viscoelastic Dampers for Structural Applications," ASCE Journal of Structural Engineering, Vol 118, No 5, 1992, pp. 1375-1392.

Chang, K.C., Soong, T.T., et al., "Effect of Ambient Temperature on a Viscoelastically Damped Structure," ASCE Journal of Structural Engineering. Vol 118. No. 7, 1992, pp. 1955-1973.

Chang, K.C., Soong, T.T., et al., "Viscoelastic Dampers as Energy Dissipation Devices for Seismic Applications," Earthquake Spectra, Vol. 9, No. 3, 1993, pp. 371-388

Lobo, R.F., Bracci, J.M., Shen, K.L., Reinhorn, A.M. and Soong, T.T., "Inelastic Response of R/C Structures with Viscoelastic Braces," Earthquake Spectra, Vol 9, No. 3, 1993, pp. 419-446.

NCEER Reports

Lin, R.C., Liang, Z., Soong, T.T., and Zhang, R.H., "An Experimental Study of Seismic Structural Response with Added Viscoelastic Dampers," Technical Report NCEER-88-0018, National Center for Earthquake Engineering Research, University at Buffalo, June 30, 1988.

Bracci, J.M., Reinhorn, A.M., Mander, J.B., and Kunnath, S K., "Deterministic Model for Seismic Damage Evaluation of Reinforced Concrete Structures," Technical Report NCEER-89-0033, National Center for Earthquake Engineering Research, University at Buffalo, September 27, 1989.

Chang, K.C., Soong, T.T., Oh, S-T, and Lai, M.L., "Seismic Response of a 2/5 Scale Steel Structure with Added Viscoelastic Dampers," Technical Report NCEER-91-0012, National Center for Earthquake Engineering Research, University at Buffalo, May 17, 1991

Lobo, R.F, Bracci, J.M , Shen, K L., Reinhorn, A.M., and Soong, T.T, "Inelastic Response of R/C Structures with Added Viscoelatic Braces," Technical Report NCEER-93-0006, National Center for Earthquake Engineering Research, University at Buffalo, April 12, 1993

Chang, K.C., Lai, M.L., Soong, T.T, Hao, D S , and Yeh, Y.C., "Seismic Behavior and Design Guidelines for Steel Frame Structures with Added Viscoelastic Dampers," Technical Report NCEER-93-0009, National Center for Earthquake Engineering Research, University at Buffalo, May 1, 1993.