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Seismic response of steel-frame structures with added viscoelastic dampers

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ABSTRACT: Seismic response characteristics of a 2/5-scale steel frame structure with added viscoelastic dampers are studied experimentally. The major emphasis is placed on the ambient temperature effect. Results 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 dampers added.

The design of viscoelastic dampers by taking into account the ambient temperature is addressed. Numerical simulations on equivalent structural damping and structural response under various ambient temperatures are carried out. It is demonstrated that the dynamic behavior of structures with added viscoelastic dampers can be satisfactorily predicted by conventional analytical tools.

1 INTRODUCTION

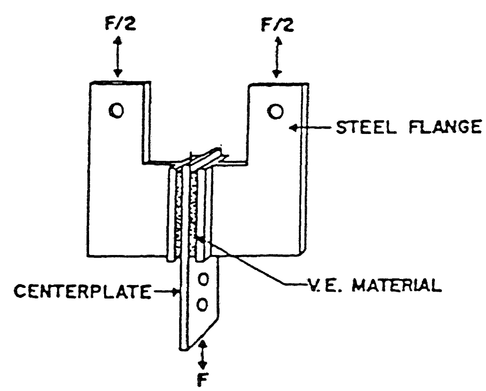
Earthquake resistant design and retrofit of moment resisting steel frames using energy absorption devices has received considerable attention in recent years. Among the available devices, viscoelastic dampers have shown to be capable of providing structures with added damping to dissipate energy resulting from severe earthquake ground motions.

Viscoelastic dampers are normally made of viscoelastic layers bonded with steel plates placed under direct shear to dissipate the dynamic input energy. When added to a structure, experimental studies have shown that, while they can be effective in attenuating seismic response of the structure, their proper design for maximum efficiency must take into account important factors such as excitation frequencies and the environmental temperature within which they operate (Lin et al. 1991; Aiken et al. 1990).

This paper is concerned with experimental investigations on the dynamic characteristics of viscoelastic dampers and on the seismic response of a viscoelastically damped 2/5-scale five-story steel-frame structure under precisely controlled ambient temperatures. Based on test results of individual viscoelastic dampers, empirical formulae on dynamic damper properties as functions of excitation frequency, ambient temperature, and strain range, are derived. Based on these equations, numerical studies on the prediction of equivalent structural damping and on the simulation of dynamic structural response under earthquake excitations are carried out.

2 PROPERTIES OF VISCOELASTIC DAMPERS

Damper property tests were carried out using an MTS axial-torsional testing system. The damper (Figure 1), with an area of 1.5 in^2 and a thickness of 0.2 in, was studied under six different ambient temperatures (21°C, 24°C, 28°C, 32°C, 36°C and 40°C). At each temperature, six tests were conducted at frequencies of 0.1, 1.0, 2.0, 3.0, 3.5 and 4.0 Hz, respectively, for up to twenty cycles of deformation in three different



(A = 1.5 in^2, THICKNESS = 0.2 in)

Figure 1. Viscoelastic Damper

strain ranges (5%, 20% and 50%). A typical force-deformation relationship of the damper (20% strain) at the temperature of 24°C subjected to an excitation frequency of 1.0 Hz is given in Figure 2.

An examination of the test results (Chang et al. 1991) show that, while vibration frequency and ambient temperature play important roles in the dynamic characteristics of the VE dampers, the effect of deformation is less significant for the strain ranges applied in this study (< 50%). In order to consider all the factors which affect the properties of viscoelastic dampers in the design, empirical formulae for the damper stiffness and the loss factor based on regression analysis using the data obtained from damper tests are as follows:

$$k = e^{14.78}(\omega)^{0.69}(T)^{-2.26} \quad (1)$$

and

$$\eta = e^{0.85}(\omega)^{-0.27}(T)^{-0.12} \quad (2)$$

where k = stiffness of the damper (Kip/in), ω = frequency (Hz), T = ambient temperature (°C), and η = damper loss factor.

The above formulae were derived based on the average of the first twenty cycles of damper deformation with an average strain of 5% for the frequency range (3 Hz-4 Hz) used in this study, which is considered to be reasonable during a typical medium size earthquake.

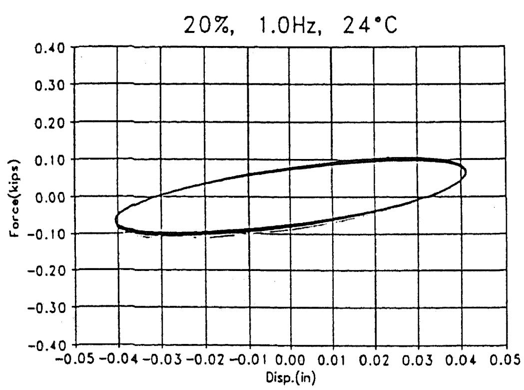


Figure 2. Force-Deformation Relationship of Damper

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″ in plane and 224.0″ 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 for the first four floors and 1.12 kips 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 viscoelastic dampers are connected by bolts to the gusset plates welded to the girders. Each set of bracing is composed of two $L1\frac{1}{2} \times 1\frac{1}{2} \times \frac{1}{8}$ double angles with a viscoelastic 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 viscoelastic dampers under accurately controlled ambient temperatures. 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 at high temperatures.

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. Figures 3a and 3b show the temperature dependence of the first natural frequency and structural damping, respectively, of the test structure under five controlled ambient temperatures. Also shown in these figures are the corresponding values of the structure without added viscoelastic dampers. These two figures indicate that, while structural damping increases significantly with the addition of viscoelastic dampers, both the natural frequency and damping ratio of the structure become smaller under higher ambient temperatures. This can be realized from the results of damper tests that the stiffness and energy dissipation capacity of viscoelastic dampers decrease as a result of rising ambient temperature.

Figures 4a-4c show the response envelopes of the test structure with and without added dampers at five different ambient temperatures under 0.12g Hachinohe earthquake. The influence of ambient temperature on seismic responses can be easily visualized by comparing the envelope values at each floor level. It can be concluded that the addition of viscoelastic dampers effectively reduce maximum floor accelerations, floor displacements and inter-story drifts under seismic excitations. The damper efficiency decreases

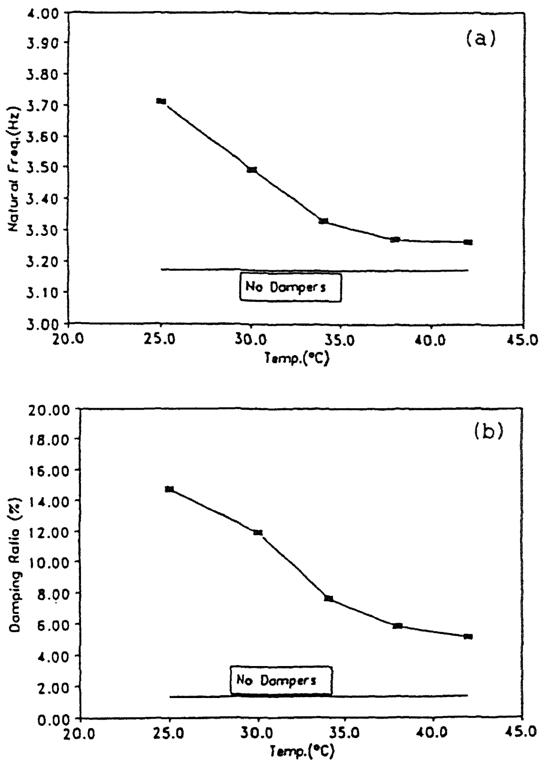


Figure 3. Ambient Temperature Dependence of Structural Dynamic Characteristics. (a) Natural Frequency, (b) Damping Ratio

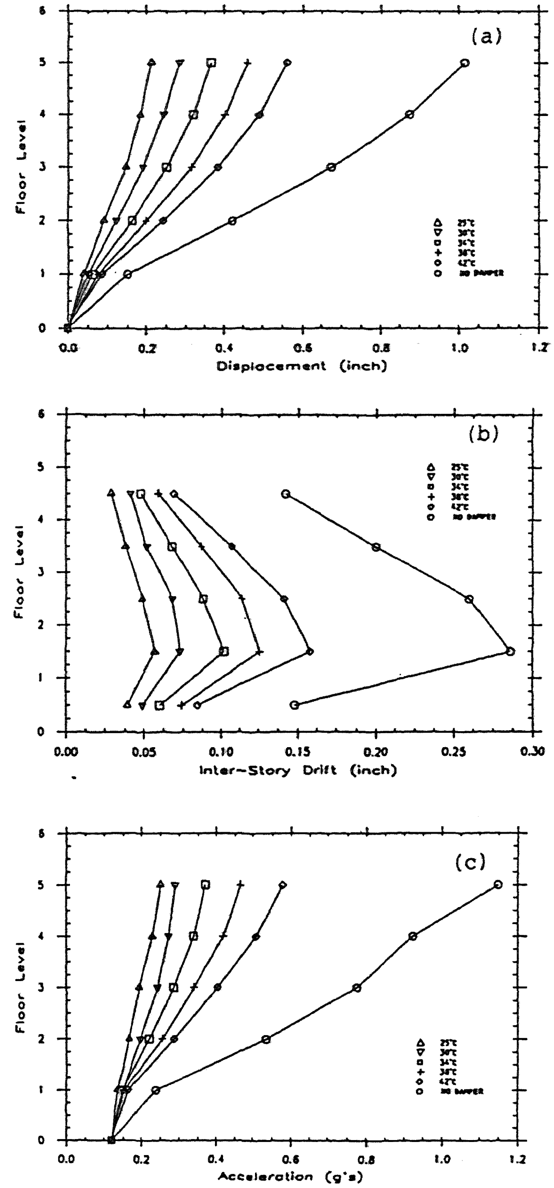


Figure 4. Envelopes of Structural Response at Different Ambient Temperatures under 0.12g Hachinohe Earthquake. (a) Relative Displacement, (b) Inter-Story Drift, (c) Floor Acceleration

as the ambient temperature rises. This is partially due to the softening in damper material. In addition, deformation of the viscoelastic dampers also increases with increasing temperature. However, even at the highest temperature tested (42°C), the viscoelastically damped structure can still achieve a significant reduction of the structural response as compared to the structure without dampers.

4 ANALYTICAL SIMULATIONS

4.1 *Estimation of equivalent structural damping*

Viscoelastically damped structures dissipate seismic input energy through extra damping provided by the added viscoelastic 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 (Zhang et al, 1989), by assuming a proportionally damped system, the resultant damping ratio for the ith mode of vibration of the structure with added dampers can be expressed as

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

where ξ_i = structural damping ratio for the ith vibration mode, E_d^i = energy dissipated by the dampers for the ith vibration mode, and E^i = maximum strain energy of the structure of the ith vibration mode.

The above equation can also be expressed in terms of modal strain energy as (Soong and Lai, 1991; Johnson and Kienholz, 1982)

$$\xi_i = \frac{\eta}{2} \frac{\Phi_i^T K_d \Phi_i}{\Phi_i^T K_s \Phi_i} \quad (4)$$

where Φ_i = ith modal shape vector, K_d = structural stiffness matrix due to the contribution of dampers alone, K_s = structural stiffness matrix including the contribution of dampers, and η = loss factor of the viscoelastic damper.

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.

Figures 5a and 5b show the comparisons between the experimental and the predicted natural frequencies and the structural damping, respectively, under various ambient temperatures. As can be seen, the natural frequency and equivalent structural damping of the viscoelastically damped structure under various ambient temperatures can be satisfactorily predicted using the modal strain energy method.

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 various ambient temperatures were carried out and the damping ratios predicted in Figure 5b were used in the analysis. It was observed that the numerical simulations agree very well with the experimental results at varying temperatures.

5 SUMMARY AND CONCLUSIONS

Experimental studies on the dynamic properties of viscoelastic dampers and on the seismic behavior of a viscoelastically damped 2/5-scale five-story steel-frame model structure have been carried out under precisely controlled ambient temperatures between 25°C and 42°C.

Test results show that viscoelastic dampers are very effective in reducing excessive vibration of the test structure due to seismic excitations. At 25°C, the dampers can achieve a reduction of about 80% of the maximum floor acceleration, maximum story drifts and maximum lateral displacements of the test structure without added dampers. With increasing ambient temperature, however, the viscoelastic material softens and the effectiveness of the dampers decreases. However, even at 42°C, the dampers can still reduce the structural response by more than 40%.

Empirical equations for estimating the stiffness and loss factor of the viscoelastic dampers used in this study were established based on regression analysis using data obtained from component tests of the dampers. These equations can adequately estimate the dynamic properties of the dampers under various ambient temperatures, excitation frequencies and deformations. Numerical predictions on structural damping under various ambient temperatures were carried out using the modal strain energy method and the aforementioned empirical formulae. Numerical results show that structural damping with added dampers can be satisfactorily estimated by the modal strain energy method.

Numerical simulations using conventional modal analysis methods were also carried out to predict the dynamic response of viscoelastically damped structures under seismic excitations. Comparison between numerical simulation and test results shows 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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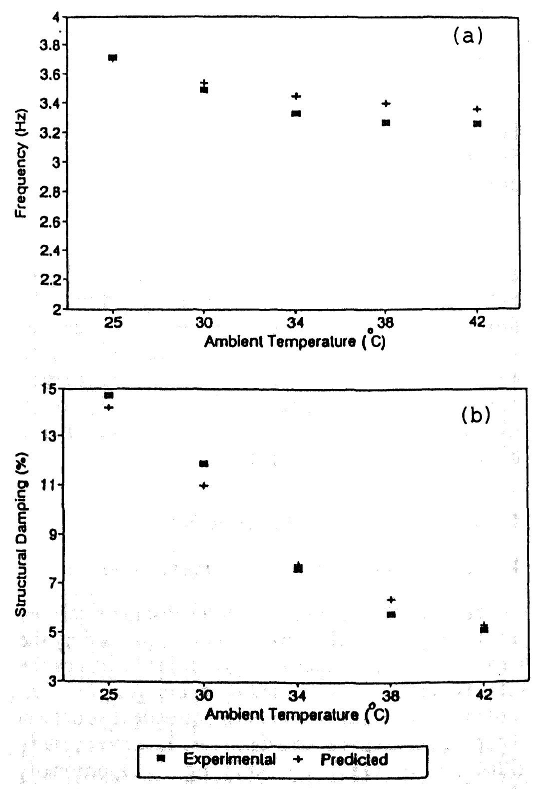

Figure 5. Experimental vs. Predicted Structural Dynamic Properties Using Modal Strain Energy Method. (a) Natural Frequency, (b) Equivalent Structural Damping

in this study were designed and denoted by the 3M Company, St. Paul, Minnesota.

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