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Damping of Frame Structures: An Educational Shake Table Test

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Summary

This paper describes an experimental study on the effects of viscous damping walls on structures. The experimental tests were performed using an instructional shake table developed by the University Consortium on Instructional Shake Tables (UCIST). A simple model of a viscous wall, created using a Plexiglas container and a steel blade, was attached to a building model. The container was filled with different liquids and the structure-wall system was subjected to free-vibration excitation. In order to increase the damping provided by the wall, fins were added at the bottom of the steel blade. The damping coefficient, the logarithmic decrement and the structural period of the building-wall model were obtained for the original and the modified wall (i.e., before and after adding the fins) and for the different viscous fluids used to fill the wall container. Results indicate that a fluid with higher viscosity and a smaller gap between the container and the blade increase the effectiveness of the viscous wall to dissipate energy.

Introduction

Although nothing can be done to prevent earthquakes, precautions can be taken to mitigate their destructive effects. In order to reduce damage caused by seismic events, civil engineers incorporate a variety of technologies into structures. Many techniques can be used either individually or in combination to reduce external forces and to control deformations caused by earthquakes.

An available seismic protection method consists of incorporating any of several types of energy dissipation devices. Friction dampers have moving parts that slide over each other to create friction, which is used to dissipate the seismic energy (Li and Reinhorn 1995). Metallic dampers dissipate energy through plastic deformation of metal elements (MCEER Information Service 2001). Viscous dampers are hydraulic devices that dissipate energy when a fluid is forced to pass through an orifice (Constantinou 1994).

Damping is the process by which vibration steadily decreases its amplitude (Chopra 1995). It occurs when the kinetic and strain energy of the vibrating system are dissipated by various mechanisms such as heat and friction. Figure 1 displays the displacement response of undamped and damped structures. The undamped structure keeps oscillating forever with the same amplitude and period, while the vibration amplitude of the damped structure gradually decays with time. The motion of most freely oscillating systems eventually dies out and reduces to zero with time. Free vibration occurs when a structure is disturbed from its static equilibrium and is then allowed to vibrate without the interference of external forces (Chopra 1995).

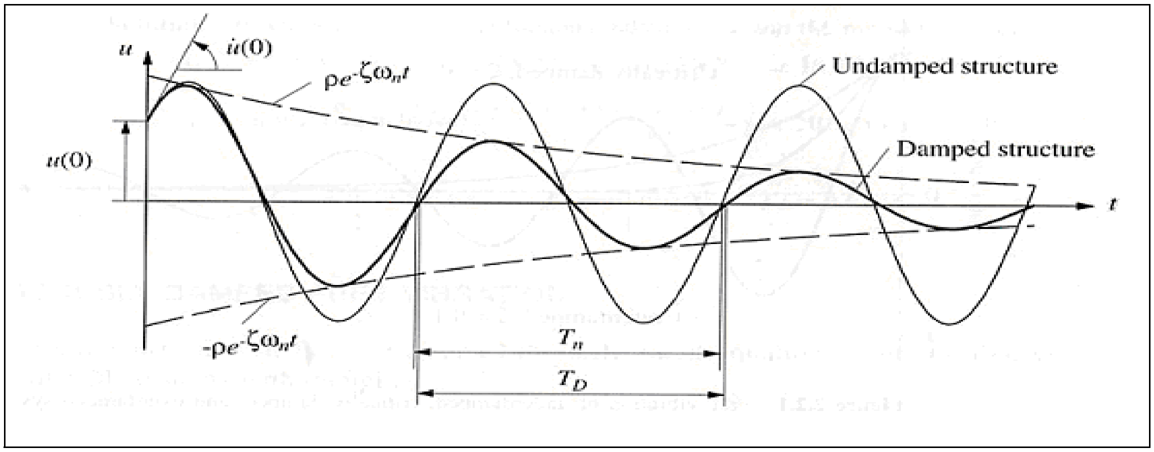


Figure 1. Effects of damping on free vibration (Chopra 1995)

Also illustrated in Figure 1 are the so-called envelope curves (dotted lines). They touch the displacement-time curve at points slightly to the right of its peak values (Chopra 1995). The equation $\pm \rho e^{-\zeta\omega_n t}$ denotes the decay for the envelope curves. The natural period T of the system can be determined from the displacement-time plot by measuring the time required to complete one cycle of vibration.

The rate at which the motion decays in free vibration is controlled by the damping ratio ζ, which is a dimensionless measure of damping expressed as a percentage of the critical damping. Figure 2 displays the free-vibration response of several systems with varying levels of damping ratios. It can be observed that the amplitude of the vibration decays more rapidly as the value of the damping ratio increases.

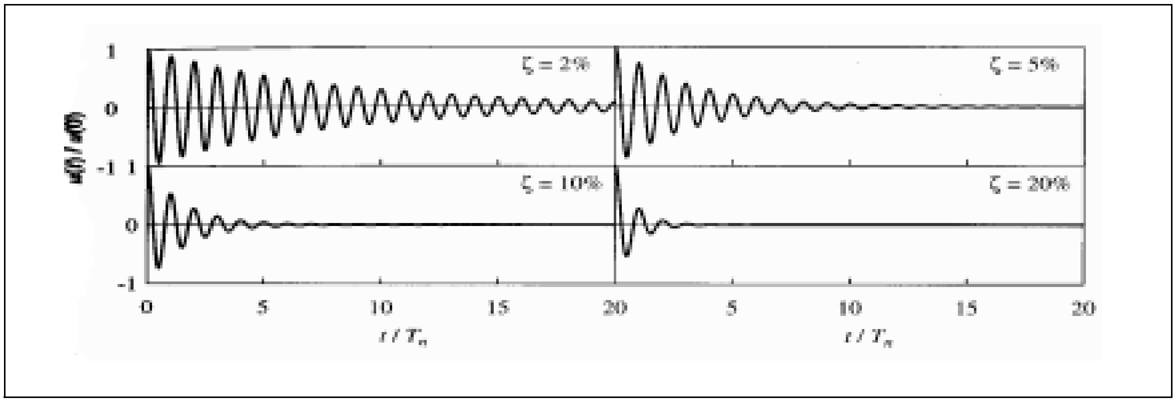


Figure 2. Free vibration of systems with different levels of damping (Chopra 1995)

The logarithmic decrement δ is a measure of the mechanical damping (Chopra 1995). It is calculated from the natural logarithm of the ratio of the amplitudes of any two oscillations (u_i and u_{i+j}) and is directly correlated to the damping ratio:

$$\delta = \ln \frac{u_i}{u_{i+j}} = 2\,\pi\,\zeta \qquad (1)$$

Background

The research project described in this paper is based on previous studies by Reinhorn and Li (1995), who conducted extensive research on the effect of viscous damping walls on structures. A concrete structural model 1:3 in length scale with different damping devices (fluid viscous, friction and viscous wall dampers) was tested in a shake table. Results (Table 1) indicated that dampers have the potential to significantly diminish inelastic deformation demands and damage to the structure. The damping ratio of the bare structure was less than 10%. It increased to 20%-30% with the addition of fluid or friction dampers and to nearly 50% when the viscous damping walls were added. Viscous walls were by far the most effective damper tested, which indicate the great potential of this kind of dampers to reduce structural damage during earthquakes.

Table 1. Dynamic characteristics of the structure (Reinhorn and Li 1995)

Ground motion	PGA [g]	Damping (% of critical) Low amplitude testing	Strong motion testing	Approximated analytically	Fundamental period Low amplitude testing	Strong motion testing
		Without dampers				
El Centro S00E	0.30	3	6	6	0.62 sec	0.76 sec
Taft N21E	0.20	3	5	5	0.62 sec	0.76 sec
		With fluid dampers (Taylor)				
El Centro S00E	0.30	16	28	26	0.53 sec	0.62 sec
Taft N21E	0.20	16	26	25	0.50 sec	0.55 sec
		With friction dampers (Sumitono)				
El Centro S00E	0.30	7	23	28	0.31 sec	0.42 sec
Taft N21E	0.20	7	26	22	0.31 sec	0.50 sec
		With viscous damping walls				
El Centro S00E	0.30	50	46	44	0.25 sec	0.27 sec
Taft N21E	0.20	49	47	44	0.25 sec	0.27 sec

Testing

As illustrated in Figure 3, a viscous wall consists of a plate floating in a thin container filled with a highly viscous fluid. Damping provided by viscous walls protects the structure from seismic events as well as from other natural occurrences such as winds and heat.

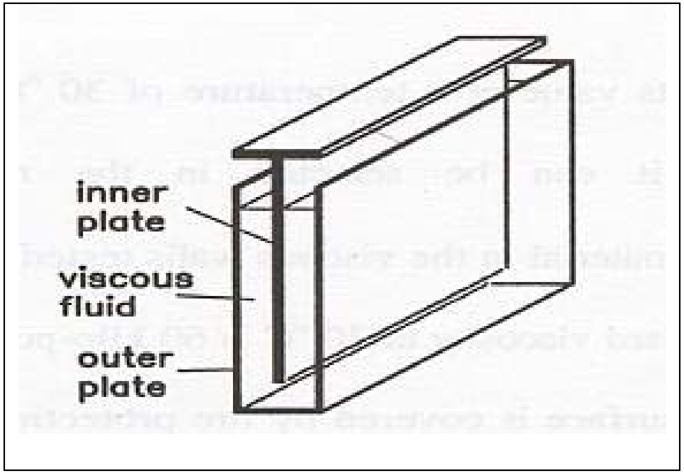


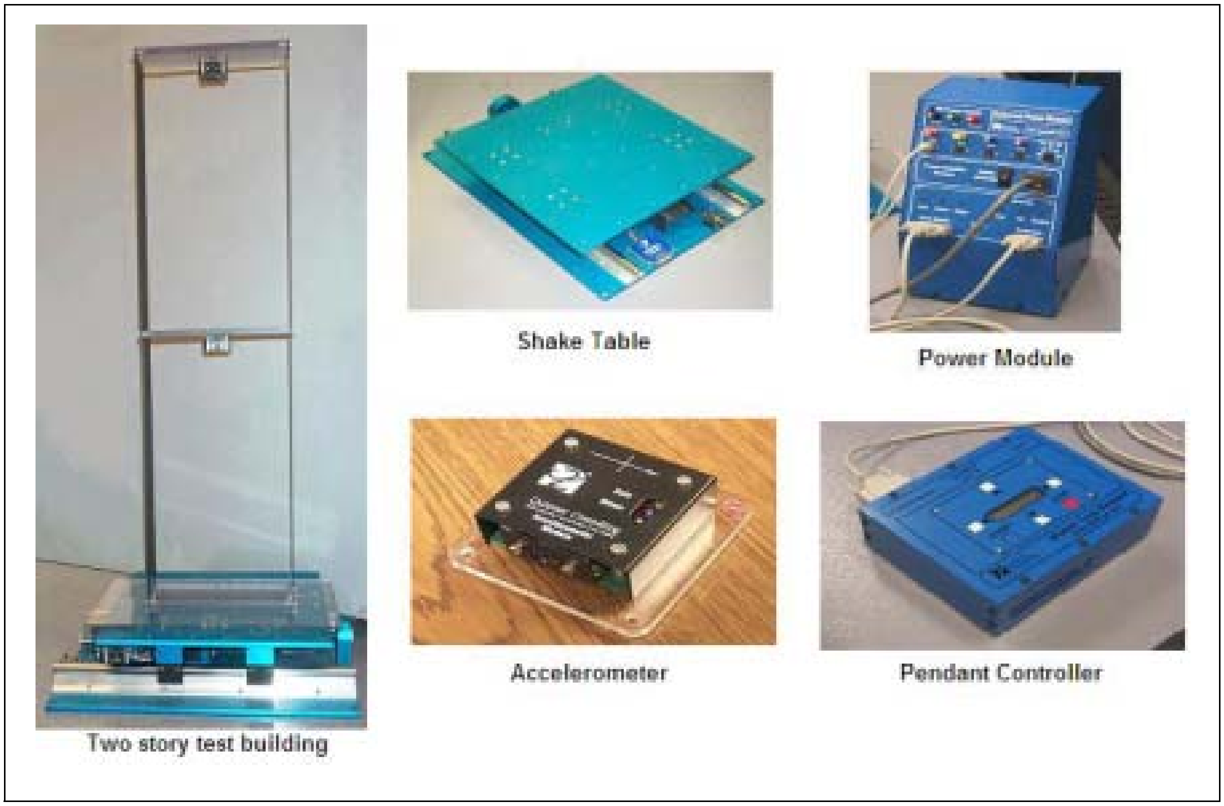
Figure 3. Viscous wall (Reinhorn and Li 1995)

An experiment on viscous damping was designed and implemented using an instructional shake table developed by the University Consortium on Instructional Shake Tables (UCIST), which is intended to introduce structural dynamics and earthquake engineering to undergraduate students. The shake table "package" includes a power module to drive the shake table, a data acquisition board to collect data and drive the power amplifier, a portable pendant capable of generating pre-programmed earthquakes, a 2-story test building, three accelerometers (one for the shake table and one on each floor of the structure) and a Pentium-class computer. WinCon realtime software, along with computer programs MATLAB and SIMULINK, controls the shake table. Figure 4 contains pictures of the shake table hardware.

A container was constructed with Plexiglas and bolted to the shake table. The dimensions of the contained were 4.25" wide, 11.5" long and 8" high. In order to emulate a 1-story viscous wall, the first floor of the test structure and its accelerometer were removed and then a steel plate was hung from the top floor and inserted into the container. An approximately 1" gap was provided between the edge of the steel plate and the bottom of the container. An accelerometer was attached to the steel plate at the top of the structure. The test setup is illustrated in Figure 5.

The container was filled with several viscous fluids in order to test the corresponding damping effects. Water, soap water, oil and detergent were used. Free vibrations were induced by tapping the structure at the top. The structure was then allowed to vibrate freely until motion stopped. The data was collected using Wincon software and analyzed using MATLAB.

Viscous resistance is the resulting force of the viscous fluid in the container against the moving steel plate (Reinhorn and Li 1995). The frictional force resists the movement of the steel plate in the fluid. The smaller the gap between the plate and the wall, the higher the resistance provided by the fluid. This concept (illustrated in Figures 6 and 7) led to make some modifications in the initial test structure. In order to obtain a larger damping ratio, the container must be slimmer or the plate wider. To resolve the conflict, two U-shaped metal fins (Figure 8) were added at each side of the steel plate and bolted to the bottom portion of the steel plate.



Two story test building

Shake Table

Power Module

Accelerometer

Pendant Controller

Figure 4. The instructional shake table (UCIST)

Figure 5. Test setup: A simplified model of a viscous wall

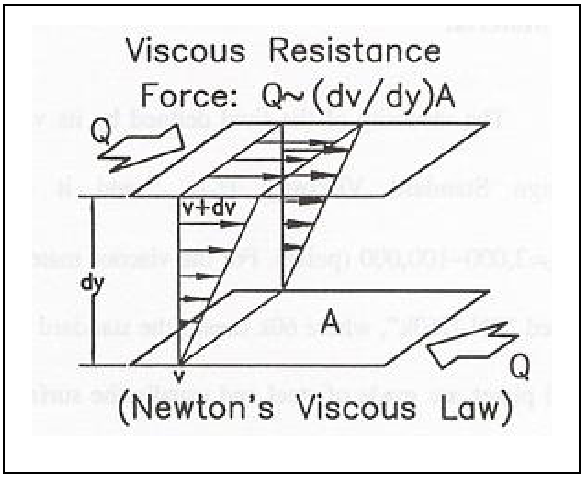


Figure 6. Viscous resistance

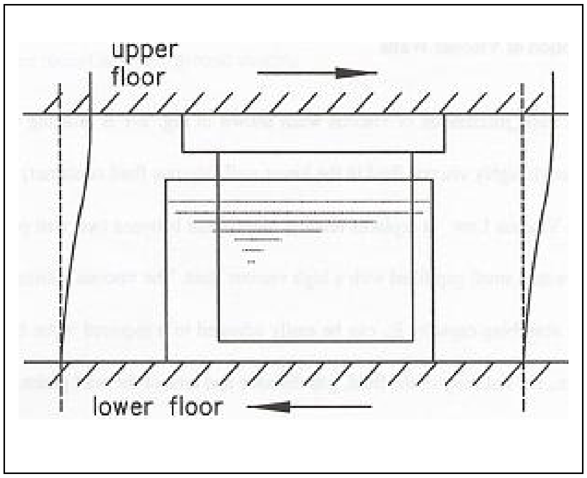


Figure 7. Viscous wall

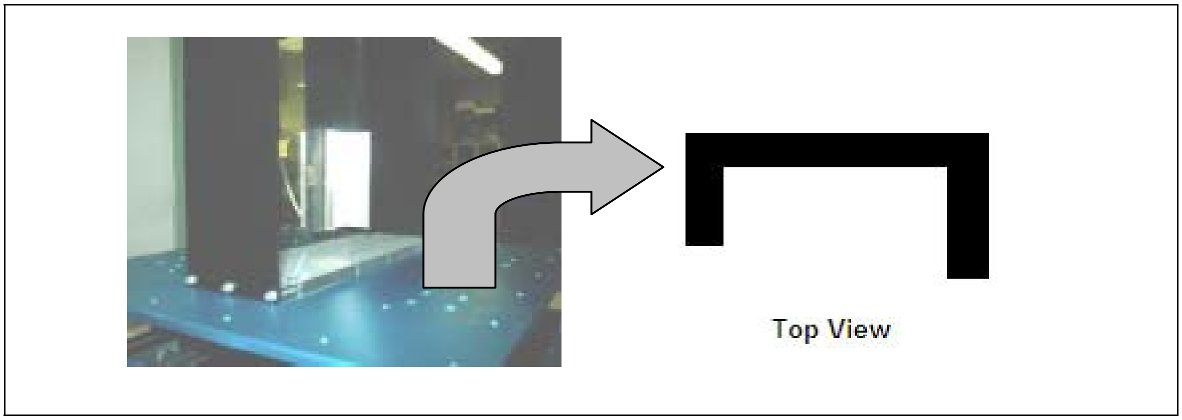


Figure 8. Steel plate with added fins

The structure with the modified walls was then re-tested. In addition to free vibration testing, records from the Kobe and Northridge earthquakes were also simulated. However, the corresponding results did not prove to be of much use on their own since the earthquakes were not simulated when testing the original walls.

Results

The response of the table and the steel plate was collected from the accelerometers and plotted. The plot was then saved as an m-file and then MATLAB was used to evaluate the plot and determine the period (frequency) of the structure, the damping ratio and the damping coefficient. Results are presented in Table 2, whose are the average of results from three tests. While the results of each of the three tests were in most cases similar to each other, some of them showed erratic behavior. Since only three tests were performed per fluid, even one test could alter the average. This observation could explain the fact that the damping ratios were different from what was expected and from what should possibly have been. Due to a shortage of time and resources, tests with the added fins and oil were not conducted.

Table 2. Test results

Viscous fluid	Damping ratio ζ [%] (before/after)	Logarithmic decrement δ (before/after)	Period [sec] (before/after)	Frequency [Hz] (before/after)
Nothing	1.55 / 1.79	13.37 / 11.26	0.32 / 0.32	3.18 / 3.10
Water	1.97 / 6.61	12.39 / 41.54	0.32 / 0.33	3.15 / 3.10
Soap	1.80 / 7.86	11.28 / 49.35	0.32 / 0.43	3.15 / 2.41
Oil	1.86 / NA	11.66 / NA	0.32 / NA	3.12 / NA
Detergent	3.54 / 7.08	22.25 / 44.51	0.32 / 0.37	3.12 / 2.72

Figure 9 shows the damping ratios of the model viscous wall before and after the modification. There is a significant contrast between the two conditions. The damping ratios increased once the extra fins were added to the steel plate. The most significant change occurred between the damping ratios of the soap water. It increased from 1.8% to 7.8%, a 6% increase in damping. This is illustrated in Figure 10, where the response of the original viscous wall is compared with the response of the wall with the fins added to the steel plate.

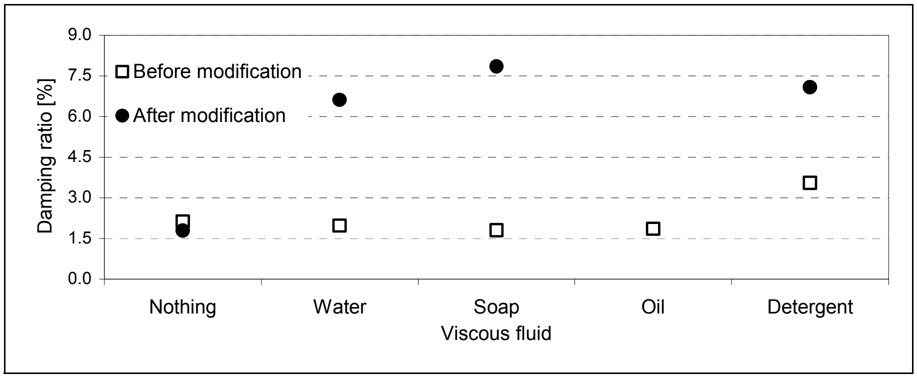


Figure 9. Comparison of damping ratios

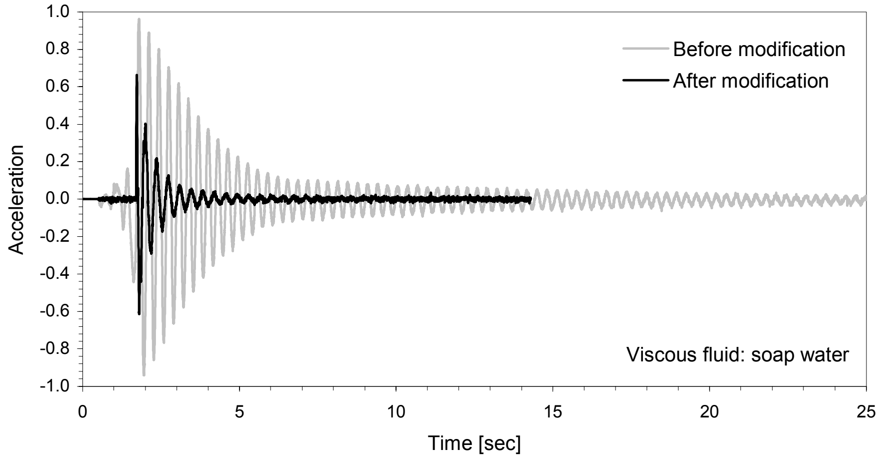


Figure 10. Response before and after adding fins to the plate of the viscous wall

Conclusion

Due to an oversight in the original test setup, the model viscous wall had to be modified. Viscous resistance was brought into focus and the damping characteristics of the viscous wall were improved. As results clearly show, there was a significant increase in damping once the fins were added to the viscous wall. Once the length of the gap between the wall of the container and the steel blade was reduced, the friction between the fluid and the blade increased. Because of that, the movement of the blade was dampened at a faster rate. Besides, thicker and more viscous fluids proved to provide better damping characteristics as opposed to fluids with lower viscosity.

Possible future work includes the development of a better version of the viscous wall. Comparison between the response of the modified viscous wall tested in this study and that of a viscous wall with a slimmer container will indicate which approach is more effective. Future tests should include several earthquake simulations. Other possibilities include test of viscous walls of different size, different amount of fluid and different (new) types of fluids.

The experiments described in this paper were intended as an introductory experience about structural dampers in general and viscous damping walls in particular. Although the device tested is a simplified model of an actual viscous wall, it nevertheless operates on the same principles. It allows the building to move during an earthquake and quickly dampens the vibrations so that structural damage is minimized.

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