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SUPPLEMENTAL DAMPING FOR IMPROVED SEISMIC PERFORMANCE OF BUILDING

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SYNOPSIS

A number of imaginative approaches to improve earthquake response performance have been developed and others are forthcoming. The effects of adding supplemental damping devices to building structural systems in terms of its seismic response, the characterization of equivalent viscous damping for hysteretic damping devices, and a description of several supplemental damping devices are presented. It is concluded that supplemental damping devices can provide dependable energy dissipation during earthquakes thereby resulting in improved performance of structures.

INTRODUCTION

The building motions and damage caused by the Chilean and Mexican earthquakes of 1985 have amply demonstrated that single measures of earthquake motions, such as peak ground acceleration, do not provide an adequate basis from which to anticipate building response amplitudes or building damage. Even the use of multiple measures of ground motion as incorporated in the Response Spectra do not explain the survival or failure of buildings subjected to different earthquake ground motions. Many engineers believe that the duration of the ground motion is an important factor in exciting the response and causing damage to a building. Some have suggested that an additional design parameter is need to complement the current Response Spectral procedure (Code Lateral Force procedure). Earthquake input energy is currently being investigated as a logical complementary consideration for the design of earthquake resistant buildings.

Simultaneously, the expectations of building owners and engineers are increasing. That is, they expect that their buildings will not experience serious damage in a large earthquake, such as occurred in Mexico City in 1985, and that the buildings will continue to be operational following moderate earthquake ground motions, such as the Whittier event in 1987 and in San Francisco during the Loma Prieta earthquake of 1989. Limits on lateral drift calculated for code seismic forces are being used implicitly to control building damage. These greater expectations for the behavior of our earthquake resistance building designs should be faced directly with knowledge and imagination rather than indirectly through implicit methods.

A number of imaginative approaches to improve earthquake response performance and damage control have been developed and others will be forthcoming. These can be divided into two groups, Passive Systems of which base isolation and supplemental mechanical damping are examples and Active Systems which require active participation of mechanical devices whose inputs depend upon measured building response. The discussion in this paper focuses on only passive supplemental mechanical damping systems. It is hoped that as a result of the information summarized in this paper the reader will be able to conclude that supplemental damping can provide performance and economical advantages for the earthquake resistant design for some new buildings and provides other advantages when developing strengthening systems for existing buildings. The advantages and disadvantages among the damping devices discussed is left to the reader. However, information necessary to make decisions between the use of supplemental damping systems, base isolation or active control systems is beyond the scope of this paper.

The paper is divided into two main sections. The first summarizes analytical studies of the earthquake response of buildings with added supplemental damping in both the elastic and inelastic range of response. The results are presented in a form of response spectra modifications which are appropriate as damping is added to the building. Although data also exists for presentation as energy input spectra modifications, that data is not included in this paper. The second section of the paper discusses the characteristics of supplemental energy dissipation device for earthquake resistant design utilization. Experimentally determined characteristics of these devices are given. It is concluded that added damping can provide significantly improved earthquake response performance and that practical commercial damping devices are available.

EFFECT OF ADDED DAMPING ON SEISMIC RESPONSE

The displacement response spectra, SD, is a key parameter in estimating the maximum displacement responses in each mode of a building for past earthquakes or for a specified design spectra. This spectral displacement decreases as damping increases. Ashour (1987) developed a relationship for the change in SD of elastic system with changes in damping and correlated these with results obtained from existing earthquake accelerogram records.

Elastic Response. The natural period, Tn, used in the study were 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 seconds which covers a representative range of natural periods. Three real and twelve artificial earthquake records were used for excitation input. Damping values used were 0, 2, 5, 10, 20, 30, 50, 75, 100, 125 and 150 percent of critical. The values of SD for a given Tn and damping factor were normalized with respect to the SD at Tn for zero damping for each earthquake record and were than averaged over the 15 records to obtain a mean value for each period and fraction of critical damping. Figure 1 shows the resulting relation for the mean value of SD as a function of period and damping for zero and five percent damping normalizations.

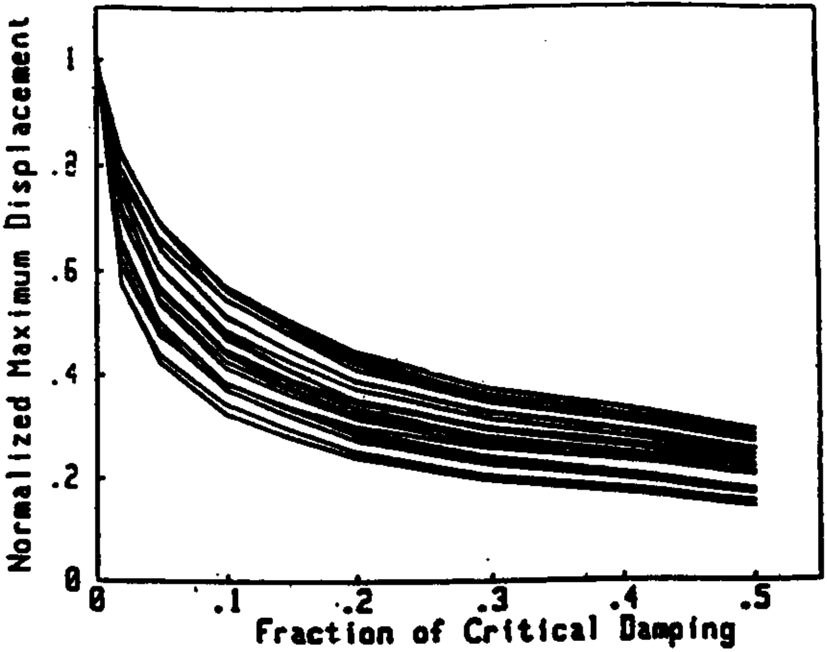
These curves can be represented by simple decaying functions,

$$R = [\{1 - e^{-\beta B}\}/\{\beta B\}]^{1/2}$$

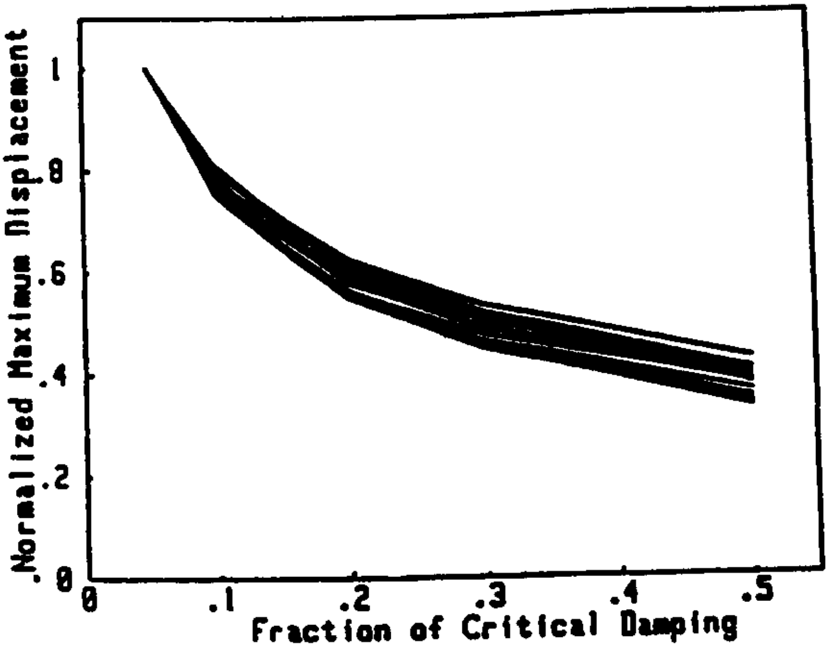
where β is the selected fraction of critical damping and B is a coefficient which was evaluated for zero initial damping normalization to be 24 for the upper bound and 140 for the lower bound, Figure 2(a). For an initial elastic spectral normalization of α, the simple decaying function can be expressed by

$$R = [\alpha \{1 - e^{-\beta B}\}/\beta\{1 - e^{-\alpha B}\}]^{1/2}$$

The system damping must be greater than or equal to the initial elastic spectral

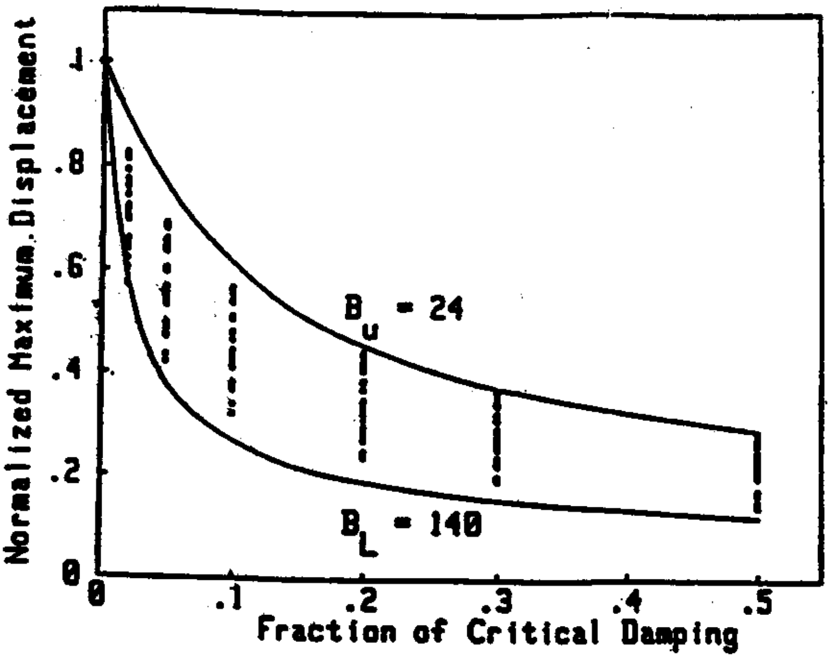


(a) Zero Damping Normalization

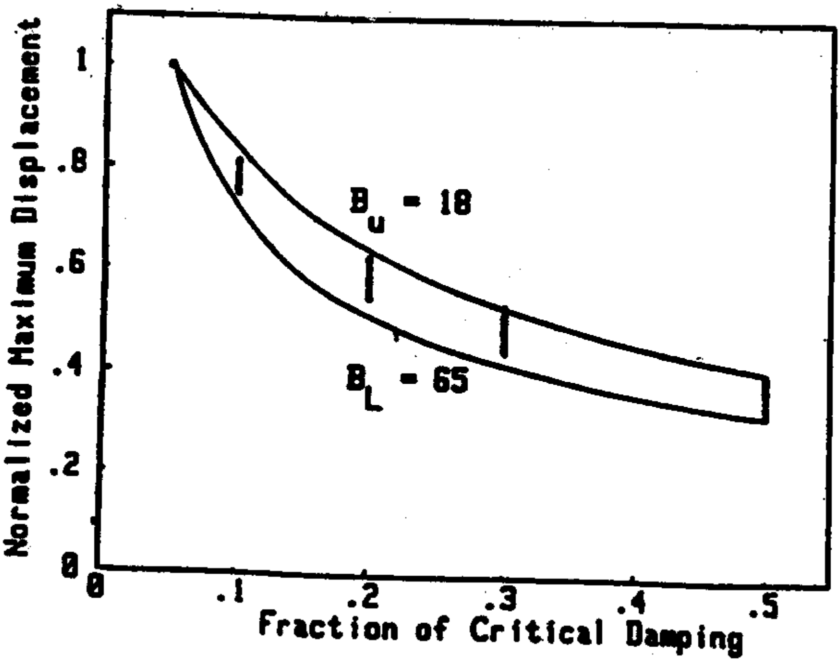


(b) Five Percent Damping Normalization

Figure 1. Normalized Mean Displacement for Spectra of 15 Earthquake Records [from Ashour (1987)]



(a) Zero Damping Normalization



(b) Five Percent Damping Normalization

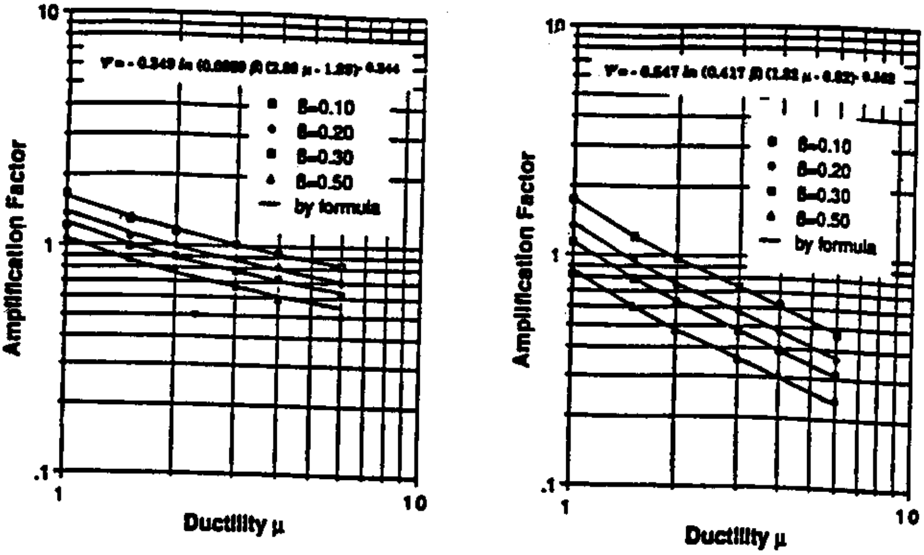
Figure 2. Envelope of Normalized Mean Displacement Response [from Ashour (1987)]

normalization damping to use this equation. For five percent (5%) damped spectra normalization, set $\alpha = 0.05$. Ashour (1987) found the upper bound B = 18 and the lower bound B = 65 for this case, Figure 2(b).

Inelastic Response. The inelastic response evaluations are more difficult to establish on a comparative basis. Wu (1987) used one artificial and nine real earthquake records to study the elastic-plastic response of single degree systems. One form for presentation of his conclusions uses the peak ground parameters as a basis to derive the inelastic response spectra. Figure 3 gives the Response Spectra amplification factor in the acceleration region at periods of 0.1 second and 0.5 second for damping from 10 to 50 percent and ductilities from one to six. The effect of increasing damping and ductility can be seen. The amplification factor in the velocity region is shown in Figure 4 and in the displacement region at periods of three seconds and ten seconds in Figure 5. In these figures β is the fraction of critical damping and μ is the structural ductility factor. Thus, it can be seen that supplemental damping can effectively reduce structural yielding demands of an earthquake.

It is interesting to note that these amplification factors can be divided into terms which include the viscous damping of the system and separate terms which include the structural inelastic yielding. The inelastic deamplification factors for the three regions of concern are plotted in Figure 6 with the corresponding data including damping from 10 to 50 percent of critical. The relatively small scatter of the data with changes in damping illustrates the point that spectral modifications for high damping and for inelastic action can be considered separately. Thus your previous experience with inelastic spectral modifications can be retained while incorporating modifications for higher damping.

As will be seen later steel yielding hysteretic characteristics are generally curvilinear and can be reasonably represented by equivalent viscous damping as was assumed in the previous studies. Friction and lead yielding characteristics are box shaped with sharp corners; for large motions equivalent viscous damping which changes with amplitude can be used, but for small motions the behavior is more of a stick-slip nature for which equivalent linear modelling is not very accurate.



(a) At 0.1 sec Period

(b) At 0.5 sec Period

Figure 3. Amplification Factors in the Acceleration Region [from Wu (1987)]

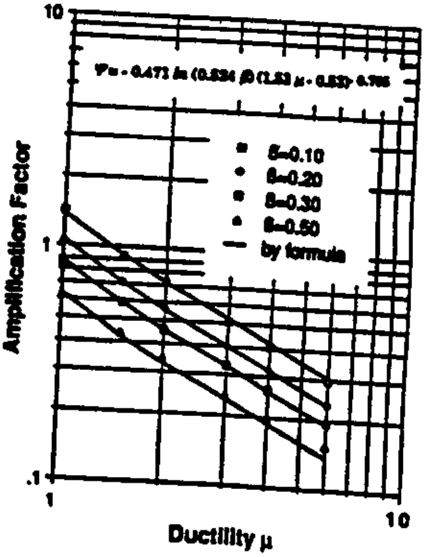
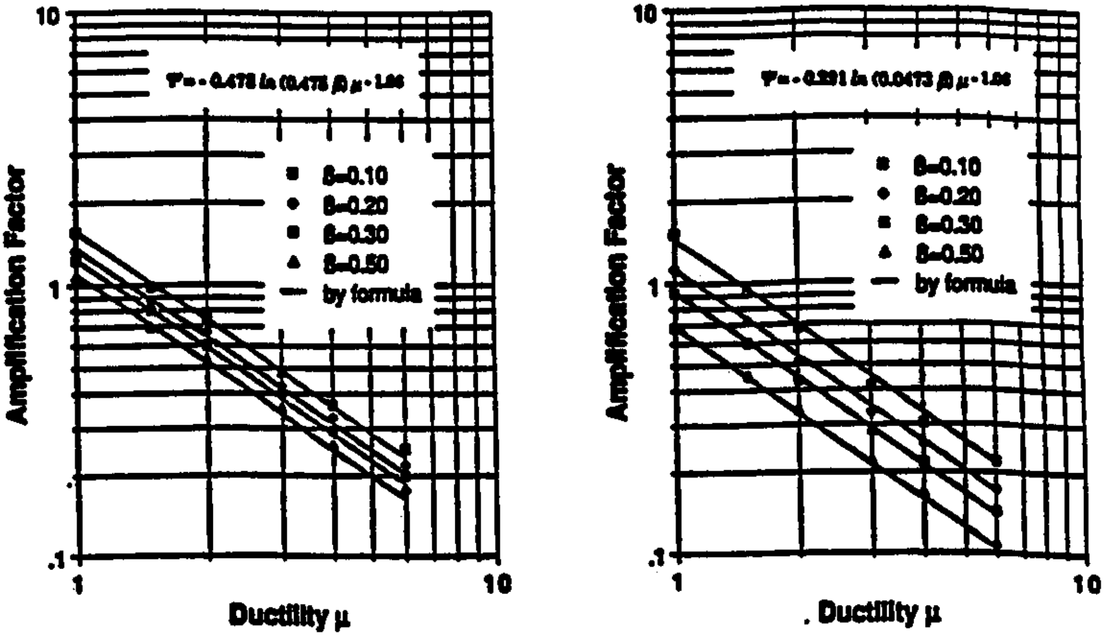
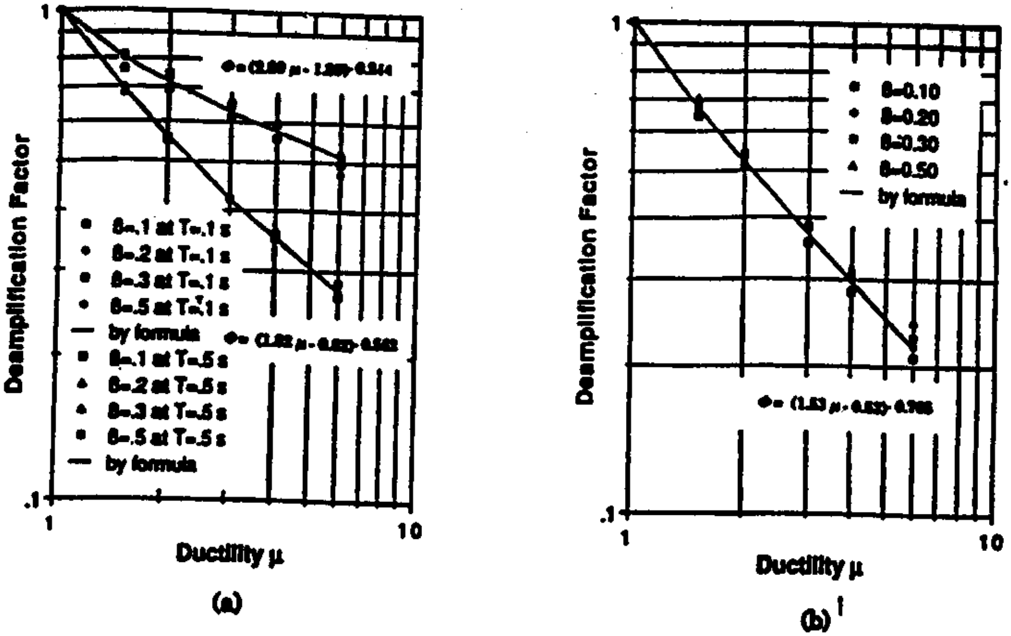


Figure 4. Amplification Factors for PSV_{max} in the Velocity Region [from Wu (1987)]



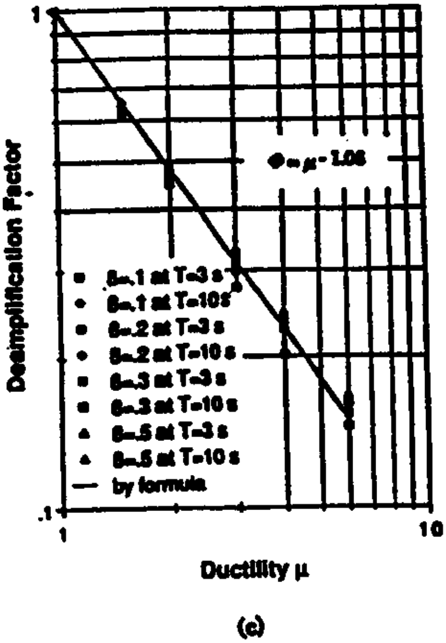
(a) At 3.0 sec Period (b) At 10.0 sec Period

Figure 5. Amplification Factors in the Displacement Region [from Wu (1987)]



(a) In the Acceleration Region

(b) In the Velocity Region



(c) In the Displacement Region

Figure 6. Deamplification Factors in the Three Regions
[from Wu (1987)]

For these reasons most of the friction (and lead yielding) analytical studies have used nonlinear models to represent the damping device characteristics.

ADAS DAMPING DEVICES

Damping devices can be classified into four primary types on the basis of the material used to transform mechanical energy to heat: (i) Velocity proportional viscous material which can be liquid, such as silicon oil, or solid, such as special rubbers or acrylics; (ii) Friction devices in which the resisting forces are a constant which depends upon the interface contact pressures and the interface materials. Steel to steel, copper with graphite to steel, or brake pad to steel interface materials are most common; (iii) Metallic yielding devices in which the resisting forces depend upon the nonlinear stress-strain characteristics and geometrical configuration of the material. Mild steel and lead are the two most commonly used materials; and (iv) Magnetic damping devices. The following discussion will concentrate on one metallic yielding device because it appears to be practical for earthquake resistance applications.

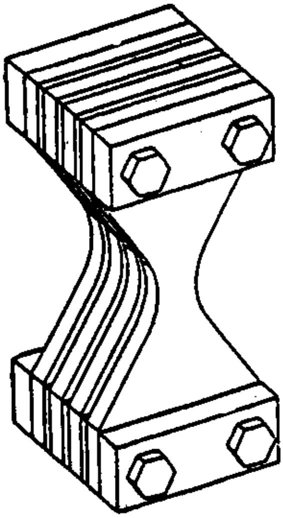


Figure 7. Added Damping and Stiffness (ADAS) Steel Plate Damper [from Bergman (1987)]

The ADAS device was originally developed by the Bechtel Corp. for pipe restraints in nuclear power plants. The concepts were extended to building structures by the CounterQuake Corp. (Scholl, 1987). The configuration of the device (Figure 7) is selected to maximize the amount of material yielding without excessive localized strains. Experimental data on smaller sized ADAS devices have been reported (Bergman, 1987; Bergman, 1988) and are illustrated in Figure 8. Three story steel frame shaking table tests using these devices has been recently completed at the University of California

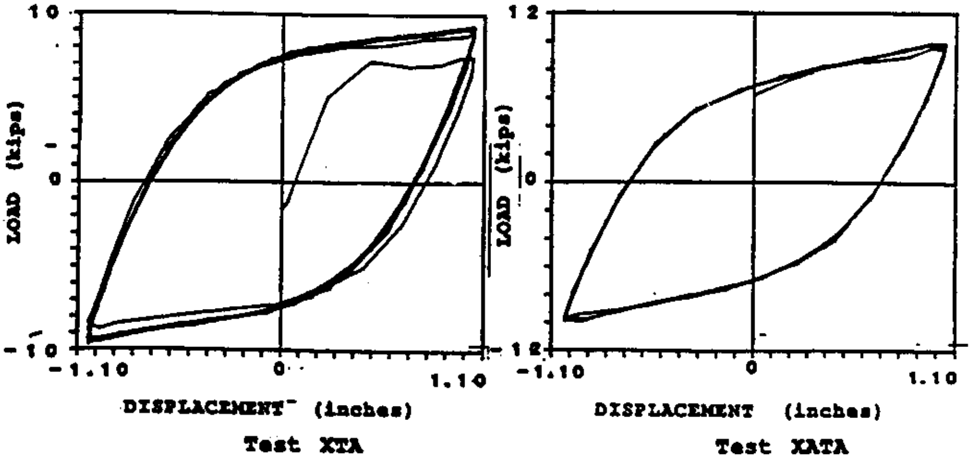


Figure 8. Characteristic Hysteresis Curves for Seven Plate, Five Inch High 5/16 Inch Thick ADAS Device [from Bergman (1988)]

at Berkeley (Whittaker, 1989). Test results from a two story reinforced concrete frame (Su, 1989) will be presented next.

TWO-STORY REINFORCED CONCRETE FRAME WITH ADAS DEVICE TEST

Two different ADAS devices were used in this test. The device installed on the top story had seven X-shaped steel plates and the device installed on the bottom story contained nine steel plates. The steel plates used in previous tests were reused here. In order to increase the initial stiffness and energy dissipation capacity of the device, four 1" x 1/4" steel plates were welded along both sides of the device to enhance the constraint on end blocks, spacer plates and X-shaped steel plates. Before the welding, the previous end blocks were shortened from 10" to 6" to match the width of X-shaped steel plates.

Test Structure. A two-story, single-span reinforced concrete frame with 16'-0" span and 5'-0" net story heights previously used in evaluation of strengthening methods in U.S./Mexico Research Project [Krause, et al, 1988] was used in this study. The project includes study of the following three systems of strengthening existing buildings:

1. Toughening of RC Frame Members and addition of Infill Walls
2. Steel Bracing System
3. Supplemental Damping Devices.

The frame had typical 8x12" columns, a top story beam 8"x12" and a bottom story beam 8"x18". Each floor slab was 3" thick and 5'-0" wide. The two-story bare frame had structural details that are typical of many school buildings in Mexico. The specific yield stress for reinforcing bars was 60 ksi and the specified compressive strength for concrete was 4000 psi. The amount of transverse reinforcement in the joint region and the columns was intentionally kept below the amount required by the Uniform Building Code. The arrangement of member reinforcement has been given by Krause, et al. [1988] The columns were founded on a two feet high floor beam which was anchored to the reaction floor. The member moment capacities show that the frame is a strong column and weak beam system.

The concrete bare frame was subjected to cyclic loading up to 2% drift of top floor displacement for its first test. Damage concentrated in the beam-column joints at the first level and the bases of the columns. The damage was not severe. Then, the frame was infilled with unreinforced brick masonry and was tested under the same loading procedure up to 1.5% drift of top floor displacement. Extensive and severe damage was observed at the beam-column joints of the bottom story.

Next, a steel bracing system, consisting of braces in an inverted V-pattern and horizontal and vertical members (collectors), was added for retrofitting of the two-story R/C frame after it had been substantially damaged during the previous two tests. The concrete frame used beam collectors of C 5x6.7 and column collectors of four L 2x2x3/16 with batten plates 10x3x1/4 to help transfer the story shears from the double angle toe to toe braces with L 2x2x1/8. To repair the column to foundation connection, each column base was stiffened with a pair of L 5x5x1/2 welded on a pair of L 8x6x3/4 which are tightened together through the floor beam by bolts. The strengthened structure showed excellent performance under cyclic deformations larger than 2% of story drift. The hysteresis loops of the strengthened frame were very stable.

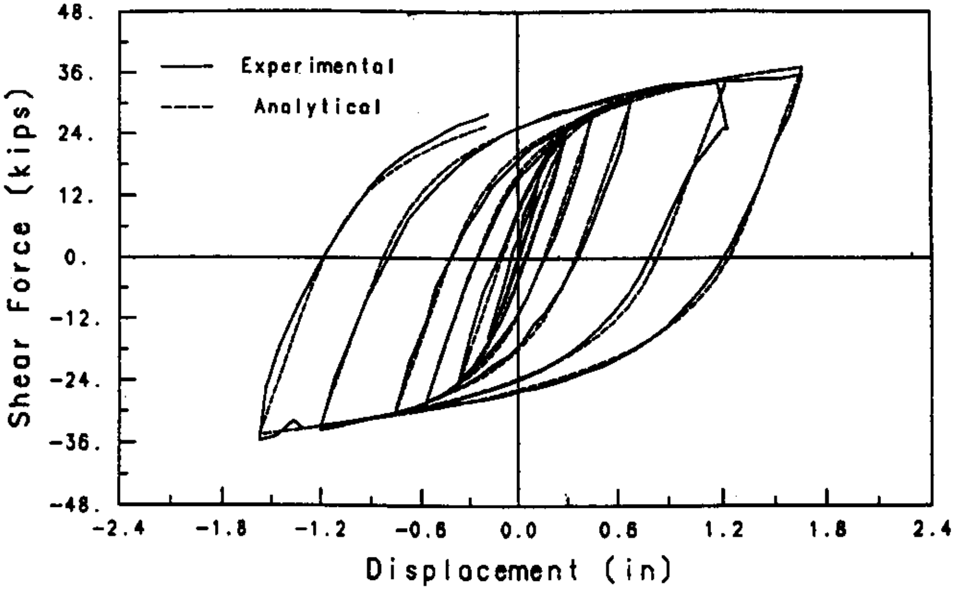


Figure 14. Hysteresis Correlation Betweeen Experimental and Analytical [from Su (1990)]

REMARKS

Analytical studies have demonstrated that supplemental damping can effectively control the response of buildings during earthquakes. These studies have shown that the response of a highly damped building is not sensitive to the peculiarities of specific earthquakes. Thus the added viscous type damping effectively decreases response variability and uncertainty from a broad spectrum of earthquake inputs; thereby improving the performance of the building and reducing the risk of severe damage.

A large number of damping devices are currently available and others under development. This is a tribute to the imagination of earthquake engineers. While most of the devices developed in Japan are intended for use with base isolation systems for the nuclear power industry, their application to commercial and residential buildings is moving rapidly.

CONCLUSIONS

The following conclusions are the result of a number of analytical studies and the information summarized herein:

1. The incremental effect of adding supplemental damping devices is greater when the total damping is small than when the total damping is high.

2. The combined effect of added damping and inelastic response of the structure can be separated into the effects resulting from higher damping and the effects resulting from member yielding.

3. Supplemental damping devices are more effective in reducing the corresponding earthquake response spectral values in the mid period region (velocity region) than in the low (acceleration controlled region) and high (displacement controlled region) period regions. Nevertheless additional damping makes the structures less sensitive to earthquake peculiarities.

4. The selected damping devices should be dependable and require a minimum amount of maintenance. The delivered devices should have quality controlled manufacturing to ensure that the characteristics established through testing programs and specified by the designers is achieved in field installations.

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REFERENCES

Ashour, Samir A., (1987), ELASTIC SEISMIC RESPONSE OF BUILDINGS WITH SUPPLEMENTAL DAMPING, Ph.D. Dissertation, Department of Civil Engineering, University of Michigan, January.

Bergman, David M. and Subhash C. Goel, (1987), EXPERIMENTAL CHARACTERISTICS OF THE ADAS DEVICE, Department of Civil Engineering, University of Michigan, Report UMCE 87-10, November.

Bergman, David M. and Robert D. Hanson, (1988), CHARACTERISTICS OF MECHANICAL DAMPERS, Ninth World Conference on Earthquake Engineering, Tokyo/Kyoto, Japan, August, (#6052).

Hanson, R.D., David M. Bergman and Samir A. Ashour, (1986), SUPPLEMENTAL MECHANICAL DAMPING FOR IMPROVED SEISMIC RESPONSE OF BUILDINGS, Third USA National Conference on Earthquake Engineering, Charleston, SC, August, Vol. II, pp. 1129-1140.

Hanson, Robert D., (1988), ENERGY DISSIPATION SYSTEMS, Proceedings of the 1988 Structural Engineers Association of California Convention, Kona, Hawaii, October.

Krause, G.L., Lopez, C.J. and Wight, J.K., (1988), THE MEXICO CITY RESEARCH PROGRAM: TESTING OF A TWO-STORY REINFORCED CONCRETE FRAME, Report No. UMCE 88-10, Department of Civil Engineering, University of Michigan, Ann Arbor Michigan, October

Scholl, Roger E., (1988), ADDED DAMPING AND STIFFNESS ELEMENTS FOR EARTHQUAKE DAMAGE AND LOSS CONTROL, Proceedings of Conference XLI: A Review of Earthquake Research Applications in the National Earthquake Hazards Reduction Program: 1977-1987, U.S. Geological Survey, Open File Report No. 88-13-A, San Diego, CA.

Su, Yung-feng, (1990), SEISMIC RESPONSE OF BUILDING STRUCTURES WITH MECHANICAL DAMPING DEVICES, Ph.D. Dissertation, Department of Civil Engineering, University of Michigan, Ann Arbor, January.

Whittaker, A.S., V.V. Bertero, L.J. Alonso, and C. Thompson, (1989), EARTHQUAKE SIMULATOR TESTING OF STEEL PLATE ADDED DAMPING AND STIFFNESS ELEMENTS, Report No. UCB/EERC-89/02, Earthquake Engineering Research Center, University of California, Berkeley, January.

Wu, Jian-ping, (1987), STATISTICAL STUDY OF THE INELASTIC RESPONSE OF STRUCTURES WITH HIGH DAMPING SUBJECTED TO EARTHQUAKES, Ph.D. Dissertation, Department of Civil Engineering, University of Michigan, Ann Arbor, November.

Wu, Jian-ping, and Robert D. Hanson, (1989), INELASTIC RESPONSE SPECTRA WITH HIGH DAMPING", Journal of the Structural Division, ASCE, Vol. 115, No. 7, July, pp. 1675-1696.