SEMI-ACTIVE CONTROL OF EARTHQUAKE INDUCED VIBRATION

M.D. SYMANS[1] and M.C. CONSTANTINOU[2]

1. Assistant Prof., Dept. of Civil & Env. Engrg., Washington State Univ., Pullman, WA 99164-2910, USA.
2. Professor, Dept. of Civil Engrg., State Univ. of New York at Buffalo, Buffalo, New York 14260, USA.

Paper No. 95. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

ABSTRACT

A semi-active control system for protection of structures subjected to earthquake induced motion is described in this paper. The semi-active control system is based on passive fluid dampers which were modified to behave as adjustable damping elements. The adjustable mechanical properties of the semi-active dampers were experimentally determined and utilized in the control of a three-story building model on a shaking table which was capable of simulating earthquake ground motion. The results of the shaking table tests indicated that the semi-active control system was capable of significantly reducing the response of the structure as compared with the bare frame structural system. When compared with a properly designed passive control system, the semi-active dampers were not able to appreciably reduce the response.

KEYWORDS

Fluid Damper, Viscous Damping, Damping, Energy Dissipation, Structural Control, Semi-Active Control, Active Control

INTRODUCTION

A wide variety of systems have been proposed for controlling structures subjected to earthquake induced ground motion. However, these systems may be categorized according to one of the following definitions.

Passive Control Systems: Systems which do not require a power source for operation. The energy associated with the motion of the structure is utilized to develop the control forces. The magnitude and direction of the control forces depend on the "localized" structural response (i.e., the response of the structure at the location of the passive control system).

Active Control Systems: Systems which require a power source for operation. Usually, the term "active control" is associated with a control system which utilizes electrohydraulic actuators to provide control forces. The electrohydraulic actuators typically require large power sources for operation. The magnitude and direction of the control forces may depend on the "localized" structural response, the "remote" structural response (i.e., the response of the structure at locations remote from the location of the electrohydraulic actuators), and the ground excitation.

Semi-Active Control Systems: Systems which offer a combination of features associated with passive and active control systems. Semi-Active control systems utilize the energy associated with the motion of the structure to develop control forces. The magnitude of the control force is usually adjusted using a small power source and may be based on the "localized" structural response, the "remote" structural response, and the ground excitation. The direction of the control force is usually dependent upon the "localized" response of the structure.

SEMI-ACTIVE FLUID DAMPERS

The semi-active fluid dampers described in this paper are based on the design of a passive fluid damping device which has been studied by Constantinou *et al* (1992) for seismic isolation and Constantinou and Symans (1993 and 1992) for seismic energy dissipation. The passive portion of the semi-active fluid damper consists of an outer cylinder, a stainless steel piston rod, a bronze piston head, and is filled with a thin silicone oil (see Fig. 1). The piston head orifices are designed such that the fluid flow is altered according to the fluid speed resulting in a force output which is proportional to the relative velocity of the piston head with respect to the damper housing. The development of restoring force is prevented by the use of a rod make-up accumulator. The orifice flow around the piston head is passively compensated through the use of an orifice design which utilizes a bi-metallic thermostat such that the mechanical properties remain relatively stable over a wide temperature range (-40°C to 70°C).

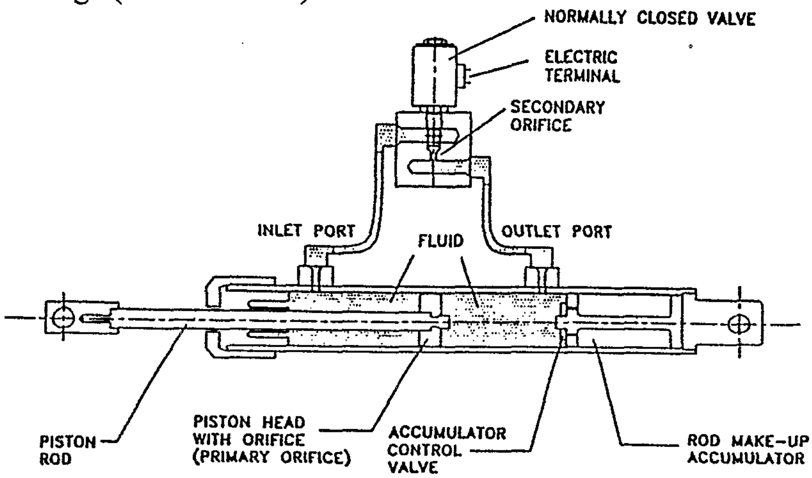

Fig. 1 Semi-Active fluid damper.

The passive fluid damper described above was modified to create a semi-active fluid damper by including an external bypass loop containing a control valve. Two semi-active damper systems were tested: 1) a two-stage damper utilizing a solenoid valve and 2) a variable damper utilizing a direct-drive servovalve. Physical characteristics of the dampers include a cylinder length of about 190 mm, a stroke of ±76.2 mm, and a maximum output force of 8,900 N. In this paper, only the variable damper system will be described further (see Symans and Constantinou (1996 and 1995) for a detailed description of the two-stage damper system).

The damping characteristics of the variable damper are controlled by varying the amount of flow passing through the external bypass loop using a control valve. The control valve used on the variable damper is a direct-drive servovalve which was originally developed for control of the primary flight control servo-actuation system on the U.S. Air Force B-2 Stealth Bomber. The servovalve can be off (valve closed), fully on (valve open), or between off and fully on (valve partially open). Therefore, a full range of damping levels is available from the system and hence the designation, variable damper. Normally, when there is no command voltage to the coils, fluid flow is blocked and all fluid flow in the semi-active damper system is through the piston head orifices and its damping performance is simply that of a standard passive fluid viscous damper. When a command voltage is sent to the coils, a D.C. drive motor is used to impose a spool displacement in proportion to the command voltage. When the spool is in the full open position, a majority of the fluid flow in the damper is through the external bypass loop and the damping is reduced by a factor of about 7. The operation of the direct-drive servovalve requires a peak power of 3.5 W.

The mechanical properties of the variable damper were obtained by subjecting the dampers to cyclic motions over a wide range of frequencies. A typical force-displacement loop is shown in Fig. 2 for the variable damper subjected to constant velocity motion with damping switching from high to low. The loops of Fig. 2 clearly indicate that the damper behaves essentially as a pure energy dissipator with no ability to develop restoring forces. At higher frequencies (beyond about 4 Hz) the device begins to develop stiffness associated with compression of the silicone fluid. The relationship between peak velocity and peak force for three different command signal voltages is shown in Fig. 3. The data for each command signal voltage level can be fit with straight lines having a slope equal to the corresponding damping coefficient.

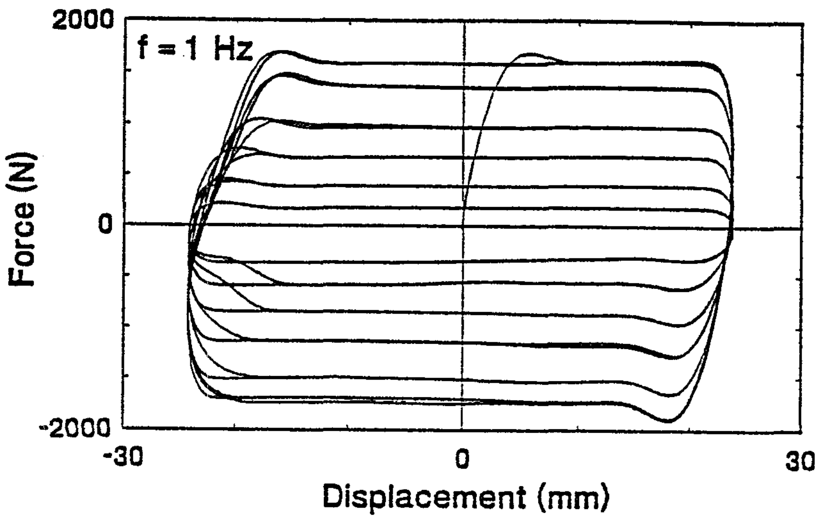

Fig. 2 Typical force-displacement loop of semi-active variable damper subjected to constant velocity cyclic motion.

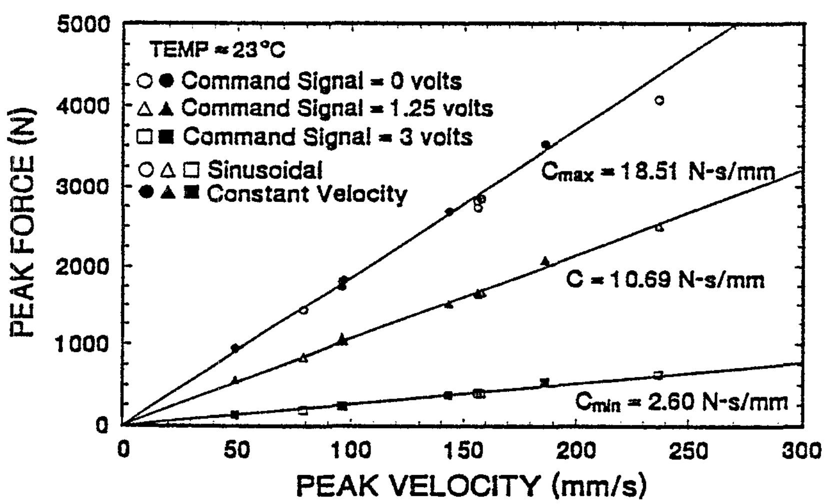

Fig. 3 Experimental values of peak force versus peak velocity at three different command signal voltage levels.

SEISMIC SIMULATION TESTS

A three-story single bay model structure was used for seismic simulation testing. The structure was a 1:4 scale steel moment-resisting frame which modeled a shear building by the method of artificial mass simulation (Soong *et al*, 1987). The mass associated with each floor of the structure was 956 kg and the height of each story was about 76 cm. The structure was tested with no dampers and with two variable dampers placed within the diagonal bracing of the first story. The bare frame structure was identified to have, at small amplitudes of vibration, natural frequencies of 1.8, 5.8, and 11.5 Hz and corresponding damping ratios of 1.74, 0.76, and 0.34 %. The structure with two variable dampers in the first story (valves closed / high damping) was identified to have, at small amplitudes of vibration, natural frequencies of 1.8, 6.0, and 11.5 Hz and corresponding damping ratios of 14.4, 18.8, and 4.8 %. Evidently, the dampers had a negligible effect on the stiffness of the structure while significantly modifying the damping of the structure. Shaking table motions included two historical earthquake records (1940 El Centro (comp. S00E) and 1968 Hachinohe (comp. NS)) and a harmonic signal of constant frequency and amplitude. During the shaking table tests in which semi-active dampers were attached to the model structure, a computer was used for control of the dampers and a separate computer was used for data acquisition. The control computer received signals from the measured response of the structure, processed the signals according to a pre-determined control algorithm, and sent an appropriate command signal to the semi-active damper valves.

CONTROL ALGORITHMS

Control algorithms were developed for the variable dampers in which the required constraint on the damping coefficient (i.e., $C_{min} \leq C(t) \leq C_{max}$) was not directly taken into account. Rather, during experimental application of the control algorithms, the damping coefficient was clipped at the upper and lower bounds. In general, the control algorithms for the variable dampers may require that the dampers perform work on the structure such that the energy within the structural system is increased. The effect of clipping the damping coefficient at the lower bound is to account for the inability of the semi-active dampers to perform this type of work on the structure (i.e., the dampers are only capable of absorbing energy).

An LQR (Linear Quadratic Regulator) optimal control algorithm was utilized for control of the structure. The general philosophy behind optimal control is as follows: given a system subjected to external inputs, determine the control which minimizes a certain measure of the performance of the system. The system is therefore optimized only with respect to that specific performance measure. The performance index for the LQR problem is given by the following scalar quantity

$$J = \int_0^{t_f} \left(\{Z(t)\}^T [Q] \{Z(t)\} + \{d(t)\}^T [R] \{d(t)\} \right) dt \tag{1}$$

where t_f is the final time of the control interval, $\{Z(t)\}$ and $\{d(t)\}$ are time-dependent state and control force vectors, respectively, and [Q] and [R] are constant weighting matrices. The relative values assigned to the state and control weighting matrices reflect the importance attached to minimization of the state variables and control forces, respectively. The optimal control problem is to minimize the scalar functional J subject to the constraint equation given by the equation of motion of the structure. For closed-loop control, the minimization process results in

$$\{d(t)\} = -\frac{1}{2}[R]^{-1}[B]^T[P]\{Z(t)\} \tag{2}$$

where [B] is a control force location matrix and [P] is the constant Ricatti matrix which satisfies the algebraic matrix Ricatti equation

$$[P][A] - \frac{1}{2}[P][B][R]^{-1}[B]^T[P] + [A]^T[P] + 2[Q] = [0] \tag{3}$$

where [A] is a matrix which describes the structural system. Note that the control force vector given by Eq. (2) is based on the assumption that the unknown earthquake excitation can be neglected and that the Ricatti matrix is constant (see Soong *et al*, 1994 and Soong, 1990 for more details). In the case of semi-active linear viscous dampers in the first story of the three-story structure, it can be shown (see Symans and Constantinou, 1995) that the necessary variation in the damping coefficient of each semi-active damper is given by

$$C = [\eta \cos^2\theta\, \dot{u}_1]^{-1} \left[\sum_{i=1}^{3} (\alpha_i u_i + \beta_i \dot{u}_i) \right] \tag{4}$$

where η is the number of dampers, θ is the angle of inclination of the dampers, u_i and $\dot{u}_i$ are the relative displacement and relative velocity, respectively, of the i-th floor, and α_i and β_i are weighting coefficients which are obtained from Eq. (2).

A control algorithm based on sliding mode control theory was also utilized in tests on the three-story model structure. The algorithm and test results are described by Symans and Constantinou (1995).

TIME DELAY COMPENSATION

There is a considerable amount of analytical research performed in the area of active and semi-active structural control in which the response of the structure, the control computation, and the application of the control force are assumed to occur instantaneously. However, as a number of experimental studies have shown, time delays exist in the control system and, in general, must be considered to ensure stability of the structural system. Many methods of time delay compensation have been developed and experimentally tested (e.g., Soong, 1990; Reinhorn *et al,* 1992; McGreevy *et al*, 1988).

For testing of the three-story structure, a time delay compensation method was developed which utilized experimentally measured time delays and was based on the assumption that the structure responds as an undamped system in free vibration (harmonic motion) during the time interval between measuring the response and applying the control force. Clearly, this assumption is incorrect since the ground motion as well as the semi-active damper control forces act on the system during this time interval. However, if time delays are relatively small, the assumption of harmonic motion may be acceptable.

Time delays may be conveniently separated into two components: response measurement time delays and control force time delays. The time delays associated with response measurement (signal conditioning (0 ms), signal filtering (21.0 ms), and signal differentiating (3.9 ms)) and control computer computations (about 4 ms) are obtained by passing a white noise signal through each component of the system and obtaining the transfer function between the input and output signal. An upper bound on the control force time delay (20 ms) associated with the development of the semi-active damper control force was experimentally determined by measuring the response of the dampers to a command signal which modifies the damping coefficient from its maximum to its minimum value and vice-versa.

SHAKING TABLE TEST RESULTS

An example of shaking table test results is given in Fig. 4 which shows response profiles for the three-story structure subjected to 50% of the Hachinohe earthquake record. Part (a) of Fig. 4 compares response profiles of the structure with no dampers (bare frame (BF) structure), the structure with semi-active dampers set to low damping (passive low damping (LD) control system), and the structure with semi-active dampers set to high damping (passive high damping (HD) control system). Parts (b) and (c) of Fig. 4 compare response profiles of the bare frame structure and the structure with high damping, respectively, to the structure controlled according to the LQR optimal (OPT) control algorithm with harmonic time delay compensation and the structure controlled according to the sliding mode control algorithm (SMC). The results of Fig. 4 show that: 1) the response of the bare frame structure is significantly reduced with the addition of the passive high damping control system; 2) the response of the bare frame structure is significantly reduced with the addition of the semi-active control system; and 3) the response of the structure with the passive high damping control system is nearly the same as the response obtained with the semi-active control system. Evidently, in these particular tests, the use of semi-active control systems offered no significant advantage over the use of a high damping passive control system. Similar conclusions were made by Polak *et al* (1994) in a numerical study on a three-story structure with a semi-active damping system. However, the authors of that study note that, under certain special conditions, a semi-active damping system may be warranted.

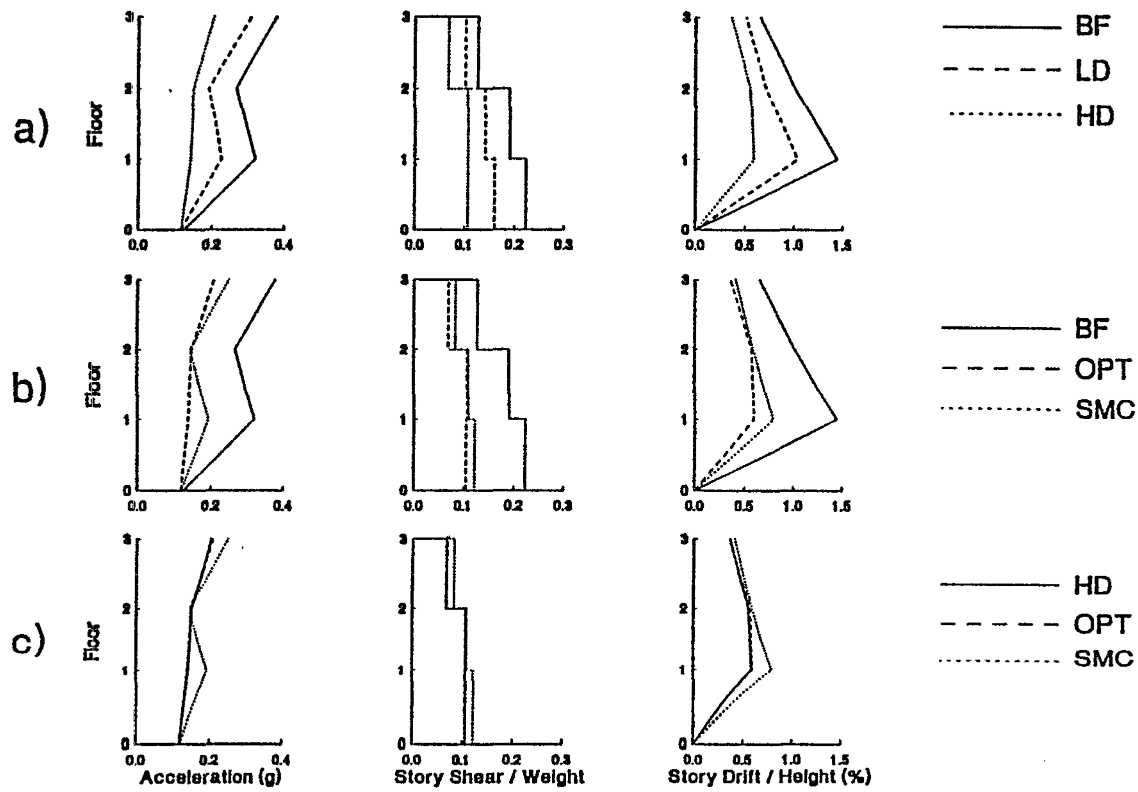

Fig. 4 Comparison of peak response profiles for structure subjected to 50% of the Hachinohe earthquake.

Analytical predictions of the shaking table test results (including the effects of time delays) compared reasonably well with the experimental results and are presented in detail by Symans and Constantinou (1995).

COMPARISON OF ACTIVE AND SEMI-ACTIVE CONTROL SYSTEMS

The three-story structure utilized in the shaking table tests has been tested previously by others for active control research. A comparison can be made between the results from the semi-active control tests described in this paper and previous results obtained from tests in which an active tendon system was used to control the structure (Chung *et al,* 1989; Soong *et al,* 1994; Soong 1990) through an optimal control algorithm which was identical to that used in the tests described in this paper except that, in the case of semi-active control, the damping coefficient is bounded by a maximum and minimum value. The results are shown in Fig. 5 for input being 25% of the El Centro earthquake. The percentage figures shown in Fig. 5 indicate the peak response reduction in comparison with the bare frame structure response. Fig. 5(a) shows that the active tendon system significantly reduces the peak response as compared with the bare frame structure. Further,

Fig. 5(b) shows that the peak response of the structure with the high damping passive control system is significantly less than that obtained with the bare frame and surpasses the reduction obtained with the active tendon system. Finally, Fig. 5(c) shows results for the semi-active control system in which the optimal control algorithm without time delay compensation was utilized. The results of Fig. 5(a) and (c) indicate that the semi-active control system was capable of achieving larger reductions in peak response in comparison to the active control system in which the same control algorithm was utilized. This was simply the result of larger effective damping in the semi-active control system.

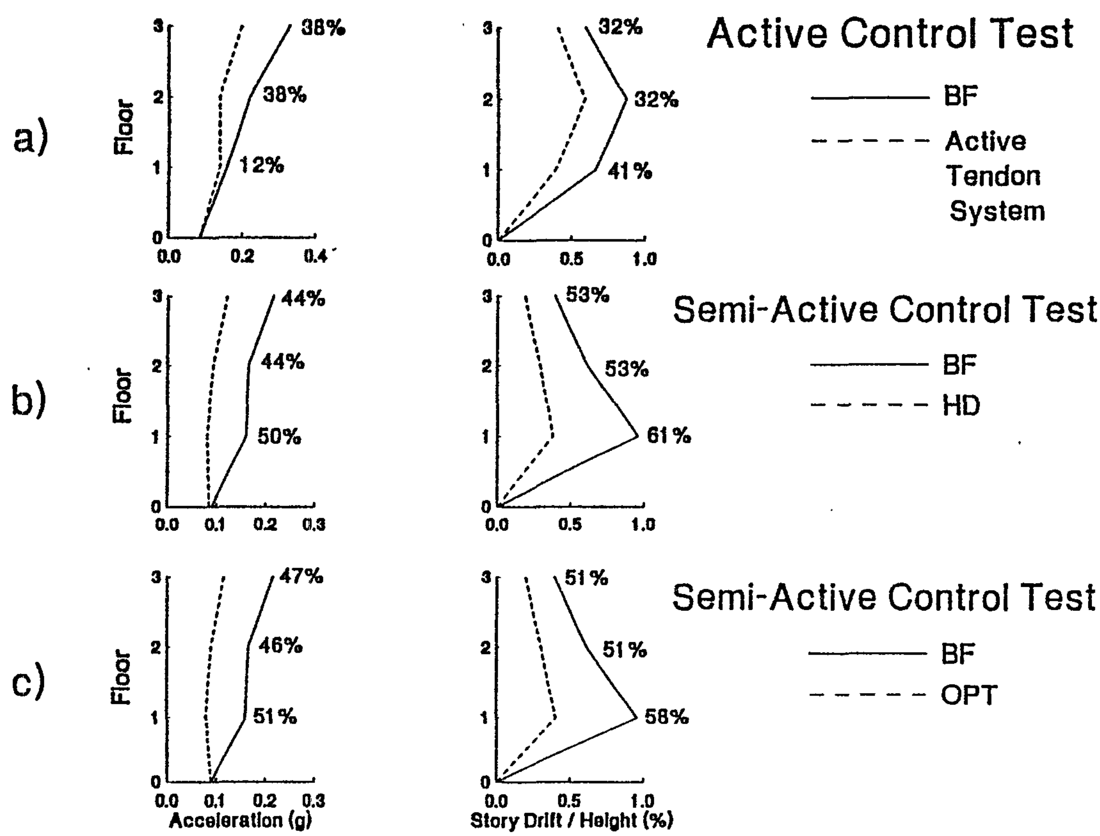

Fig. 5 Comparison of peak response profiles for structure subjected to 25% of the El Centro earthquake.

CONCLUSIONS

A seismic response control system composed of semi-active fluid dampers has been developed and experimentally tested at the component level and within a three-story scale model building structure on a shaking table. The results of the component tests showed that the dampers behave essentially as pure energy dissipators below a certain pre-determined frequency level. Further, the defining characteristic of the semi-active dampers (i.e., the damping coefficient) can be controlled using a small power source for modulation of fluid flow through an external bypass loop containing a control valve. The results of the shaking table tests on the three-story building model revealed that, in general, it is difficult to enhance the performance of a well-designed passive control system through the use of a semi-active control system. However, there may be special circumstances in which semi-active control systems are warranted. Finally, the semi-active control system was shown to perform better than an active tendon control system which was previously tested on the same model structure.

ACKNOWLEDGMENTS

The fluid dampers used in the experiments were manufactured by Taylor Devices, Inc., North Tonawanda, New York and the direct-drive servovalves were manufactured by Moog, Inc., East Aurora, New York. Financial Support was provided by the National Center for Earthquake Engineering Research, Taylor Devices, Inc., and Moog Inc.

REFERENCES

Chung, L.L., Lin, R.C., Soong, T.T. and A.M. Reinhorn (1989). Experimental Study of Active Control for MDOF Seismic Structures, *J. of Engrg. Mech.*, ASCE, **115** (8), 1609-1627.

Constantinou, M.C., Fujii, S., Tsopelas, P. and S. Okamoto (1992). University at Buffalo-Taisei Corporation Research Project on Bridge Seismic Isolation Systems, *Third Workshop on Engineering Research in Progress*, La Jolla, CA, Nov., 235-238.

Constantinou, M.C. and M.D. Symans (1992). Seismic Response of Structures with Supplemental Fluid Viscous Dampers, Report No. NCEER 92-0032, National Center for Earthquake Engineering Research, Buffalo, NY.

Constantinou, M.C. and M.D. Symans (1993). Experimental Study of Seismic Response of Buildings with Supplemental Fluid Dampers, *J. of Structural Design of Tall Buildings*, **2**, 93-132.

McGreevy, S., Soong, T.T. and A.M. Reinhorn (1988). An Experimental Study of Time Delay Compensation in Active Structural Control, *Proc. of the Sixth Int. Modal Analysis Conf.*, **1**, Orlando, FL, 733-739.

Polak, E., Meeker, G., Yamada, K. and N. Kurata (1994). Evaluation of an Active Variable-Damping Structure, *Earthquake Engrg. and Structural Dynamics*, **23**, 1259-1274.

Reinhorn, A.M., Soong, T.T., Lin, R.C., Riley, M.A., Wang, Y.P., Aizawa, S. and M. Higashino (1992). Active Bracing System: A Full Scale Implementation of Active Control, Report No. NCEER 92-0020, National Center for Earthquake Engineering Research, Buffalo, NY.

Soong, T.T. (1990). Active Structural Control: Theory and Practice. Longman, New York.

Soong, T.T. and M.C. Constantinou (1994). Passive and Active Structural Vibration Control in Civil Engineering. Springer-Verlag, Wien-New York.

Soong, T.T., Reinhorn, A.M. and J.N. Yang (1987). A Standardized Model for Structural Control Experiments and Some Experimental Results, *Proc. of Second Int. Symp. on Structural Control*, 1985, Waterloo, Canada, 669-693.

Symans, M.D. and M.C. Constantinou (1995). Development and Experimental Study of Semi-Active Fluid Damping Devices for Seismic Protection of Structures, Report No. NCEER 95-0011, National Center for Earthquake Engineering Research, Buffalo, NY.

Symans, M.D. and M.C. Constantinou (1996). Experimental Study of Seismic Response of Structures with Semi-Active Damping Control Systems, *Structures Congress XIV*, ASCE, Chicago, IL, April, in press.