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Active Controlled Friction Damped MDOF Structure with Variable Stiffness

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ABSTRACT

An active variable stiffness system was already proposed by Kobori (1991). It is a system aimed to reduce the response of structures to unpredictable earthquakes and other horizontal loads by actively controlling their stiffness. The system described in this paper has the advantage that the control forces at every structural level can be changed within a wide range due to friction dampers with variable friction forces implemented at each story. The friction forces in the dampers are actively controlled through a pressure which is applied on their sliding surfaces by special devices. The proposed dampers have an additional advantage compared to viscous or electrorheological devices, because they are velocity independent. Numerical analysis of a friction damped seven story structure is presented as an example. It shows that a significant improvement of the structural response compared to those of a passive controlled and an uncontrolled structures was obtained by using optimal active controlled friction dampers.

INTRODUCTION

Structural control is the most recent trend that enables to achieve aseismic behavior of buildings that withstand dynamic loads. Passive energy dissipating systems such as viscous dampers, tuned mass dampers and base isolation systems have been installed in existing buildings resulting in improved structural response to earthquakes. However, these systems have inherent limitations. For example they are generally tuned to the first vibration mode, while active dampers can be effective over a much wider frequency range. Hence the design of active controlled structure is a logical extension of the passive control systems. Active structural control consists of implementing actuators in the structure, controlled in such a manner that they develop forces that oppose the external effects and reduce the energy which affects the structure itself.

There are many known types of dampers used to achieve optimal behavior of structures. Kobori et al. 1991 proposed and tested an active controlled building structure with a variable stiffness system. Their device comprises of a two-rod-type hydraulic cylinder. A valve, opened or closed by an external electric signal, was installed in the connecting tube joining the cylinder chambers at both sides of the rod. Thus, the oil flow from one part of the tube to another was enabled or disabled in the unlocked or locked condition, respectively. Makris 1997 proposed to use electro-rheological dampers in order to improve the building's behavior under seismic events.

This work examines active controlled friction dampers that are placed between chevron braces and the rigid floor diaphragm at each structure level (Figure 2-b). Optimal control forces are determined at every time step by applying the active control theory. The design process which is presented in this paper can be applied to design new structures and to retrofit or to rehabilitate existing buildings.

PRINCIPAL SCHEME OF THE DEVICE

The principal scheme of the damper is shown in Figure 1. It consists of an internal element (1) connected to the rigid floor diaphragm, two external elements (2) connected to an inverted V-shaped brace, and to a pressure device (3). The friction force produced in the contact surface between the internal and external elements depends on the pressure. By changing the pressure at every time step, the friction forces in the devices at each level can be regulated according to the requirements of the optimal solution.

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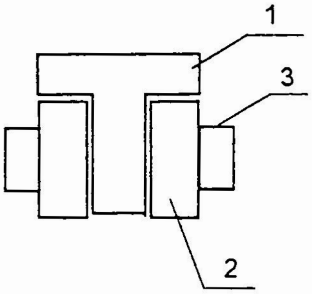


Figure 1. The principal scheme of an active friction damper

ACTIVE CONTROL THEORY

The main advantage of active control over passive control is that the knowledge of the external excitation at any time is available up to that time instant, t , and can be utilized to improve the future behavior of the building. The response of a structure provided by supplementary energy dissipating devices is described by the following dynamic equation of equilibrium (Soong 1990):

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=Lf_e(t)+Du_c(t) \tag{1}$$

where: M, C, K are the mass, the damping, and the stiffness matrices, respectively, L is the control forces location matrix, D is the external excitation location matrix, $x(t)$, $\dot{x}(t)$, $\ddot{x}(t)$ are the displacement, the velocity and the acceleration vectors, respectively, $u_c(t)$ is the vector of forces in the supplemental energy dissipating devices, and $f_e(t)$ is the external excitation.

The form of the performance index chosen for this study, $J(t)$, is time-dependent and is defined by the following equation:

$$J(t) = z^T(t)Qz(t) + u_c^T(t)Ru_c(t) \tag{2}$$

where R and Q *are* weighting matrices which define the priorities between the energies dissipated in the structural elements and in the dampers. In this study the matrices P and Q are used in a parametric range:

$$R = 10^{-m} I \qquad\qquad Q = I_{2n\times 2n} \tag{3}$$

where I is a $2n \times 2n$ unit diagonal matrix, and m is a parameter which keeps the dampind forces within dampers' practical capacity.

The state-space representation can be written in the following form (Soong, 1990):

$$z(t) = Ty(t) \tag{4}$$

where $z(t) = [x(t), \dot{x}(t)]^T$ is the 2n space state vector of the displacements and velocities for each of the structure's n Degrees Of Freedom (DOF), T, is a $2n \times 2n$ modal matrix whose columns are eigenvectors of A, and A is the system's matrix, given by:

$$A = \begin{bmatrix} 0 & 1 \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \tag{5}$$

Manipulation of Eq. 4 and Eq. 1 leads to (Soong, 1990):

$$\dot{y}(t)=\Lambda\, y(t)+q(t), \qquad\qquad y(0) = 0 \tag{6}$$

where Λ is a diagonal matrix whose diagonal elements are the complex eigenvalues of the matrix A, q(t) is given by:

$$q(t) = T^{1}\ [B \times u_c(t) + H \times f_e(t)] \tag{7}$$

and B and H are given as follows:

$$B = \begin{bmatrix} 0 \\ M^{-1}D \end{bmatrix} \quad ; \quad H = \begin{bmatrix} 0 \\ M^{-1}L \end{bmatrix} \tag{8}$$

Over a small time interval, Δt, the vector $y(t)$ becomes (Soong, 1990):

$$y(t) \cong \exp\Lambda\Delta t \times y(t-\Delta t) + \frac{\Delta t}{2}\left[\exp\Lambda\Delta t q(t-\Delta t) + q(t)\right] \tag{9}$$

For the state vector z(t), Eqs 4, 7 and 9 lead to

$$z(t) = Td(t-\Delta t) + \frac{\Delta t}{2}[Bu_c(t) + Hf_e(t)] \tag{10}$$

where

$$d(t-\Delta t) = \exp(\Lambda\Delta t)T^{-1} \times \left\{ z(t-\Delta t) + \frac{\Delta t}{2}\left[Bu_c(t-\Delta t) + Hf_e(t-\Delta t)\right] \right\} \tag{11}$$

Considering a closed-loop instantaneous control the damping forces vector, $u_c(t)$, is given by (Soong, 1990),

$$u_c(t) = -\frac{\Delta t}{2}R^{-1}B^TQz(t) \tag{12}$$

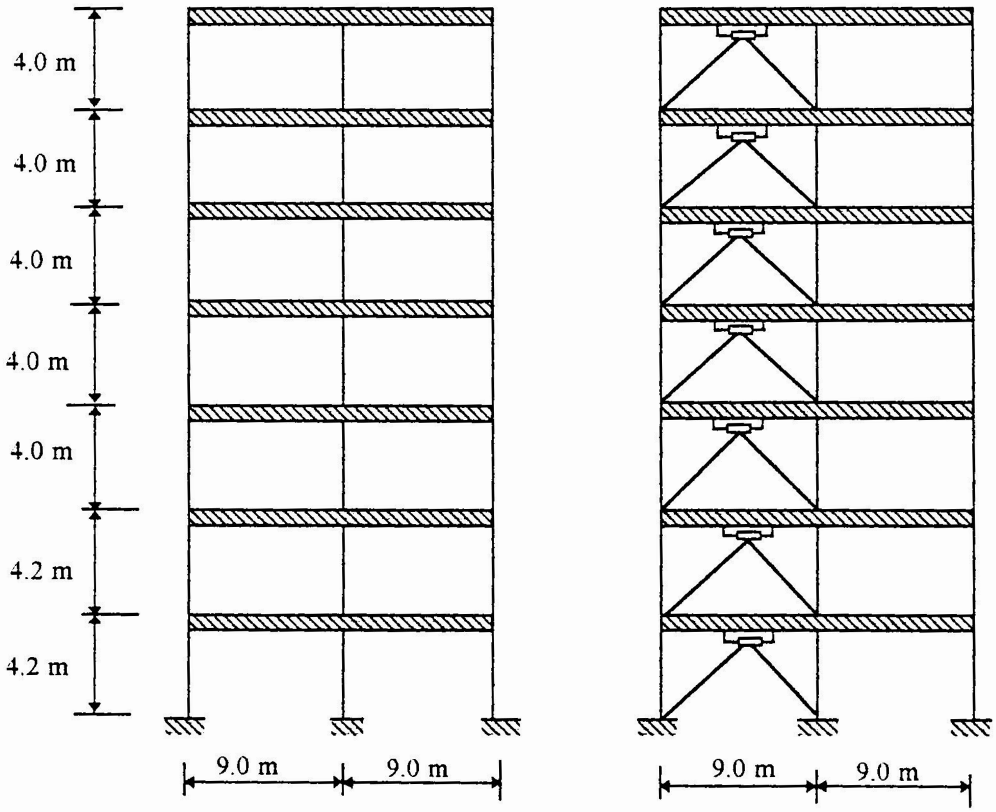
and following Eqs 10 and 12, the response state vector, $z(t)$, is:

$$z(t) = \left[I + \frac{\Delta t^2}{4}BR^{-1}B^TQ \right]^{-1} \left[Td(t-\Delta t) + \frac{\Delta t}{2}Hf_e(t) \right] \tag{13}$$

By analyzing the building's response during an earthquake, optimal forces at every structural level are obtained at each time increment. The pressure in each device at every time step is varied in such a way that the forces produced in the dampers would be equal to those obtained by the optimization procedure.

NUMERICAL EXAMPLE

To investigate the effectiveness of the proposed design technique, simulations were carried out of a seven story building. A shear framed structure, with stiff beams was examined (Figure 2-a). The response was computed for four different seismic excitations (specified below). All simulations were performed using routines written in MATLAB (MATLAB 1993). The structure was characterized by the following matrices: $M = 8.75 \times 10^{4}\ I_{7\times 7}$ [kg - mass] ,



(a) (b)

Figure 2. Seven-story structure (a) uncontrolled , (b) friction damped

$$K=\begin{bmatrix} 29.28 & -14.64 & & & & & 0 \\ -14.64 & 31.59 & -16.95 & & & & \\ & -16.95 & 30.96 & -14.01 & & & \\ & & -14.01 & 28.02 & -14.01 & & \\ & & & -14.01 & 25.13 & -11.12 & \\ & & & & -11.12 & 22.24 & -11.12 \\ 0 & & & & & -11.12 & 11.12 \end{bmatrix} \times 10^{-} \ [\mathrm{N/m}]$$

where M is the structure mass matrix, I is a unit diagonal matrix, and K is the structural stiffness matrix. An initial damping ratio of 1% was assumed for the uncontrolled structure.

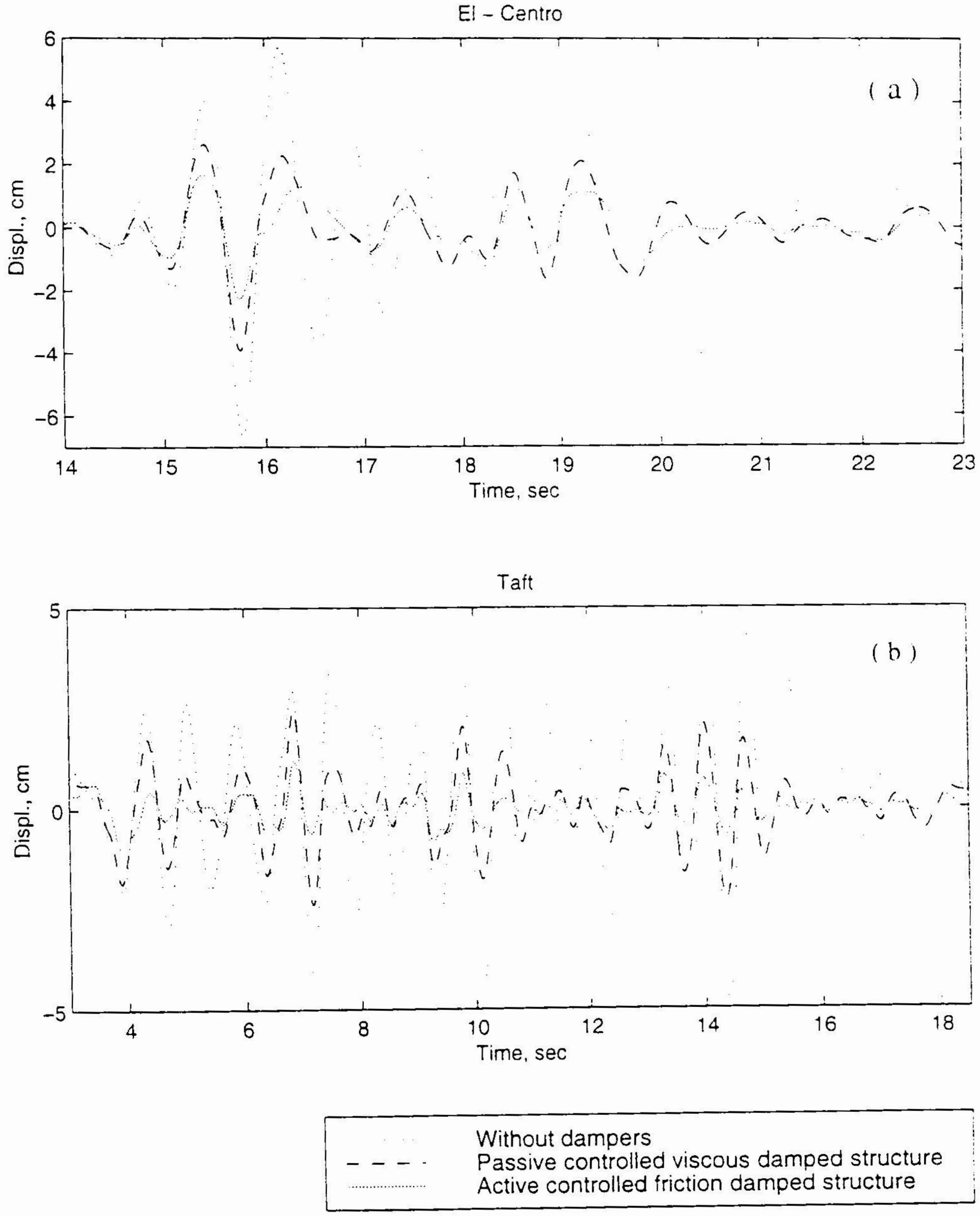


Figure 3. Roof displacement time history of the structure subjected to (a) El-Centro, (b) Taft, (c) Loma-Prieta, (d) Eilat earthquakes

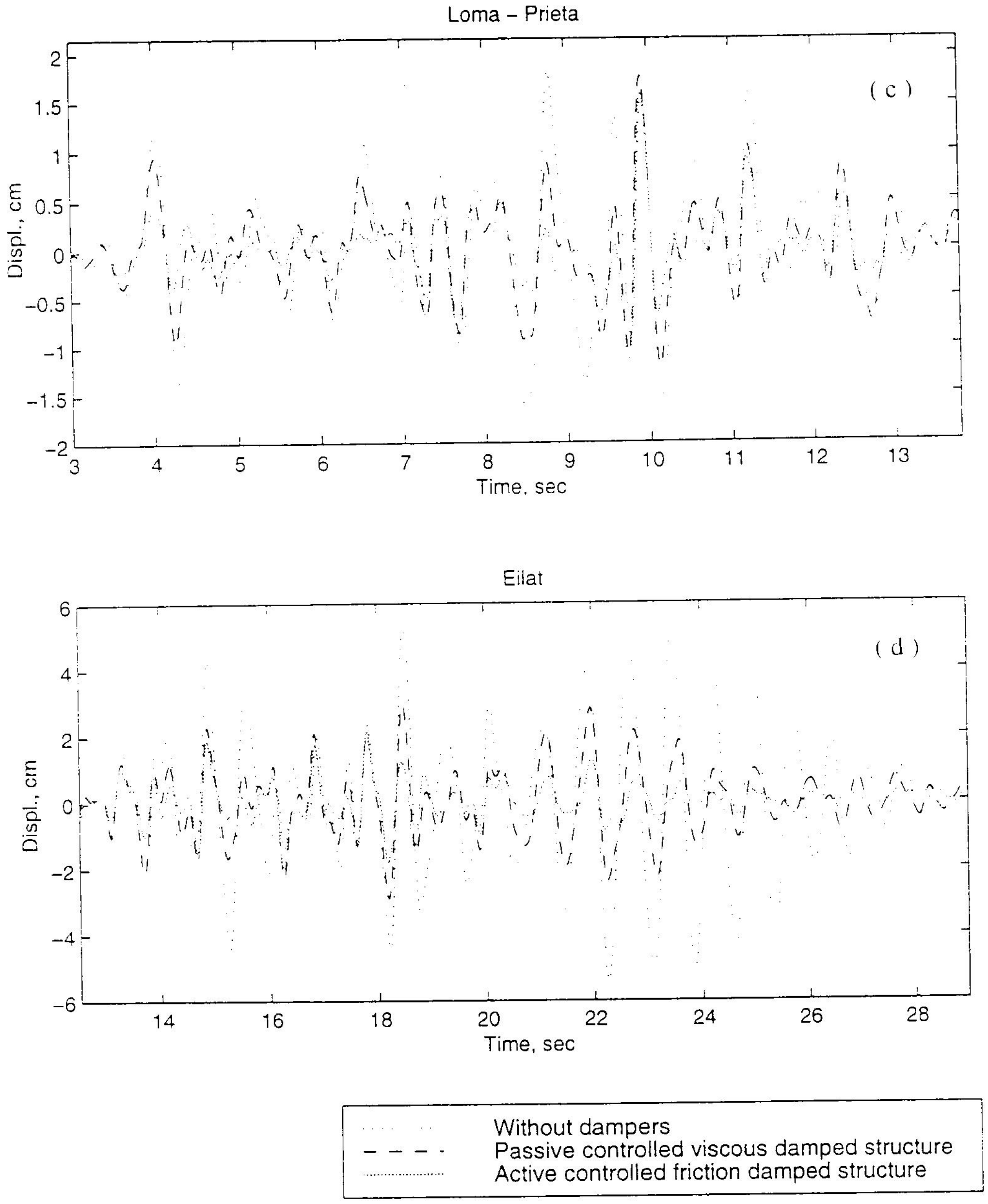


Figure 3 (cont.). Roof displacement time history of the structure subjected to
(a) El-Centro. (b) Taft. (c) Loma-Prieta. (d) Eilat earthquakes

The following four seismic excitations were used as input in the analysis: El-Centro S00E , 1940 (0.15g); Taft N21E 1952 (0.15g); Loma - Prieta N90E , 1989 (0.3g); and Eilat EL1226NS, 1995 (0.3g).

The roof displacement time histories of the structure are shown in Figure 3. Peak displacements and base shear forces of the uncontrolled, of the viscous damped passive controlled, and of the friction damped active controlled structure, respectively, are presented in Tables I, II and III.

Under the earthquake histories that were examined the passive controlled viscous damped structure had a peak displacement reduction of up to 50% compared to the uncontrolled one (see Tables I, II). For the active controlled structure a peak displacement reduction of up to 75% (compared to the uncontrolled structure) was achieved (see Tables I, III). There were no differences between the base shear forces at the three types of structures that were examined.

Table I. Peak response of the uncontrolled structure

	El-Centro	Taft	Loma -Prieta	Eilat
Roof displ., cm	6.65	4.91	1.82	5.42
Base shear. kN	910.93	892.45	2143.92	2177.09

Table II. Peak response of optimally designed viscous damped passive controlled structure

	El-Centro	Taft	Loma -Prieta	Eilat
Roof displ., cm	3.92	2.44	1.76	2.98
Base shear. kN	918.07	901.45	2122.14	2118.60

Table III. Peak response of optimally designed active controlled structure with friction dampers

	El-Centro	Taft	Loma -Prieta	Eilat
Roof displ., cm	2.26	1.21	1.60	2.14
Base shear. kN	926.02	911.86	2135.50	2132.60

CONCLUSIONS

The paper demonstrates a way to improve the behavior of multistory buildings subjected to earthquakes by application of active controlled friction dampers at each structural level. A procedure for optimal design of active controlled friction damped structures was described.

Numerical simulation of a seven-story active controlled friction damped structure was carried out. It showed reductions in peak displacements of up to 75% without an increase in the base shear forces. Hence, active controlled friction dampers are expected to significantly improve the behavior of structures during earthquakes, and buildings controlled by this type of system are likely to be less damaged by seismic loads.

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