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Optimal damper control for 3-dimensional tall buildings under earthquake excitations

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ABSTRACT: The optimal damper control for 3–dimensional tall buildings with eccentricities between the centers of mass and rigidity is performed under earthquake excitations. Firstly, an efficient passive damper controller proposed recently, named as the damper tube control system, is represented, which is shown to be conveniently installed on 3–D buildings. The damping parameters of the damper controllers are optimized to perfectly control the seismic responses of the tall buildings due to the dynamic properties of the buildings are quite sensitive to the damping values of the damper controllers. Finally, a numerical example of a 15–storey building excited by El–Centro earthquake is examined, and the results show that not only the lateral but also the torsional seismic responses of the building are significantly reduced.

1 INTRODUCTION

The safety problem of tall buildings under earthquake excitations is the most concern one of structural engineers. To alleviate seismic responses of tall buildings, the structural control has been proposed and investigated recently by Leipholz and Abdel–Rohman (1986), Li(1991), the authors(1990), McNamara (1977), Roorda (1975), Samali etc. (1985(1), 1985(2)), Yang(1982) and Yao(1972). According to the concept of Yao (1972), the structural control is divided as passive control and active control. Many researchers have indicated that the active control is more effective than the passive one, but, in the active control, external energy is needed, which is much expensive and rather limited to the practical application on actual buildings. On the contrary, in the passive control, no external energy is needed, which can be easily realized on actual buildings. Recently, some researchers, including the authors (1990), pay more attention to the investigation of the passive control systems. Most previous researches on passive control were limited to the simplified structural and excitation models in which the buildings are identically constructed with coincidental centers of mass and rigidity and only one horizontal excitation is considered. In fact, the absulate identical building is a rare case. Generally, the buildings are constructed with either designed or accidental eccentricities between the centers of mass and rigidity, which responds in coupled lateral and torsional motions of the buildings even under the horizontal earthquake excitaions, as described by Kan and Chopra(1977). Obviously, control for coupled lateral and torsional motions of buildings is also an important problem in structural control, which has been involved more recently by Samali etc. (1985(1), 1985(2))

The purpose of this paper is to investigate the optimal damper control of 3–D tall buildings with eccentricities between the centers of mass and rigidity, in which the coupled lateral and torsional seismic responses are involved. An efficient passive control device named as the damper tube control system, proposed recently by the authors(1990), is firstly represented and shown to be conveniently installed on 3–D buildings. The damping parameters of the damper controllers are optimized to perfectly control the coupled lateral and torsional seismic responses of 3–D buildings. In seismic responses analysis, the traditional methods are not suitable due to the nonclassical damping properties of the buildings controlled by the damper controllers, and the Lanczos algorithm developed recently by Nour–Omid and Regelbrugge(1989) is adopted. Finally, a 15–storey building excited by the El–Centro(1940) earthquake is numerically examined to show the control effect of optimal damper controllers on the coupled lateral and torsional seismic responses of the building.

2 THE DAMPER TUBE CONTROL SYSTEM

Some passive control devices have been proposed and applied on actual buildings, for example the tuned mass damper by McNamara(1977) and the tendon system by Roorda(1975). Here, a new passive control device proposed recently by the authors(1990) is represented, which has been proved to be efficient to control the horizontal response of tall buildings excited by strong earthquake. The new device is named as the damper tube control system, which consists of a tube filled with heavy oil and a piston with some holes, as shown in Figure 1(a). When the relative motion between the piston and the tube occurs, the heavy oil passes through the holes and produces a striking damping on the piston to restrain the relative motion, and the damping property of the damper controller conforms to the hypothesis of fluid damping.

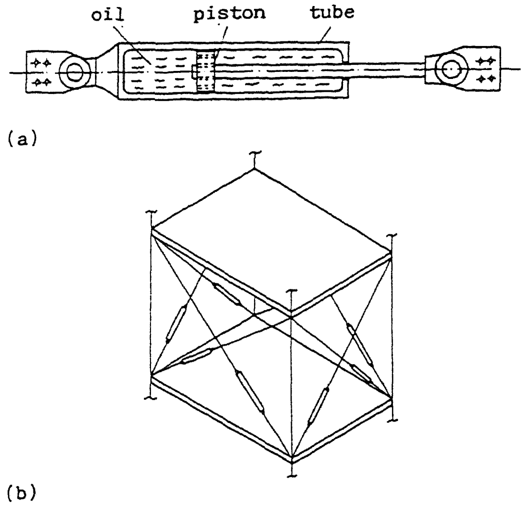

Figure 1. The damper tube control system and its installation on 3–D buildings

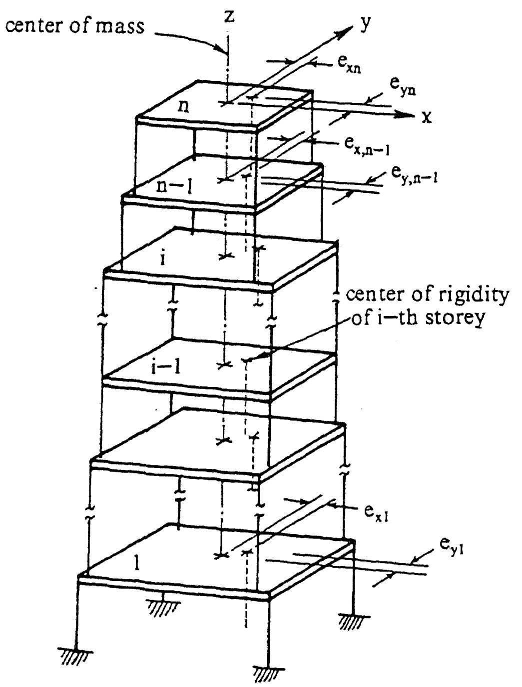

Figure 2. An idealized N–storey 3–D building

One of the remarkable advantages of the damper tube control system is to be conveniently installed even on 3–D tall buildings, as sketched on a standard storey of 3–D tall buildings in Figure 1(b). The lateral damping parameters of the damper controllers on 3–D buildings are defined as C_x and C_y along the x and y axes, and the torsional damping parameters, C_θ, should be determined. Taking a standard storey as example and assuming the pure relative torsional motion, i.e. rotation about the center of mass, the following relationship between the torsional damping moment, M_d, and the lateral damping forces, F_{dx} and F_{dy}, along the x and y axes exists:

$$M_d = 2F_{dx}\frac{b}{2} + 2F_{dy}\frac{a}{2} \tag{1}$$

in which,

$$M_d = C_\theta\dot{\theta}, \quad F_{dx} = \frac{C_x}{2}\frac{b}{2}\dot{\theta}, \quad F_{dy} = \frac{C_y}{2}\frac{a}{2}\dot{\theta} \tag{2}$$

Substituting equation (2) into equation (1), get:

$$C_\theta = \frac{1}{4}(b^2C_x + a^2C_y) \tag{3}$$

where a and b are the sizes of the building along the x and y axes.

3 EQUATIONS OF MOTION

3.1 The idealized model

Consider an idealized N–storey building model consisting of rigid floor decks supported on massless axially inextensible columns and shear walls, as shown in Figure 2, with the following assumptions: (1) The inertia of the i–th floor is lumped at the i–th floor level, and characterized by a mass, m_i, and a mass moment of inertia, J_i, about the center of mass of the i–th floor; (2) the linear rigidity of the i–th storey is provided by the massless columns and shear walls and characterized by three constants, the lateral stiffnesses, k_{xi} and k_{yi}, along the x and y axes, and the torsional stiffness, $k_{\theta i}$, about the z axis; (3) the centers of mass of the floors lie on one vertical axis, which coincides with the axis z, but the centers of rigidity of the storeys lie on different vertical axes, with static eccentricities, e_{xi} and e_{yi}, along the x axis and y axis for the i–th storey.

3.2 The equations of dynamic equilibrium of the floors

Taking the i–th floor of an idealized undamped building excited by two horizontal earthquakes along the x and y axes as example, as shown in Figure 3, a set of equations of dynamic equilibrium for the undamped case are given as:

$$\begin{aligned} &S_{x,i+1} - S_{xi} - I_{xi} = 0 \\ &S_{y,i+1} - S_{yi} - I_{yi} = 0 \\ &M_{i+1} - M_i + S_{y,i+1}e_{x,i+1} - S_{yi}e_{xi} \\ &\quad - S_{x,i+1}e_{y,i+1} + S_{xi}e_{yi} - I_{\theta i} = 0 \end{aligned} \tag{4}$$

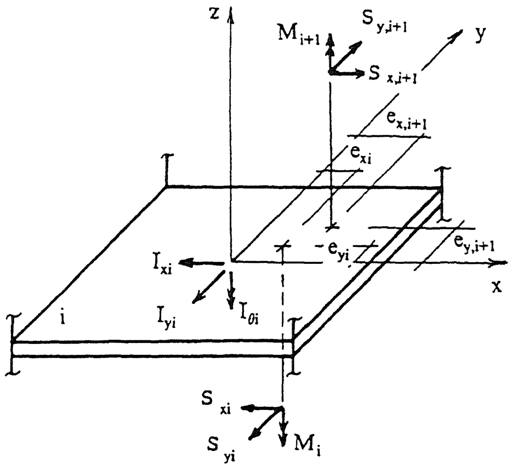

Figure 3. The dynamic equilibrium of the i–th floor

in which:

$$\begin{aligned} S_{xi} &= k_{xi}(u_i - u_{i-1}) \\ S_{yi} &= k_{yi}(v_i - v_{i+1}) \\ M_i &= k_{\theta i}(\theta_i - \theta_{i-1}) \end{aligned} \tag{5}$$

and:

$$\begin{aligned} I_{xi} &= m_i(\ddot{u}_i + \ddot{u}_g) \\ I_{yi} &= m_i(\ddot{v}_i + \ddot{v}_g) \\ I_{\theta i} &= J_i \ddot{\theta}_i \end{aligned} \tag{6}$$

where u_i and v_i are respectively the lateral displacements of the i–th floor along the x and y axes,, and θ_i is the rotation of the i–th floor about the z axis; u_g and v_g are the accelerations of the earthquake ground motion along the x and y axes.

Similarly, N sets of undamped equations of dynamic equilibrium for an idealized N–storey building can be easily obtained according to equation (4).

3.3 Equations of motion

The equations of motion of an idealized N–storey 3–D building, described above, controlled by the damper controllers, subjected to ground accelerations, $\ddot{u}_g(t)$ and $\ddot{v}_g(t)$, along the x and y axes, can be written as:

$$\mathbf{M}\ddot{\mathbf{d}} + \mathbf{C}\dot{\mathbf{d}} + \mathbf{K}\mathbf{d} = -\mathbf{M}\mathbf{R}\ddot{\mathbf{d}}_g \tag{7}$$

in which:

$$\mathbf{d} = [u_1, u_2, \cdots, u_N, v_1, v_2, \cdots, v_N, \theta_1, \theta_2, \cdots, \theta_N]^T \tag{8}$$

is the 3N dimensional relative displacement vector;

$$\mathbf{M} = \begin{bmatrix} \mathbf{m} & & \\ & \mathbf{m} & \\ & & \mathbf{J} \end{bmatrix}, \mathbf{K} = \begin{bmatrix} \mathbf{K}_{xx} & 0 & \mathbf{K}_{x\theta} \\ 0 & \mathbf{K}_{yy} & \mathbf{K}_{y\theta} \\ \mathbf{K}_{x\theta}^T & \mathbf{K}_{y\theta}^T & \mathbf{K}_{\theta\theta} \end{bmatrix} \tag{9}$$

are respectively the 3N–dimensional positive definite mass and stiffness matrices, where the sub–matrices of m and J are diagonal, and the sub–matrices of $\mathbf{K}_{xx}$, $\mathbf{K}_{yy}$, $\mathbf{K}_{\theta\theta}$, $\mathbf{K}_{x\theta}$ and $\mathbf{K}_{y\theta}$ are tridiagonal;

$$\mathbf{R} = \begin{bmatrix} \mathbf{1} & & \\ & \mathbf{1} & \\ & & 0 \end{bmatrix}, \ddot{\mathbf{d}}_g = \begin{bmatrix} \ddot{u}_g \\ \ddot{v}_g \\ 0 \end{bmatrix} \tag{10}$$

where $\mathbf{1}$ is a N–dimensional unity vector; and C is the total viscous damping matrix, and can be divided into two parts as:

$$\mathbf{C} = \mathbf{C}_b + \mathbf{C}_d \tag{11}$$

where C_b is the natural viscous damping matrix of the building–self, which is classical and can be expressed as $C_b = \alpha M + \beta K$ according to the Rayleigh's damping hypothesis. C_d is the additional viscous damping matrix of the damper controllers on the building, which generally gives the rise of nonclassical damping. Obviously, the matrix C is nonclassical, and the equations of motion of the building, equation (7), cannot be decoupled by means of the classical normal modes.

4 SEISMIC RESPONSE ANALYSIS

Because of the nonclassical damping property of the building controlled by the damper controllers, the traditional mode superposition methods cannot be employed in the dynamic analysis. Here, the Lanczos algorithm, proposed early by Lanczos(1950) and extended recently by Nour–Omid and Regelbrugge (1989), is utilized in the seismic response analysis.

Firstly, the set of coupled equations of motion, equation (7), is rewritten as a set of state equations:

$$\mathbf{A}\dot{\mathbf{y}} - \mathbf{B}\mathbf{y} = -\mathbf{G}\ddot{\mathbf{d}}_g \tag{12}$$

in which,

$$\mathbf{y} = \begin{bmatrix} \mathbf{d} \\ \dot{\mathbf{d}} \end{bmatrix} \tag{13}$$

is a 6N–dimensional state vector; and:

$$\mathbf{A} = \begin{bmatrix} \mathbf{C} & \mathbf{M} \\ \mathbf{K} & 0 \end{bmatrix}, \mathbf{B} \doteq \begin{bmatrix} -\mathbf{K} & 0 \\ 0 & \mathbf{M} \end{bmatrix}, \mathbf{G} = \begin{bmatrix} \mathbf{M}\mathbf{R} \\ 0 \end{bmatrix} \tag{14}$$

Furtherly, pre–multiplying by $\mathbf{B}^{-1}$, the equation (12) is regiven as:

$$\mathbf{H}\dot{\mathbf{y}} - \mathbf{I}\mathbf{y} = -\mathbf{B}^{-1}\mathbf{G}\ddot{\mathbf{d}}_g \tag{15}$$

where $\mathbf{H} = \mathbf{B}^{-1}\mathbf{A}$ is a 6N–dimensional unsymmetric matrix, and $\mathbf{I}$ is an unity matrix.

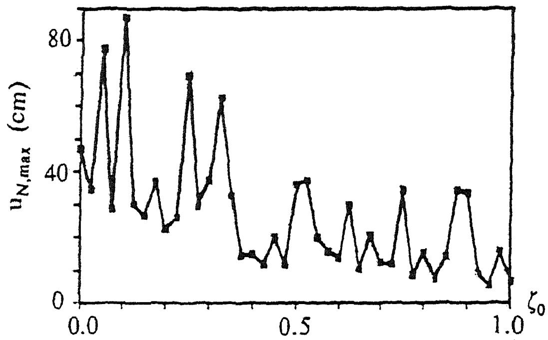

Figure 4. The influence of damping ratio on maximum top floor displacement

$$\begin{aligned} Q_m &= [q_1 \ q_2 \ \cdots \ q_j \ \cdots \ q_m] \\ P_m &= [p_1 \ p_2 \ \cdots \ p_j \ \cdots \ p_m] \end{aligned} \tag{16}$$

where $\mathbf{q}_j$ and $\mathbf{p}_j$ are respectively the 6N–dimensional right and left Lanczos vectors.

Introduce a linear transform:

$$y = Q_m z_m \tag{17}$$

where $z_m = [z_1 \ z_2 \ \cdots \ z_m]^T$ is an m–dimensional column vector of Lanczos principal coordinates.

Substituting equation (17) into equation (15) and pre–multiplying by $\mathbf{P}_m^T$, a reduced equation is gotten as:

$$T_m \dot{z}_m + U_m z_m = -W d_g \tag{18}$$

in which:

$$T_m = \begin{bmatrix} \alpha_1 & \beta_2 & & & \\ \gamma_2 & \alpha_2 & & & \\ & & \ddots & & \\ & & & \alpha_{m-1} & \beta_m \\ & & & \gamma_m & \alpha_m \end{bmatrix} \tag{19}$$

$$U_m = \begin{bmatrix} v_1 & & & & \\ & v_2 & & & \\ & & \ddots & & \\ & & & v_{m-1} & \\ & & & & v_m \end{bmatrix} \tag{20}$$

where

$$\begin{aligned} \alpha_j &= p_j^T H q_j, \quad & \beta_j &= p_{j-1}^T H q_j, \\ \gamma_j &= p_j^T H q_{j-1}, \quad & v_j &= p_j^T q_j \end{aligned} \tag{21}$$

Therefore, the 6N–dimensional state equation of the original structural system has been reduced to an m–dimensional tridiagonal equation ($m << 6N$), which can be easily solved by usual methods reviewed by Li (1991).

5 OPTIMAL DAMPER CONTROL

5.1 Influence of additional damping parameters on seismic responses

The additional damping parameters of damper controllers have been indicated to have profound influence on dynamic behaviours of tall buildings by the authors (1990). The identical 8–storey building examined there is investigated again. The variation curve of the maximum top floor displacements with the damping ratio parameters of the damper controllers is drawn in Fiqure 4. Obviously, with the increment of the damping ratio parameter ζ_0, the maximum top floor displacement response, $u_{N,max}$, does not monotonously descend, and its varying pattern is much complicit and gradually trends to come down.

5.2 Optimum of damping parameters

In order to perfectly control seismic responses of tall buildings, additional damping parameters of damper controllers must be optimized. The uniform damper controllers are assumed to be installed on each storey along the x and y axes, and characterized by an uniform damping ratio coefficient, ζ_0.

Firstly, an object function is selected as:

$$\sigma_{max} = \{[\sum_{i=1}^{N} (u_i^2 + v_i^2 + r_i^2 \theta_i^2)]^{1/2}\}_{t,max} \tag{22}$$

where u_i, v_i and θ_i are respectively the lateral displacements along the x and y axes and the rotational angle about the z axis of the i–th floor.

Then, the optimal control problem is defined as follows: to find the optimal damping ratio parameter, $\zeta_{0,opt}$, so that the object function, σ_{max}, is minimum, subjected to the restraint conditions:

$$\begin{aligned} u_{i,max} &\leq d_R \\ v_{i,max} &\leq d_R \\ \theta_{i,max} &\leq \theta_R \end{aligned} \tag{23}$$

and the boundary conditions:

$$\zeta_{0L} \leq \zeta_0 \leq \zeta_{0U} \tag{24}$$

where d_R and θ_R are respectively the allowance values of the maximum relative lateral displacement and rotational angle. ζ_{0L} and ζ_{0U} are the lower and upper limits of the damping ratio parameters of the damper controllers. In general, ζ_{0L} is selected to zero, but ζ_{0U} must be rationally evaluated, because an excessive value of ζ_0 is difficult to be actually realized.

Table 1. Properties of a 15–storey building

floor	m_i	r_i	k_{xi}	k_{yi}	$k_{\theta i}$	a_i	b_i	e_{xi}	e_{yi}
1–5	m	3.0	3k	4k	50k	6.0	8.0	0.09	0.12
6–10	m	3.0	2k	3k	40k	6.0	8.0	0.09	0.12
11–15	m	3.0	k	2k	30k	6.0	8.0	0.09	0.12

6 NUMERICAL EXAMPLE

An idealized 15–storey building with eccentricities between the centers of mass and rigidity is numerically investigated to illustrate the control effect of optimal damper controllers on coupled lateral and torsional seismic responses of 3–D tall buildings. The building is symmetrically constructed and its two principal axes are selected as the x and y axes. The centers of mass of each floor lie on one vertical line which is selected as the z axis. The properties of the building are presented in Table 1, in which $m=35t$, $k=10^5 KN/m$, and the units of all sizes are meter. The first two natural modal damping ratio coefficients are given as: $\zeta_1=0.04$, $\zeta_2=0.05$. Furthermore, the building is excited by El–Centro (1940) earthquake, and the NS wave with the maximum ground acceleration 341.7gal and the EW wave with maximum ground acceleration 210.1gal are respectively employed along the x and y axes.

The damper tube control systems are assumed to be identically installed on each storey along the x and y axes, and the damping parameters of the uniform damper controllers are defined as:

$$C_{dx} = C_{dy} = 2\zeta_0\sqrt{km} \tag{25}$$

where ζ_0 is the uniform damping ratio coefficient of the damper controllers.

In the optimal control analysis, the restraint and boundary parameters are chosen as: $d_R=d_{N0}$, $\theta_R=\theta_{N0}$, $\zeta_{0L}=0.0$, $\zeta_{0U}=0.5$, where d_{N0} and θ_{N0} are respectively the maximum relative lateral displacement and rotational angle of the top floor when the building uncontrolled.

Through the optimum analysis, the optimal value of the damping ratio coefficient of the damper controllers $\zeta_{0,opt}=0.45$, and the effect of optimal control is given in Table 2, in which $u_{N,max}$, $v_{N,max}$ and $\theta_{N,max}$ are the maximum relative lateral displacements along the x and y axes and rotational angle about the z axis of the top floor; $S_{x0,max}$, $S_{y0,max}$ and $M_{0,max}$ are the maximum interstorey shear forces along the x and y axes and torsional moment about the z axis of the bottom storey. At the same time, the time–history curves of the top floor lateral displacements along the x and y axes and the top floor rotational angle about the z axis of the 15–storey building with and without optimal control are presented in Figure 5.

From Table 2, it is seen that not only the maximum lateral but also the maximum torsional displacement and force responses of the building controlled by the optimal damper controllers are decreased at 23–32%, and a satisfied control effect of the damper tube control system on coupled lateral and torsional seismic responses of 3–dimensional tall buildings has been

Table 2. Effect of optimal control

cases	without control	optimal control	decreasing (%)
$u_{N,max}$ (cm)	39.22	29.86	23.87
$v_{N,max}$ (cm)	13.95	10.18	27.03
$\theta_{N,max}$ (deg)	3.53	2.61	26.09
$S_{x0,max}$ (10^5KN)	7.71	5.84	24.25
$S_{y0,max}$ (10^5KN)	4.32	3.12	27.78
$M_{0,max}$ (10^4KNm)	5.86	3.94	32.76

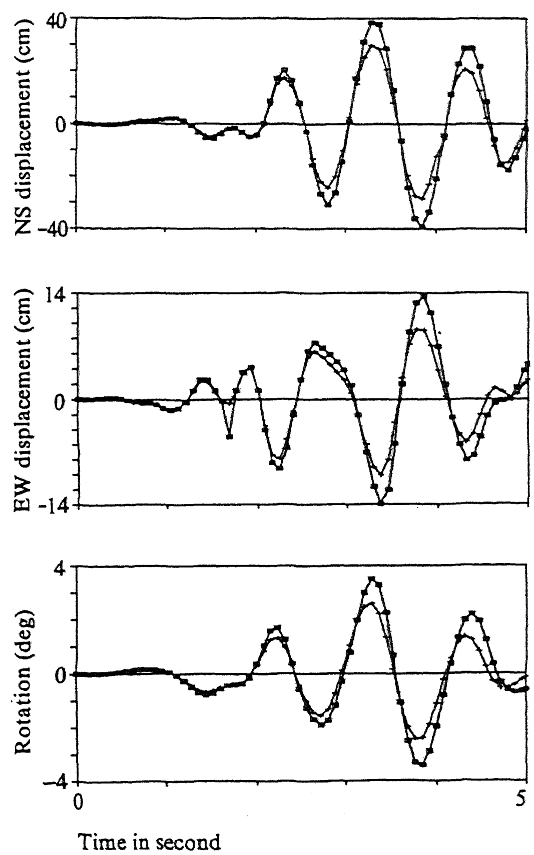

Figure 5. Coupled lateral and torsional seismic responses of a 3–D building with or without optimal damper control

obtained. From Figure 5, it is also seen that the control effect at the beginning of the earthquake excitations is unremarkable, but with increasing of time, the control effect is more striking.

7 CONCLUSIONS

The optimal damper control for 3–dimensional tall buildings under earthquake excitations has been successfully performed. The damper tube control system proposed recently is shown to be an efficient, reliable and practical passive control device, even for 3–dimensional buildings.

The control effect of the damper controllers on seismic responses of tall buildings is significantly affected by the damping parameters of the damper controllers. Therefore, the damping parameters of the damper controllers must be optimized to perfectly control the seismic responses of tall buildings.

The numerical investigation shows that not only the lateral but also the torsional seismic responses of 3–dimensional tall buildings controlled by optimal damper controllers can be remarkably decreased.

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