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ACTIVE NONLINEAR CONTROL OF STRUCTURAL SYSTEMS UNDER SEVERE EARTHQUAKE EXCITATION

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ABSTRACT

An analytical approach is presented to estimate the random seismic response of m.d.o.f. elasto-plastic structural systems with bi-linear hysteretic characteristics under saturation control force. Numerical calculations are carried out and the efficiency of the theoretical saturation control approach[1] is examined from the point of view of random seismic response and energy response. Considering the inability of installation of the saturation control system in actual structural systems, much more realistic nonlinear control systems are developed and examined from the control efficiency viewpoint through simulation analysis based on recorded earthquake accelerograms for the recent Hyogo-ken Nanbu Earthquake.

KEYWORDS

saturation control, nonlinear control, m.d.o.f.elasto-plastic systems, stochastic equivalent linearization, control energy ,hysteretic energy dissipation ,trade-off relationship

INTRODUCTION

When a deadly earthquake shook the southern part of Hyogo prefecture in Japan on 17th of January 1995, people who thought they were living in a safe place experienced vibrations so severe that all were inflicted with serious anxiety. Seismic structural response control is therefore needed not only for structural antiseismic safety but also in order to improve structural amenity under severe earthquake excitation.

In this paper, we develop an analytical approach to estimation of the random seismic response of m.d.o.f. elasto-plastic structural systems with bi-linear hysteretic characteristics under saturation control force. Numerical calculations are carried out and the efficiency of the theoretical saturation control approach is examined from the point of view of interstory displacement, ductility factor, story shear force coefficient response. The trade-off relationship between nonlinear effect of control force and attenuation effect due to hysteretic energy dissipation is examined on the basis of an energy balance equation.

Considering the inability of installation of the saturation control system in actual structural systems, further, we develop much more realistic nonlinear control systems and examine these systems from the control efficiency viewpoint through simulation analysis based on recorded earthquake accelerograms for the recent Hyogo-ken Nanbu Earthquake.

RANDOM EARTHQUAKE RESPONSE OF ELASTO-PLASTIC SYSTEMS UNDER SATURATION CONTROL FORCE

Approach to Saturation Control Based on Random Earthquake Excitation

Equation of Motion and Stochastic Equivalent Linearization of Control Force with Saturation

The structural model considered here is a lumped mass five-degree-of-freedom system , which has a viscous damper with the coefficient c_i and bi-linear hysteretic characteristics with the elastic stiffness k_i and the plastic stiffness $r_i k_i$ and the yielding defomation δ_i. The earthquake-like random excitation is idealized with a nonwhite random process which is the absolute acceleration response f of the surface layer having the damping parameter h_g and the natural angular frequency parameter ω_g subjected to white random base motion $\ddot{w}$.

The fundamental equation of motion of the system with bi-linear hysteretic characteristics can be written as :

$$\{\ddot{u}\}+[\tilde{c}]\{\dot{u}\}+[\tilde{k}]\{\phi\}=-\{1'\}f-[J]^{-1}\{p\} \tag{1}$$

$$f=\ddot{z}+\ddot{w} \quad : \quad \ddot{z}+2h_g\omega_g\dot{z}+\omega_g{}^2 z=-\ddot{w} \tag{2}$$

Utilizing a stochastic equivalent linearization[2], the bi-linear hysteretic characteristics can be expressed as :

$$\{\phi\}=[r]\{u\}+[r']([C_1]\{\dot{u}\}+[C_2]\{y\}) \tag{3}$$

$$\{\dot{y}\}=[C_3]\{\dot{u}\}+[C_4]\{y\} \tag{4}$$

in which $\{u\}$ is the interstory displacement response vector ; $[\tilde{c}],[\tilde{k}]$ are respectively the matrices associated with viscous damping and stiffness ; $\{\phi\}$ is the bi-linear hysteretic characteristics ; $\{1'\}$ is a vector with zero elements except for unity to the lowest element ; $[J]^{-1}$ is the inverse matrix for changing relative displacements to interstory displacements ; $\{p\}$ is the vector of control force per unit mass ; $\{y\}$ is the interstory displacement vector associated with the Coulomb slip element ; $[C_1]\sim[C_4]$ are the matrices associated with the stochastic equivalent linearization coefficients and f is the absolute acceleration of the surface layer subjected to the base white noise process excitation.

The optimum control force function can be approximated with a velocity response feedback type function[3] and this type of function , hereafter refered to as the optimum control force and defined by the following equation , is used for examination of the saturation effect of the control force :

$$\overline{P_i}=m_i\overline{p_i} \quad : \quad \overline{p_i}=2h_{eq}\omega_i\dot{u}_i \quad ,h_{eq}=\xi\Delta t/4\Omega_1 \tag{5}$$

in which h_{eq} is the critical damping ratio expected of the system through the control force ; ξ is the ratio of the two weighting coefficients of velocity and control force in an instantaneous optimum control theory[4] ; and Ω_1 is the fundamental angular frequency of the structural system.

On the other hand , the control force denoted by saturated P_i may be expressed with the nonlinear function of velocity response as :

$$P_i=m_i\,p_i \quad : \quad p_i=2h_{eq}\omega_i\tilde{\dot{u}}_i \tag{6}$$

$$\tilde{\dot{u}}_i=\begin{cases}\dot{u}_i:|\dot{u}_i|\le\dot{u}_{icr}\\ \dot{u}_{icr}:\dot{u}_i>\dot{u}_{icr}\\ -\dot{u}_{icr}:\dot{u}_i<-\dot{u}_{icr}\end{cases} \tag{7}$$

in which $\dot{u}_{icr}$ is the critical level of velocity response in any ith-story.
Using a unit step function $\nu(\cdot)$, Eq.(7) can be expressed as :

$$\tilde{\dot{u}}_i=\dot{u}_i\{\nu(\dot{u}_i+\dot{u}_{icr})-\nu(\dot{u}_i-\dot{u}_{icr})\}+\dot{u}_{icr}\{\nu(\dot{u}_i-\dot{u}_{icr})-\nu(-\dot{u}_i-\dot{u}_{icr})\} \tag{8}$$

and this nonlinear function can also be replaced with a linear function based on the stochastic equivalent linearization as :

$$\tilde{\dot{u}}_i = C_{5i}\dot{u}_i \quad ; \quad C_{5i} = erf\left(\frac{\dot{u}_{icr}}{\sqrt{2}\sigma_{\dot{u}_i}}\right) \tag{9}$$

in which $\sigma_{\dot{u}_i}$ is the r.m.s velocity response in any ith-story.

Utilizing the linearized bi-linear hysteretic characteristics and the saturation control force representations, the fundamental equation of motion can finally be written as :

$$\{\ddot{u}\} + \left([\tilde{c}] + [\tilde{k}][r'][C_1] + [C_5]\right)\{\dot{u}\} + [\tilde{k}][r]\{u\} + [\tilde{k}][r'][C_2]\{y\} = -\{1'\}f \tag{10}$$

$$\{\dot{y}\} = [C_3]\{\dot{u}\} + [C_4]\{y\} \tag{11}$$

$$\ddot{z} + 2h_g\omega_g\dot{z} + \omega_g{}^2 z = -\ddot{w} \tag{12}$$

Estimation of the Probabilistic Second Order Moment Response of the System

Selecting the response $\{u\}^T = \left\{\{u\}^T, \{\dot{u}\}^T, \{y\}^T, z, \dot{z}\right\}$ of the system as the state variable, Eqs.(10) ~(12) can be rewritten in a matrix form as :

$$\dot{u}_j = \sum_{i=1}^{\tilde{n}} a_{ji}u_i + b_j\ddot{w} \tag{13}$$

in which j is a variable number of the state variables with the maximum number $\tilde{n}(=3n+2)$; a_{ji} are the coefficients associated with the stiffness, viscous damping, equivalent linearization coefficients and the excitation parameters ω_g and h_g ; and b_j is the constant associated with the earthquake excitation level.

Denoting the probabilistic second order moment response of u_i and u_j by m_{ij}, , the simultaneous algebraic equation of $M_J = m_{ij}$ for stationary process[5] can be derived from Eq (13) as :

$$[A]\{M\} = \{B\}\sigma_f{}^2 \tag{14}$$

Utilizing the solution of Eq.(14), the r.m.s. story shear force response can be calculated from the following equation :

$$\sigma_{Q_i} = \sqrt{E\left[Q_i^2\right]} = m_i\omega_i{}^2\sqrt{a^2 m_{u_iu_i} + b^2 m_{\dot{u}_i\dot{u}_i} + c^2 m_{y_iy_i} + 2\left(abm_{u_i\dot{u}_i} + bcm_{\dot{u}_iy_i} + cam_{u_iy_i}\right)}$$
$$; \quad a = r_i \quad, b = r_i'C_{1i} + 2h_1/\Omega_1 \quad, c = r_i'C_{2i} \tag{15}$$

Numerical Example

The reference parameters associated with elasto-plastic structural systems under saturation control force are selected to be the elastic fundamental period $T = 1.0\,sec$; the expected critical damping ratio $h_{eq} = 0.3$; the

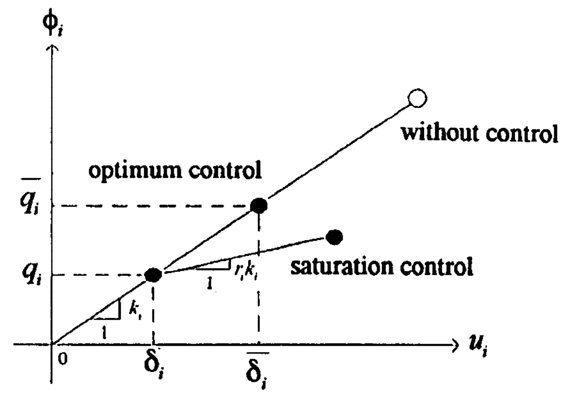


Fig. 1 Relationship among shear forces corresponding to displacement of structural systems without control, under optimum control and saturation control

second slope of bi-linear hysteretic characteristics $r_i = 0.5$; the dimensionless yielding force of structural systems $\beta_{q_i} = 0.7$; and the dimensionless critical level of saturation control force $\beta_c = 0.2 \sim 0.8$, where

$\beta_{q_i}\left(= q_i/\overline{q}_i\right)$ is the ratio of the elasto-plastic structural yielding shear force q_i under saturation control force to the maximum shear force response $\overline{q}_i$ of the elastic systems under optimum control force, while $\beta_c\left(= P_5/\overline{P}_5 = \dot{u}_{5cr}/\dot{u}_{5\max}\right)$ is the ratio of the critical velocity response $\dot{u}_{5cr}$ of the elasto-plastic systems under saturation control force to the maximum velocity response $\dot{u}_{5\max}$ of the elastic systems under optimum control force. The mutual relationships of these quantities are illustrated in Fig. 1. The parameters associated with the stationary nonwhite random excitation are selected to be the intensity level (r.m.s. value) $\sigma_f = 100$(gal.), the shaping factor $h_g = 0.5$ and the dimensionless predominant angular frequency $\rho\left(\omega_g/\Omega_1\right) = 3.0$.

Based on the response quantities calculated from Eq.(14), ① the response reduction factors, ② the mean maximum ductility factor response and ③ the mean maximum shear force coefficient response are defined as :

① response reduction factors $RF^{(1)}$, $RF^{(2)}$

$$RF^{(1)} = \frac{\text{response of elasto - plastic systems under saturation control force}}{\text{response of elastic systems without control}} \tag{16}$$

$$RF^{(2)} = \frac{\text{response of elastic systems under optimum control force}}{\text{response of elastic systems without control}} \tag{17}$$

② mean maximum ductility factor response $E[\mu_{i\max}]$

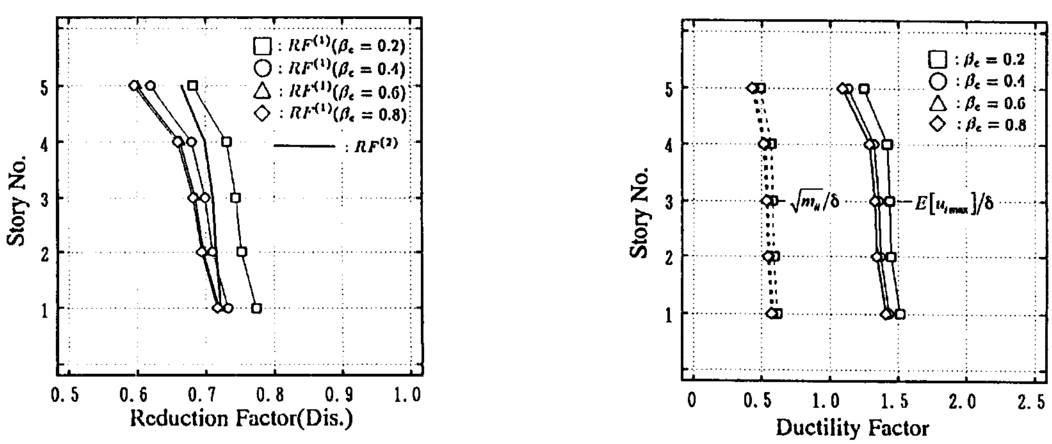
$$E[\mu_{i\max}] = \frac{E[u_{i\max}]}{\delta_i} \quad ; \quad E[u_{i\max}] = \sigma_{u_i}\sqrt{2\log_e\left(\frac{t_d}{\pi}\cdot\frac{\sigma_{\dot{u}_i}}{\sigma_{u_i}}\right)} \tag{18}$$

③ mean maximum shear force coefficient response $E[C_{i\max}]$

$$E[C_{i\max}] = \frac{E[Q_{i\max}]}{\sum_{j=i}^{n} w_j} \quad ; \quad E[Q_{i\max}] = \sigma_{Q_i}\sqrt{2\log_e\left(\frac{t_d}{\pi}\cdot\frac{\sigma_{\dot{Q}_i}}{\sigma_{Q_i}}\right)} \tag{19}$$

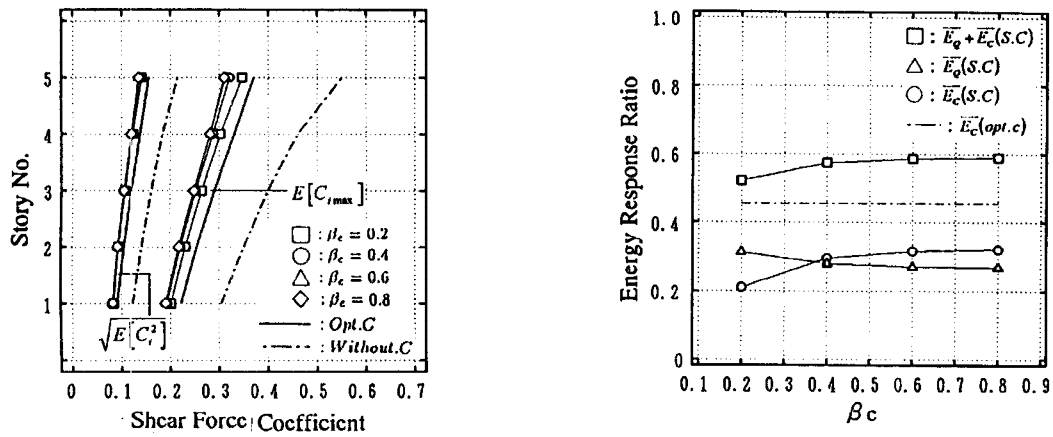
in which $E[u_{i\max}]$and $E[Q_{i\max}]$are , respectively , the mean maximum interstory displacement and the mean maximum shear force response ,and w_j is the respective story weight.

In Fig.2, the attenuation factor of structural response under saturation and optimum control force in Eqs.(16) and (17), the mean maximum ductility factor response in Eq.(18) , and the mean maximum shear force coefficient in Eq.(19) are plotted against the respective story as a function of the dimensionless critical level of saturation control force β_c ,where the attenuation factor of interstory displacement response are shown in Fig.(a), the dimensionless moment and ductility factor response is shown in Fig.(b), the story shear force coefficient in Fig.(c) , and the trade-off relationship between two response attenuation factors by control force



(a) Response reduction factor (b) Ductility factor

Fig.2 Effect of saturation control force level on structural response



(c) Shear force coefficient (d) Trade-off relationships between $\overline{E_Q}$ and $\overline{E_C}$

Fig.2 Effect of saturation control force level on structural response (continued)

and hysteretic energy dissipation in Fig.(d). Here, the energy response ratios shown in Fig.2(d) are expressed as those of the respective energy response to the total input energy response. From Fig.2(a), we see that the response attenuation factor $RF^{(1)}$, at the first floor, gradually approaches the attenuation $RF^{(2)}$ with increase of the parameter β_c , and that there is almost no difference in controlling the systems whether by saturation or by optimum control as far as the structural ductility demand is larger than 1.4 when $\beta_c \geq 0.6$.
From Fig.2(c), We learn that the shear force coefficients for the respective story under saturation control force are less than those under optimum control force , due to the combination of the energy offered dissipation by the control force and the hysteretic restoring force. These factors can be clearly seen in Fig.2(d) , in which the energy response ratios $\left(\overline{E_Q}+\overline{E_C}\right)$ offered by the restoring force and the saturation control is larger than the energy response one $\left(\overline{E_c}\right)$ offered by the optimum control.

EARTHQUAKE RESPONSE OF ELASTO-PLASTIC SYSTEMS UNDER NEW NONLINEAR CONTROL FORCE

The saturation control system discussed in the previous section is difficult to be installed in actual structural systems due to the inability of producing such nonlinear function as has sudden stop or sudden start characteristics with a certain threshold level. In this sense, much more realistic nonlinear control function should be investigated from the efficiency viewpoint. For this objective, we examine two types of function described in the following section.

Approach to New Nonlinear Control Based on Recorded Earthquake Accelerograms

The fundamental equation of motion for the simulation analysis with bi-linear hysteretic characteristics is equal to Eq.(1).
in which $\{\phi\}$and$\{y\}$ are expressed as:

$$\{\phi\}=[r]\{u\}+[r']\{y\} \tag{20}$$

$$\dot{y}_i=\frac{\dot{u}_i}{4}\left[2+sgn(y_i+\delta_i)-sgn(y_i-\delta_i)-sgn(\dot{u}_i)\{sgn(y_i-\delta_i)+sgn(y_i+\delta_i)\}\right] \tag{21}$$

δ_i and $sgn(\cdot)$ are respectively elastic-limit deformation of a bi-linear hysteretic characteristic and a signum type function.

The control force type I with a nonlinear function of velocity response ${}_1P_i$ is :

$${}_1P_i=m_i\ {}_1p_i \quad ; \quad {}_1p_i=2h_{eq}\omega_i\tilde{\dot{u}}_i \tag{22}$$

$$\tilde{u}_i = \frac{2}{\pi}\tan^{-1}\left(\frac{a_1 \cdot \dot{u}_i}{\dot{u}_{icr}}\right)\cdot \dot{u}_{icr} \tag{23}$$

in which a_1 governs the sharpness of an actual control force.
On the other hand , the control force type II ${}_2P_i$ is :

$${}_2P_i = m_i\, {}_2p_i \quad ; \quad {}_2p_i = 2h_{eq}\omega_i\tilde{\tilde{u}}_i \tag{24}$$

$$\tilde{\tilde{u}}_i = \tanh\left(\frac{a_2 \cdot \dot{u}_i}{\dot{u}_{icr}}\right)\cdot \dot{u}_{icr} \tag{25}$$

in which a_2 also governs the sharpness of control force.
In Fig.3, two nonlinear control functions in Eqs.(23) and (25) are plotted as a function of $\dot{u}_i/\dot{u}_{icr}$.
The fundamental equation of motion under nonlinear control force can finally be written as :

$$\{\ddot{u}\} + [\tilde{c}]\{\dot{u}\} + [\tilde{k}]([r]\{u\} + [r']\{y\}) = -\{1'\}f - [J]^{-1}\{p\} \tag{26}$$

$$\dot{y}_i = \frac{\dot{u}_i}{4}\left[2 + sgn(y_i + \delta_i) - sgn(y_i - \delta_i) - sgn(\dot{u}_i)\{sgn(y_i - \delta_i) + sgn(y_i + \delta_i)\}\right] \tag{27}$$

$$p_i = 2h_{eq}\omega_i\tilde{\tilde{u}}_i \tag{28}$$

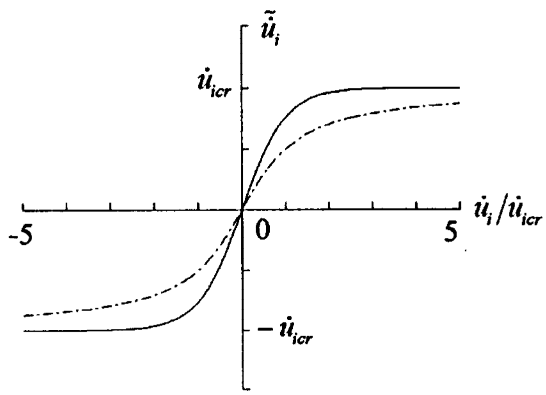


Fig.3 Nonlinear function of control force ; —-·:type I ,——:type II

Numerical Example

The reference parameters with elasto-plastic systems under two nonlinear control forces are equal to the parameters associated with structural systems under saturation control force except for the equivalent damping parameter h_{eq} and two factors governing the sharpness of control force a_1 , $a_2(=1.0)$.

The equivalent damping parameter is determined so that the maximum control force may be 2% magnitude of the total structural weight used for the reference value ; $h_{eq} = 0.139$.

The NS component of recorded earthquake accelerogam for the Hyogo-Nanbu Earthquake(1995) is used for the simulation analysis with an intensity level of 300(gal.).

In order to discuss the validity of analytical results under nonlinear control force, the structural response ratio and the control force ratio are defined as :

$$\gamma^{(1)} = \frac{\text{maximum response of elasto-plastic systems under nonlinear control force}}{\text{maximum response of elasto-plastic systems under saturation control force}} \tag{29}$$

$$\gamma^{(2)} = \frac{\text{maximum nonlinear control force}}{\text{maximum saturation control force}} \tag{30}$$

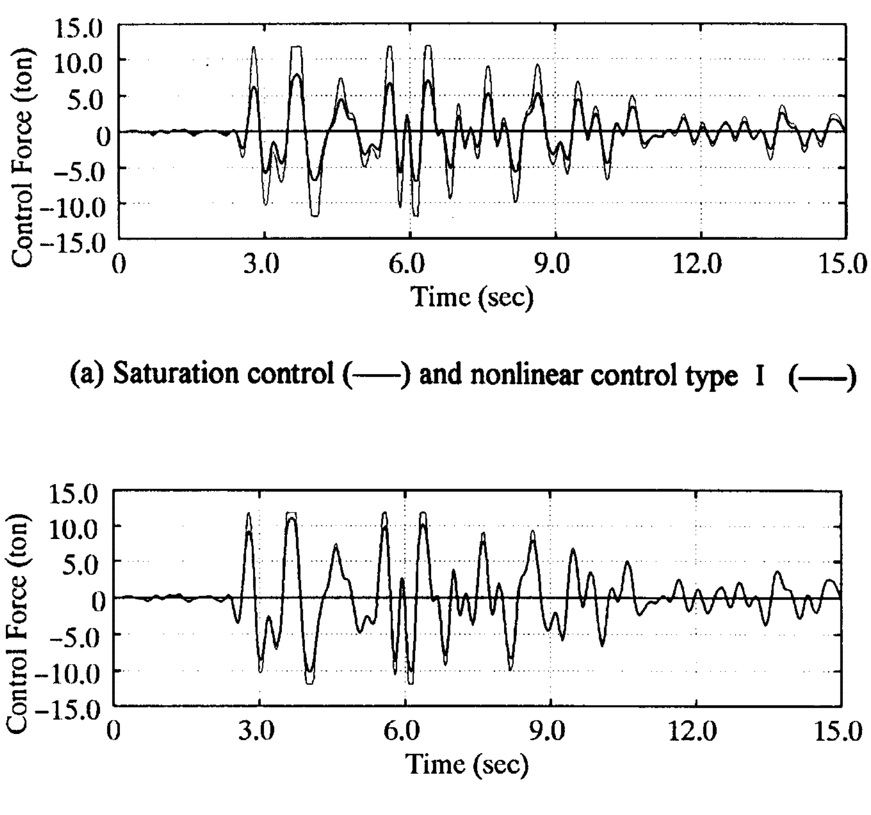
In order to make a comparison between saturation and nonlinear control force type I , II , the time histories of these control forces are plotted in Figs.4(a)and(b),where the critical damping level of control force $\beta_c = 0.6$.
From Fig.4(a), we see that the nonlinear control force type I is less than the saturation control force as a whole. From Fig.4(b) ,we learn that there is almost no difference between the nonlinear control and the

saturation control forces.

In Figs.5, the structural response ratio under nonlinear control force type I and II in Eq.(29) and the control force ratio in Eq.(30) are plotted as a function of the critical damping level β_c for the respective story, where the ratios of interstory displacement response are shown in Figs.(a) and (b), the control force ratio in Fig.(c). From Fig.5(a), we see that the response ratios $\gamma^{(1)}$ for the respective story are scattered and increase with increase of the parameters β_c, that is,the effects of nonlinear control on structural response attenuation gradually decrease as compared with those of saturation control. From Fig.5(b), we learn that there is almost no difference in the response ratio $\gamma^{(1)}$ except for $\beta_c = 0.8$. From Fig.5(c), we learn that the control force ratios for nonlinear control type I rapidly decrease with increase of the parameters β_c, as compared with those for type II. Nonlinear control force type II ,therefore, is much more effective than the force type I for actual nonlinear control systems.

CONCLUSION REMARKS

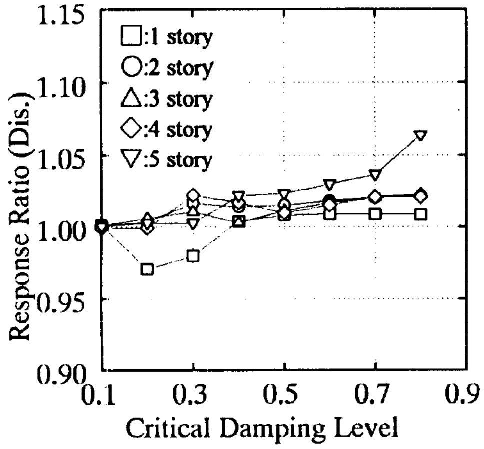
This paper developed a theoretical active nonlinear control approach useful for structural systems under severe earthquake excitation. The theoretical saturation control approach was based on a probabilistic approach in which seismic response was estimated for elasto-plastic structural systems with bi-linear hysteretic characteristics. The efficiency of the control approach was demonstrated for random seismic response of five-degree-of-freedom structural models. The trade-off relationship between nonlinear effect of control force and attenuation effect due to hysteretic energy dissipation was examined on the basis of an energy balance equation. Further, for physical realization of actively controlled structures, we examined two nonlinear control functions from the control efficiency viewpoint through simulation analysis based on recorded earthquake accelerograms and these functions were found to be effective for this objective.



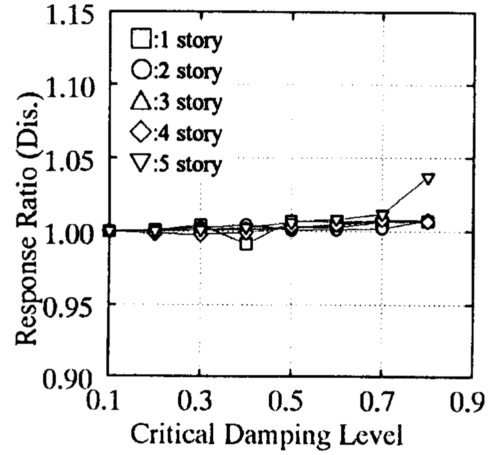
(a) Saturation control (——) and nonlinear control type I (——)

(b) Saturation control (——) and nonlinear control type II (——)

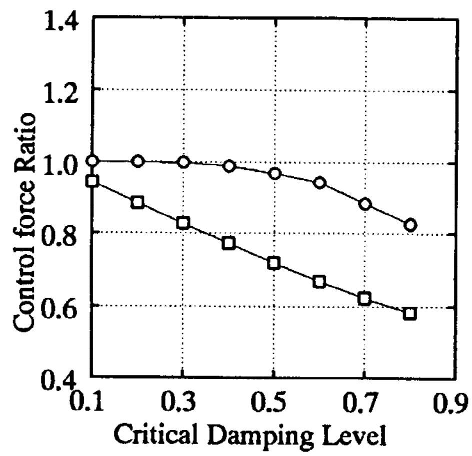
Fig.4 Time-history of saturation and nonlinear control force



(a) Response ratio (nonlinear type Ⅰ)



(b) Response ratio (nonlinear type Ⅱ)



(c) Control force ratio; □:type Ⅰ ○:type Ⅱ

Fig.5 Validity of analytical results under nonlinear control force

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