RESPONSE CONTROL EFFECT OF COUPLED VIBRATION CONTROL STRUCTURES USING HYSTERESIS DAMPER UNDER GROUND MOTION

K. Tahara [1], S. Yamazaki [2] and S. Minami [3]

[1] *Dr. Eng., Fujita Corporation, Tokyo, Japan*
[2] *Prof. Emeritus, Tokyo Metropolitan University Tokyo, Japan*
[3] *Assistant Prof., Dept. of Architecture and Building Engineering, Tokyo Metropolitan University, Tokyo, Japan*
E-mail: kenichi.tahara@fujita.co.jp

ABSTRACT :

"Coupled vibration control structures" is a method for reducing earthquake responses by connecting buildings with different periods using dampers. In this paper, two single-degree-of-freedom systems connected with a hysteresis damper are used for the vibration model. The objective of this paper is to reveal the general characteristics of coupled vibration control structures analytically. The criteria of the response control effect are the reduction of the deformation of the buildings. The optimum damper conditions and the relationship between the response control effect and the combination of buildings are investigated. By comparing the deformation of the buildings connected with the optimum damper to that of rigidly connected buildings, equations to predict the effect of vibration control can be obtained.

KEYWORDS: Coupled vibration control, Optimum damper, Hysteresis damper, Response control effect, Prediction of response

1. INTRODUCTION

"Coupled vibration control structures" is one kind of response control system. By connecting two or more buildings using dampers (energy absorption device) the responses of connected buildings can be reduced. It can be assumed that the effect of response control of this system is superior to that of the other kind of response control system.

In this paper, a method is proposed to predict the effect of response control of the coupled vibration control structures. It can be said that the response control effect of this system is caused by the energy absorption of connecting damper and the influence of the transition of the dominant period.

2. VIBRATION MODEL AND INDEX OF RESPONSE CONTROL EFFECT

2.1. Vibration Model

The vibration model is composed of two buildings connected with a hysteresis damper. These buildings are modeled as a single-degree-of-freedom (SDOF) with an elastic resistance (See. Figure 1).

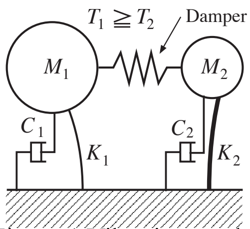


Figure 1 Vibration model

2.1.1 Buildings to connect

The connected building with longer natural period will called "B1" and that with shorter period "B2". The period, the mass and the stiffness of the buildings will be expressed as follows with a suffix 1 or 2 to indicate B1 or B2.

Period of Bn: T_n Mass of Bn: M_n Stiffness of Bn: K_n
where n =1 or 2

$$T_2 > T_1 \tag{2.1}$$

The ratio of the period, the mass and the stiffness of two buildings is written as following.

Period ratio: $t = T_2/T_1$ Mass ratio: $m = M_2/M_1$ Stiffness ratio: $k = K_2/K_1$

The buildings connected with a rigid link are termed BR. The period, the mass and the stiffness of BR can be written as following.

Mass of BR: $M_R = M_1 + M_2$ Stiffness of BR: $K_R = K_1 + K_2$

$$\text{Period of BR:} \quad T_R = 2\pi\sqrt{M_R/K_R} \tag{2.2}$$

The damping factor (ξ) of B1, B2 and BR is 2%.

2.1.2 Connecting damper

The connecting damper is modeled as an elasto-plastic model without viscous damping.
The yield strength and the elastic stiffness will be indicated as a non-dimensional index α and β as follows

$$\alpha = Q_p / (a_{R\max} \cdot M_R) \qquad (2.3) \qquad\qquad \beta = K_e / K_R \qquad (2.4)$$

where Q_p : yield strength of the damper
$a_{R\max}$: peak acceleration of BR
K_e: elastic stiffness of the damper

The energy absorption of the damper will be indicated by a non-dimensional index η as follows

$$\eta = \frac{E_D}{Q_p \cdot \delta_p} \qquad (2.5)$$

where E_D: energy absorption of the damper
δ_p: yielding deformation of the damper

2.2. Response Control Effect

The response control effect will be judged by the reduction of the peak deformation of the buildings by using the following index d_n.

$$d_n = D_n / D_{nNC} \qquad (2.6)$$

where D_n: deformation of connected B*n*
D_{nNC}: deformation of unconnected B*n*

In the case of the target of response control being the reduction of the deformation of one building (B1 or B2), the effect of response control will be judged by using d_1 or d_2. In the case of the target being reduction of the deformation of both buildings together (B1 and B2), the effect of response control will be judged by using d_{12} as following,

$$d_{12} = \max(d_1, d_2) \qquad (2.7)$$

If d_n or d_{12} are greater than 1.0 the response of the building is increased by connecting. The objective of this system is to minimize d_n or d_{12}.

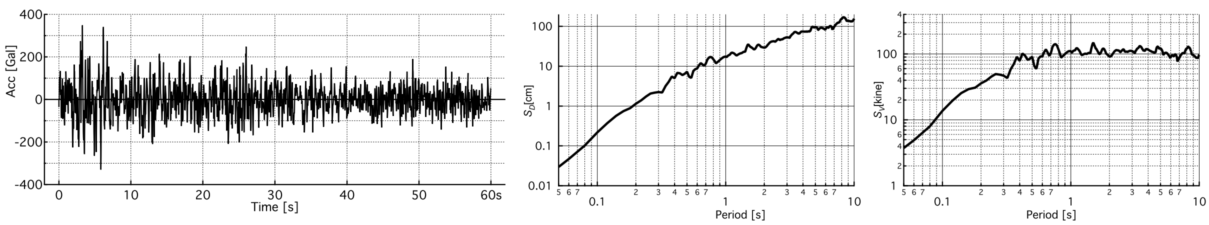
2.3. Input Waves

The seismic wave input is a simulated wave BCJ-L2 (See Figure 2). The response spectrums of this seismic wave is shown in Figure 2.

3. CHARACTERISTICS OF DAMPER AND RESPONSE CONTROL EFFECT

3.1. Subject of Analyses

In this section, the optimum damper conditions will be investigated by analyzing the coupled vibration control structures system whilst varying the characteristics of the connecting damper.
Then, four combinations of connected buildings are used for the analyses (See Table 1). The relationships between these four combinations of buildings are shown in Figure 3. The horizontal axis of this figure indicates the stiffness ratio *k* and the vertical axis indicates the mass ratio *m*. When the *k* and *m* axes are drawn as logarithmic axes, *t* axis can be drawn as a 45 degree axis (See Figure 3). By defining the period of BR as 0.2, 0.5, 1.0 and 2.0 sec., the period of B1 and B2 can be calculated as shown in the Table 1.



Figrue 2 Time histpry and response spectram (ξ = 2%) of input seismic wave

Table 1 Combnations of buildings

combination		(1)	(2)	(3)	(4)
ratio	k	0.4	2.0	10.0	10.0
	m	0.1	0.5	2.5	0.1
	t	0.5	0.5	0.5	0.1
case (A)	T_1	0.23 s	0.28 s	0.36 s	0.63 s
$T_R = 0.2$	T_2	0.11 s	0.14 s	0.18 s	0.063 s
case (B)	T_1	0.56 s	0.71 s	0.89 s	1.58 s
$T_R = 0.5$	T_2	0.28 s	0.35 s	0.44 s	0.16 s
case (C)	T_1	1.13 s	1.41 s	1.77 s	3.16 s
$T_R = 1.0$	T_2	0.56 s	0.71 s	0.89 s	0.32 s
case (D)	T_1	2.26 s	2.83 s	3.55 s	6.32 s
$T_R = 2.0$	T_2	1.13 s	1.41 s	1.78 s	0.63 s

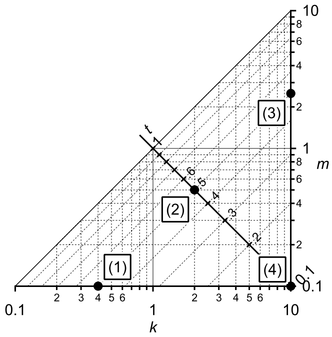


Figure3 Relationship of combinations of buildings

3.2. Contour Plot of Response Control Effect

The relationship between the characteristics of the damper and the response control effect are shown in Figure 4. The vertical axis of each graph shows β and the horizontal axis shows α on a logarithmic scale. From left to right, the results of the combinations of buildings being (2) and (4) of the case (A), (2) and (4) of the case (B), from (1) to (4) of the case (C), (2) and (4) of the case (D) are shown. From top to bottom, the contour line shows the d_1, d_2, d_{12} and e_D gain from the result of the analyses of the each case. e_D is the non-dimensional index of the energy absorption of the damper as followings.

$$e_D = E_D / E_{GR} \tag{3.1}$$

where E_{GR}: Energy input from ground motion

3.3. Optimum Damper

When the target of the response control is Bn, d_n is the index of the effect of response control. Where the value of d_n is smallest is the optimum conditions of the damper characteristics α and β are met. When the target of the response control is to control both buildings together, d_{12} is the index. The conditions of the damper with d_n or d_{12} being less than its smallest value + 0.1 will be called "virtually optimum" conditions.

By examining each graph, the following can be said. In the area with α being large value(right area), the contour lines are horizontal. This is because the damper is not yielded and the responses are not dependent on the yield strength of the damper. In the area with α being small (left area), the value of d_n or d_{12} is almost 1.0. In such area, the restoring force of the damper is almost zero so that the responses of the connected buildings are similar to that of unconnected buildings. The range of the virtually optimum α is from half to double of the optimum value of α. It can be said that the virtually optimum β is grater than 0.5. By comparing the different cases of the period (case(A), (B), (C) and (D)), d_2 and d_{12} are smaller as the period becomes smaller. But d_1 is not vary according to the period.

In the case of the combinations of buildings being (4) of the case (A), (B) and (C), d_2 and d_{12} is greater that 1.0 in almost every area. In such cases this system is not suitable for application.

3.4. Influence of Period Ratio

By comparing the results of the different combinations of buildings, the following observations were made.

While the combinations (1), (2) and (3) have the same period ratio, 0.5, the areas of the characteristics of the damper on virtually optimum condition to control B1 and B2 are almost the same. These virtually optimum areas are also similar to the area of higher e_D.

This means that it is easy to control both buildings together. And it can be said that the damper with high energy absorption can reduce the responses of the connected buildings effectively.

The combination (4) has a period ratio, 0.1. The virtually optimum areas of d_1, d_2 and d_{12} of the combination (4) are not similar to each other. This means that it is difficult to reduce the responses of both buildings together.

3.5. Damage of Damper

Energy absorption of the hysteresis damper is caused by plastic damage to the material of the damper. So, the energy absorption capacity is limited by the fracture of the damper. Some test results indicate that the energy absorption capacity is from 100 to 3000 expressed as the index η.

In Figure 4, the energy absorption index η (including the index of damage of the damper) of the damper is represented as dashed contour lines. The contour lines are skipped which indicate η greater than 10000 and less than 100. By considering the energy absorption capacity being 1000 in η, the virtually optimum areas are not beyond the area of the η less than 1000 in most cases.

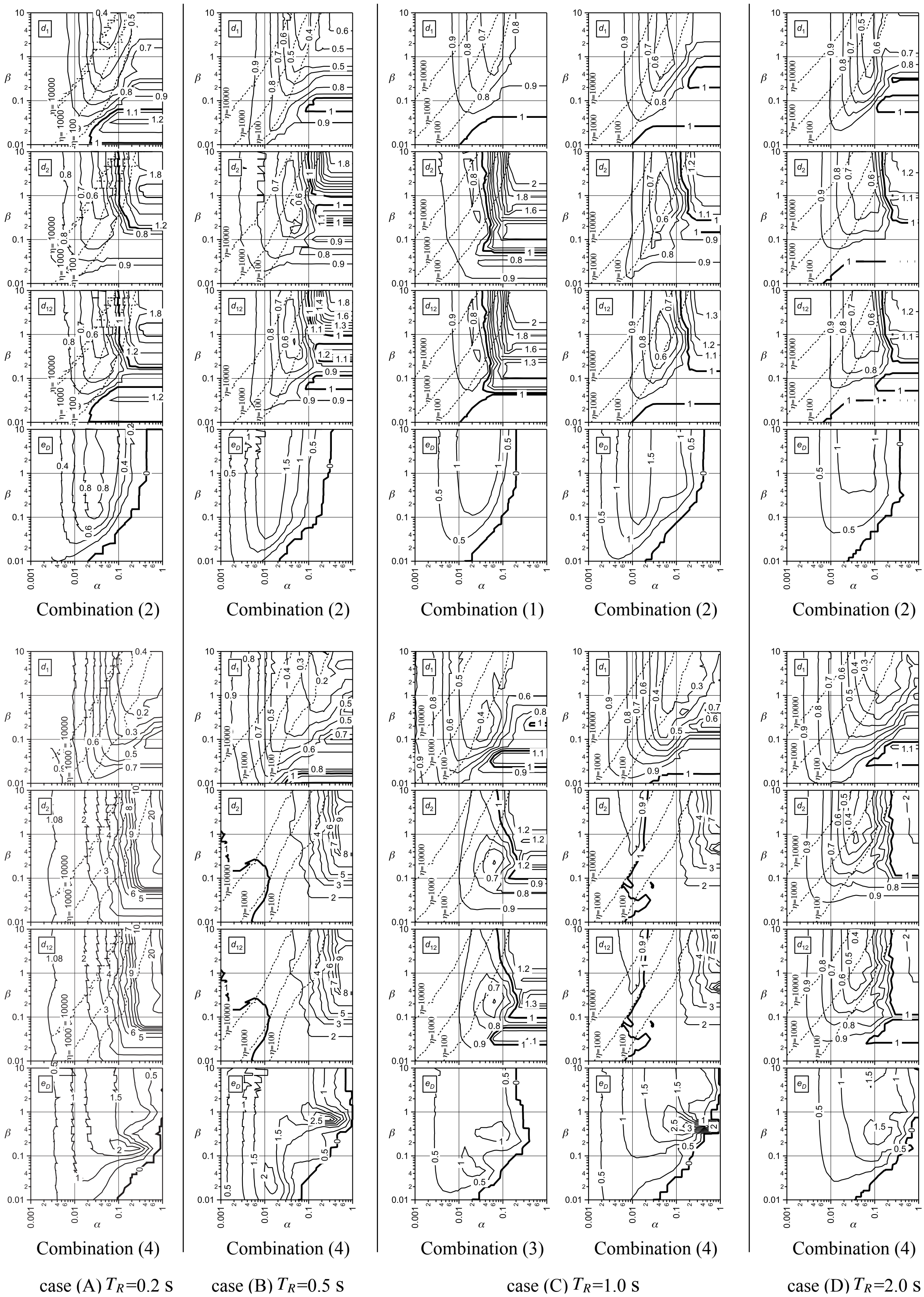


Figure 4 Peak deformation vs. caracteristics of damper

4. COMBINATIONS OF BUILDINGS AND RESPONSE CONTROL EFFECT

In section 3, some difference in the response control effect can be seen between different kinds of the combinations of buildings. In this section, the influence of different building combinations on the response control effect using the optimum damper is investigated.

4.1. Subject of Analyses

The analyses are done by varying the combinations of buildings and splitting as a grid in the range of the parameters as followings,

- $0.1 < m < 10.0$
- $0.1 < k < 10.0$ (also see Figure 5)

The white dots and the black dots plotted on the Figure 5 show the points of analyses. The period of both buildings are calculated by fixing the T_R as 0.2 (case (A)), 0.5 (case (B)), 1.0 (case (C)) and 2.0 (case(D)). The connecting dampers are set as the optimum condition with the value of η (the index of the energy absorption) of the damper less than 1000.

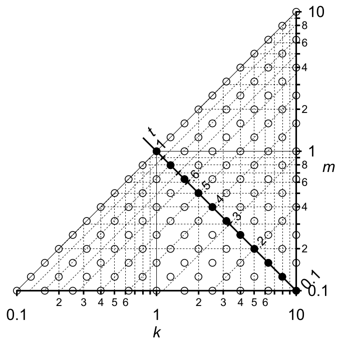
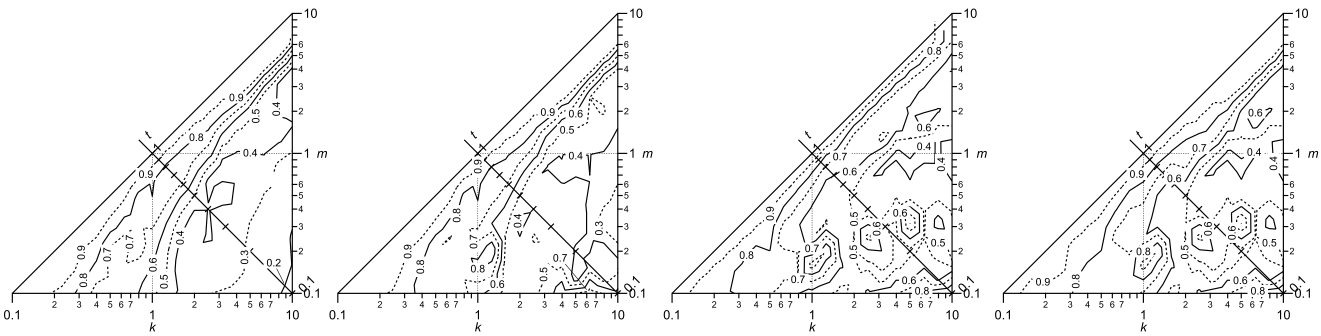


Figure 5 Combinations of buildings

4.2. Response Control Effect vs. Mass Ratio, Stiffness Ratio and Period Ratio

Figure 6 shows the relationship between the response control effect and the combination of buildings under the conditions of analyses being case (C). The horizontal axis shows the the stiffness ratio k and the vertical axis displays the mass ratio m. Each contour line shows the index of response control effect: d_{1opt1} (Figure 6 (a)), d_{1opt12} (Figure 6 (b)), d_{2opt2} (Figure 6 (c)) and d_{2opt12} (Figure 6 (d)). The value d_{1opt12} is the response control effect of B1 (d_1) using the damper to minimize d_{12}, although d_{1opt1} is the index of the response control effect of B1 using the damper to minimize d_1. d_{2opt12} is the same index of B2. This means that d_{1opt12} and d_{2opt12} are the non-dimensional index of the deformation of B1 and B2 when the target of response control is on both buildings together.

It can be seen that most contour lines are cross the period ratio (t) axis at right angles. This means that the response control effect using an optimum damper is mainly affected by the period ratio. However, by comparing the cases of the same period ratio with different mass ratio (m) and stiffness ratio (k), it can be seen that large value of m and k (left and upper side of the figure) have a better response control effect especially where t is smaller than 0.5.



(a) d_{1opt1} (b) d_{1opt12} (c) d_{2opt2} (d) d_{2opt12}

Figure 6 Response control effect vs. combinations of buildings (case (C))

4.3. Response Control Effect vs. Period Ratio

To see in detail, the relationships between the response control effect and the period ratio t are investigated by using the combinations of buildings of the black dot of Figure 5. Figure 7 shows the relationships between the response control effect and the period ratio. The left-hand figure shows d_{1opt1} and d_{1opt12} vs t, and right-hand figure shows d_{2opt2} and d_{2opt12} vs t.

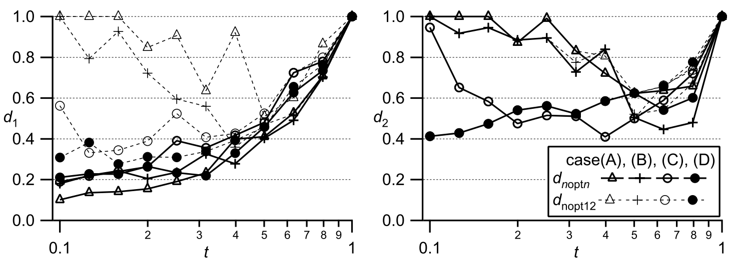


Figure 7 Response control effect vs. period ratio

4.3.1 In case of target of response control being one building

It can be seen that d_{1opt1} gets smaller as t gets smaller and d_{1opt1} vs t relationship of case (A), (B), (C) and (D) show similar results. On the other hand, d_{2opt2} is smallest when t is about 0.5 especially in the case of (A) and (B).

4.3.2 In case of target of response control being both buildings together

Because the response control effect of B2 is less than that of B1 in most cases and the damper is intended to reduce the greater of d_1 or d_2 (See Eqn. 1.7) to control both buildings together, the optimum damper to control the responses of both buildings together is same with the optimum damper of B2. So, d_{2opt12} is almost same with d_{2opt2} as it can be seen in Figure 7. d_{1opt12} is larger than d_{1opt1} as the t gets smaller especially in case (A) and (B).

4.4. Influence of Response Spectrum on Response Control Effect

The response control effects of the coupled vibration control structures can be considered as a combination of two causes. The first is the energy absorption of the connecting damper. It gives the buildings some damping effect. The other cause is the rise or fall of the displacement response caused by the transition of the dominant period of connected buildings (See Figure 8). By connecting two buildings, the period of a building with longer period (B1) gets shorter and that with shorter period (B2) gets longer. If the displacement spectrum increases as the period increases as is the often case with the general seismic waves, the response of B1 decreases as the period of B1 gets shorter and the response of B2 increases as the period gets longer. So the effect of the transition of the dominant period makes the response control effect of B1 better and that of B2 worse.

The response spectrum of the seismic wave used in this study (BCJ-L2) was made to fit its velocity spectrum a multi-liner curve. The velocity response spectrum increases where the period is less than 0.64 sec. and is constant where the period is greater than 0.64 sec. Where the period is less than 0.64 sec., the displacement response spectrum increases at a steep angle. When the period of B2 is less than 0.64 sec., the response control effect is much worse because the negative effect of the transition of the dominant period is much stronger. So, it is difficult to control the response of B2 or both buildings if the period of B2 is very short.

The effect of the transition of the dominant period is affected by the relationship between the natural period of BR (T_R) and that of B1 (T_1) or B2 (T_2). When connected, the dominant period of B1 and B2 tends towards T_R. If the T_1 or T_2 is close to T_R, the change of the dominant period is small and rise or fall of the displacement spectrum is also small. On the other hand, if T_1 or T_2 is very different from T_R, the transition of the dominant period is large and rise or fall of displacement spectrum is also large.

In the area of $k < 1/m$ (thin hatching area in Figure 9), T_1 is closer to T_R and T_2 is further from T_R. In the area of $k > 1/m$ (thick hatching area in Figure 9), T_1 is further from T_R and T_2 is closer to T_R. As has already been described, the transition of dominant period has positive influence on B1 and negative influence on B2 and that influence is large when the natural period of B1 or B2 is very different from T_R. So the response control effect of B1 and B2 in the area of $k < 1/m$ is better than that of $k > 1/m$, compared in the same period ratio. This tendency has previously noted in the last sentence of section 4.2.

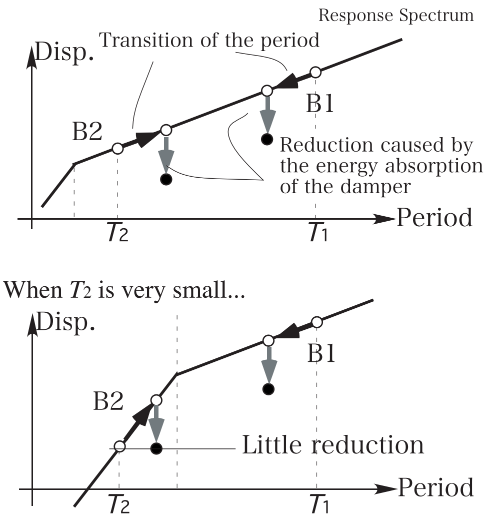


Figure 8 Two factor of response control effect

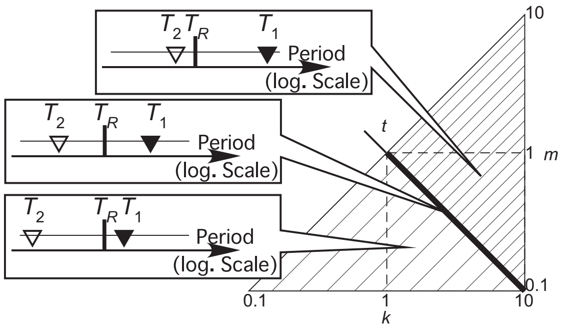


Figure 9 Relationship between period of B1 and B2 vs. BR

5. ESTIMATION OF RESPONSE CONTROL

5.1. Response Control Effect In Case of Target Being One Building

The method for estimating the response control effect of the coupled vibration control structures is led by using the argument in the section 4.2.

In this paper, it is considered that the dominant period of B1 and B2 become same as T_R when connected. Then the influence of the rise or fall of displacement spectrum can be expressed by the ratio of deformation of BR and that of B1 or B2 as following factor: d_{Rn},

$$d_{Rn} = D_R / D_{nNC} \tag{5.1}$$

The following index d_{noptnR} is defined as the response control effect divided by d_{Rn},

$$d_{noptnR} = d_{noptn}/d_{Rn} = \frac{D_{noptn}/D_{nNC}}{D_R/D_{nNC}} = \frac{D_{noptn}}{D_R} \quad (5.2)$$

where D_{noptn} represents the peak deformation of Bn using a damper for optimum control on Bn. This factor also means the ratio of the deformation of B1 or B2 using optimum damper and the deformation of BR.

Figure 10 shows the relationship between d_{noptnR} and t of the combinations of buildings indicated as black dots in Figure 5. The left-hand figure shows the relationship of d_{1opt1R} vs. t and right-hand figure shows that of d_{2opt2R} vs. t. Although d_{noptn} vs. t shown in Figure 7 has some dispersion, d_{noptnR} vs. t has clear tendency with less dispersion. The fitting curves shown as thick lines in Figure 10 can be gained from d_{1opt1R} vs. t and d_{2opt2R} vs. t by a method of least squares as follows,

$$d_{1opt1R} = 0.41t^{1.5} + 0.59 \quad (5.3)$$

$$d_{2opt2R} = 0.83t^{2.1} + 0.17 \quad (5.4)$$

d_{noptnR} closely describes the factor of the reduction of response caused by the energy absorption of a damper while d_{Rn} describes the influence of the transition of dominant period on a displacement response spectrum shown in a section 4.4. It can be said that the response control effect d_{noptn} can be gained by multiplying d_{noptnR} and d_{Rn}.

5.2. Response Control Effect in Case of Target Being Both Buildings Together

Because the optimum damper to control both buildings together is decided to optimize the response of a building with less reduction of response (it is often B2), the response control effect of a building with better reduction of response (it is often B1) becomes worse than if a damper was used to optimize the response of only one building. In this paper, it is assumed that the factor of the influence of spectrum of the other building of the two (it is called as "Bm") has something to do with the response control effect of a building using the damper to control both buildings together.

Figure 11 shows the relationship between the ratio of response control effect using a damper to control both buildings together and one building (d_{nopt12} / d_{noptn}) and the factor of the influence of spectrum of Bm (d_{Rm}). In the area where d_{Rm} is greater than 1.0, d_{nopt12} / d_{noptn} gets increased as d_{Rm} increases. This relationship can be expressed as a curve of following equations virtually fitted on upper bound shown in a thick line in Figure 11.

$$d_{nopt12}/d_{noptn} = 0.1{d_{Rm}}^2 + 0.9 \qquad \text{under } d_{Rm} > 1.0 \quad (5.5)$$

$$d_{nopt12}/d_{noptn} = 1.0 \qquad \text{under } d_{Rm} < 1.0 \quad (5.6)$$

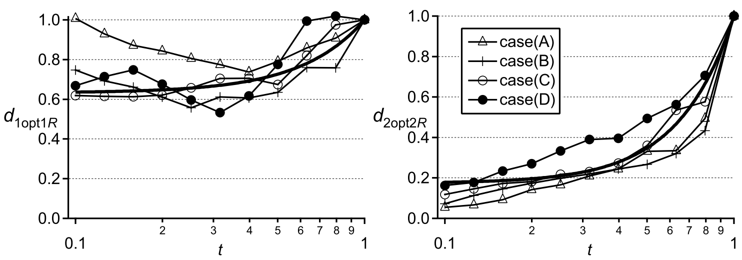


Figure 10 d_{noptnR} vs. period ratio

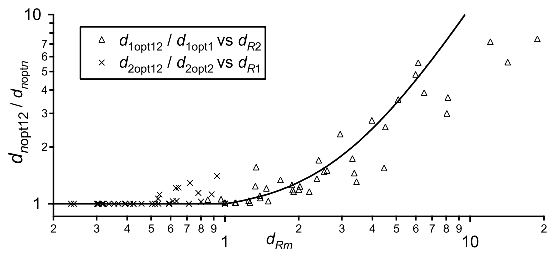


Figure 11 d_{nopt12} / d_{noptn} vs. d_{Rm}

5.3. Prediction of Response Control Effect

The method to predict the response control effect can be summarized by the above discussion.

1. Calculate d_{Rn} (the ratio of the response of Bn and BR) by using a spectrum estimated in design.
2. Multiply d_{noptnR} calculated by using Eqn. 5.3 or 5.4 on d_{Rn} and get d_{noptn}. If d_{noptn} is greater than 1.0, d_{noptn} must be 1.0.
3. Multiply d_{nopt12} / d_{noptn} calculated by using Eqn. 5.5 or 5.6 on d_{noptn} and get d_{nopt12}. If d_{nopt12} is greater than 1.0, d_{nopt12} must be 1.0.

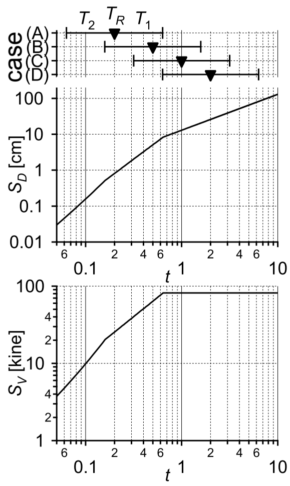
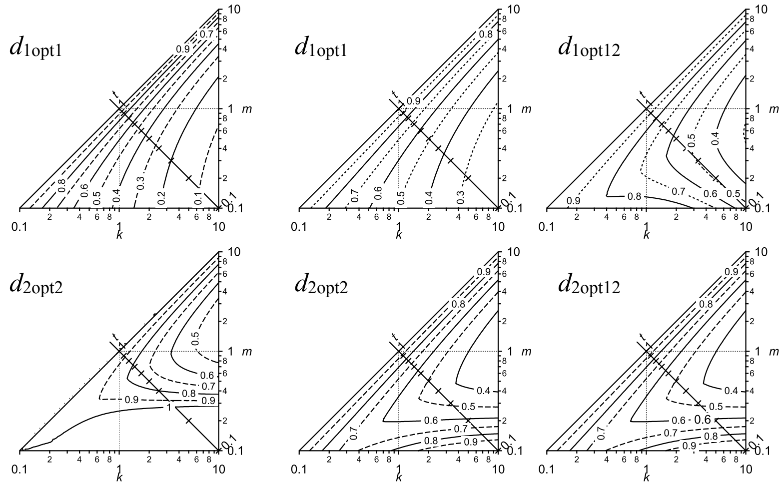


Figure 12 Modeled response spectrum



(a) case (A) (T_R = 0.2 s) (b) case (C) (T_R = 1.0 s)

Figure 13 Standard response control effect

5.4. Standard of Response Control

By using a modeled spectrum shown in the technical bulletin of Construction Ministry of Japan (See Figure 12) for the prediction of response control, the standard of the response control effect can be gained. Figure 13 shows the results. These standard response control effects correspond with the results of earthquake response analyses not only in a qualitative manner but also from a quantitative standpoint (compare Figure 6 with Figure 13 (b)). As can be seen in Figure 13 (a), the area without response control effect (the area of =1.0) that was seen in the result of analyses can be predicted.

6. CONCLUSIONS

The characteristics of the response control effect of the coupled vibration control structures were investigated and a method to predict the response control effect was proposed in this paper. The response control effect was evaluated by the reduction of the peak deformation of the connected buildings compared with the peak deformations of uncoupled buildings. The conclusions of this paper can be summarized as follows

1. The response control effect of the coupled vibration control structures is due to a combination of two factors; the energy absorption of a damper and the rise or fall of the displacement response cased by the transition of dominant period of the connected buildings. The influence of the transition of dominant period can be evaluated by the ratio of the peak displacement of the unconnected building and the displacement of the rigid-connected building. These peak displacement can be gained from the response spectrum. The influence of the energy absorption can be calculated by using fitting curves. The response control effect can be gained by multiplying these two factors.
2. In general, the response control effect of the building with longer period is better than that of the building with shorter period. The response control effect of a building with longer period is better as the period ratio (the period of a building with shorter period divided by the period of a building with longer period) gets smaller. The response control effect of a building with shorter period is best when the period ratio is about 0.5.
3. If period of a building with shorter period is in the area of the displacement spectrum rising steep gradient, the response control effect sometimes cannot be gained. This phenomenon can be predicted by using the method proposed in this paper.

ACKNOWLEDGMENT

This study was partially conducted as a part of the 21st Century COE Program of Tokyo Metropolitan University's "Development of Technologies for Activation and Renewal of building Stocks in Megalopolis" when the first author was a graduate student of Tokyo Metropolitan University.

REFERENCES

Yamazaki, S., Minami, S., Toyama, K. and Tahara, K. (2004). Experimental study on coupled vibration control structures. *13th World Conference on Earthquake Engineering*, Paper No. 2351.
Tahara, K., Yamazaki, S. and Minami, S. (2007). Ultimate Performance of Hysteresis Steel Rod Damper. *8th Pacific Structural Steel Conference 2007* **1**, 51-56.