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Response Prediction of Passive Controlled Building with Viscous Dampers Considering its Performance Decrement under Long-Period Ground Motion

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Abstract

This paper presents a response evaluation of a Passive controlled building with viscous dampers considering its performance decrement under long-period ground motion. From the long-time sinusoidal wave test results using a full-scale viscous damper, it was shown that the performance decrement of the viscous damper was based on energetic density. An analytical model of the viscous damper considering the performance decrement caused by long-period cyclic loading was proposed, and its accuracy was confirmed by comparing with test results. The time history response analysis using a 20-story model with the proposed viscous dampers was performed. It was verified that the response of the passive controlled building with viscous dampers increases under certain long-period ground motions. Especially, for vibration control of a building designed with insufficient dampers, it was found that the response increased with the influence of the performance decrement of the damper when the long-period ground motion was received.

Keywords: passive controlled building; viscous damper; long-period ground motion; performance decrement.

1 Introduction

Recently, long-period ground motions due to potential Nankai Trough earthquakes are expected to be generated in three major megalopolises in Japan. It is feared that high-rise buildings with long natural periods will be severely affected. Vibration control buildings have already been known to be effective when such damage is assumed. However, there is a possibility of significant performance decrease with prolonged repetition, depending on the type of vibration control damper and the action of the long-period ground motion that it is subjected to. The viscosity damper targeted in the present study is a flow resistance type [1] damper that uses the flow resistance power of the enclosed viscous fluid. Vibration energy is converted into thermal energy, and the temperature of the viscous fluid rises. As a result, the characteristics of the damper deteriorate. Therefore, a design method for vibration control buildings needs to consider the characteristic decrease of the viscous dampers under long-period ground motion.

The authors performed long-term sinusoidal wave excitation tests on full-scale viscous dampers [2]. They proposed a performance decrease evaluation method using energy density which is the cumulative absorbed energy divided by the volume of the viscous fluid, and showed that this evaluation method can be used even if the vibration frequency, amplitude, continuance time and capacity of the damper are different [2]. In this paper, the response evaluation method for a high-rise building considering the performance decrease of the viscous dampers by using energy density is shown.

2 Analytical model considering performance decrease

Three kinds of full scale viscous dampers (Table 1) were used in the tests. Figure 1 shows the relation between the decreasing rate of the damper maximum power and the single-cycle energy density obtained from various types of sinusoidal excitation tests. Parameters of sinusoidal tests are shown in Table 2. The energy density is defined by Equation (1), and is related with generated heat and the viscous fluid value [2]:

$$\Omega^{(n)} = \frac{\sum W_d^{(n)}}{V_V} \tag{1}$$

where $\Sigma W_d{}^{(n)}$ is the cumulative absorbed energy up to the n-th step of the damper, and V_V is the volume of the viscous fluid.

From Figure 1, it is found that the decrease in the maximum power of the viscous damper can be described using energy density (Equation (1)) regardless of the condition (period, amplitude, duration time, initial temperature, and volume of the damper). In addition, the decreasing rate of not only the maximum power but also of the amount of absorbed energy per cycle and of the loss factor [1] show a similar tendency because the hysteresis of these viscous dampers displays an almost rectangular shape (Figure 2). Therefore, the maximum power, energy absorption per cycle and loss factor are called the property value of the damper in this paper. The dashed line in Figure 1 shows the decreasing rate $\lambda^{(n)}$ (Equation (2)) of the viscous modulus C_d at n steps. From Figure 1, it is found that $\lambda^{(n)}$ corresponds to the decrease in the characteristic value of the viscous damper obtained from the tests [2]:

$$\lambda^{(n)} = \exp\left(-a_0 \cdot \Omega^{(n)}\right) \tag{2}$$

where a_0 is a value depending on the standard of the damper [2]. However, a_0 can be determined from a long-term excitation test with an arbitrary amplitude and a vibration frequency as found from Figure 1 [2]. From the test results (Figure 1), $a_0 = 1.695 \times 10^{-6}$ m^2/kN is used in this paper [2].

Table 1. Specifications of the viscous dampers

Name	l (mm)	Damper				Brace		
		l_d (mm)	A_d (mm^2)	ϕ_d (mm)	C_d (kN/(mm/s)$^\alpha$)	l_b (mm)	A_b (mm^2)	ϕ_b (mm)
D1-2F D2-2F	3947	606	12880	184	98	2104	8320	159
D3-2F	3849	689	28124	286	196	1542	15323	236

＊The values of α and K_d are 0.38 and ∞, respectively.

This paper proposes an analytical model considering the characteristic decrease of the viscous damper because of the long-term repetition based on the above-mentioned outcome of the experiment. When the viscous damper is expressed by the Maxwell model, the load of the viscous damper in step n, $F_d{}^{(n)}$, is given by Equation (3):

$$F_d{}^{(n)} = C_d{}^{(n)} \cdot \left|\dot{u}_d{}^{(n)}\right|^{\alpha} \cdot \mathrm{sgn}\left(\dot{u}_d{}^{(n)}\right) \tag{3}$$

where α is an exponent, and $\dot{u}_d{}^{(n)}$ is the velocity of a viscous element at n steps. The viscous modulus $C_d{}^{(n)}$ at n steps considering its repeated effects is calculated using $\lambda^{(n)}$ from Equation 4.

$$C_d{}^{(n)} = \lambda^{(n)} \cdot C_d{}^{(0)} \tag{4}$$

Here, $C_d{}^{(0)}$ is an initial value of the viscous modulus [3].

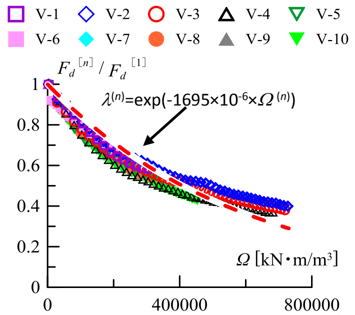
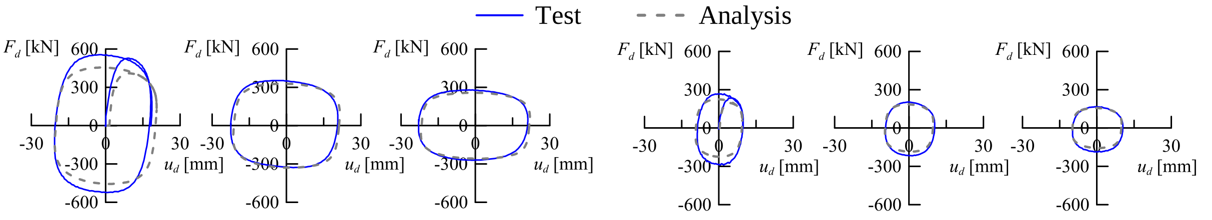


Figure 1. Reduction rate of maximum damper force

Table 2. Parameters of sinusoidal tests

Test name	Period T (s)	Amplitude u_d (mm)	Duration t_0 (s)	Number of cycles	Initial temperature θ_0 (°C)	Specimen name
V-1	4.0	20	600	150	10	D1-2F
V-2	4.0	20	1800	450	15	
V-3	4.0	20	3600	900	15	
V-4	4.0	20	10800	2700	13	
V-5	2.0	20	230	115	15	D2-2F
V-6	4.0	10	1200	300	15	
V-7	4.0	20	600	150	15	
V-8	4.0	30	400	100	15	
V-9	6.0	20	900	150	15	
V-10	4.0	20	1800	450	26	D3-2F

D3-2F is large capacity; all others are mid-capacity

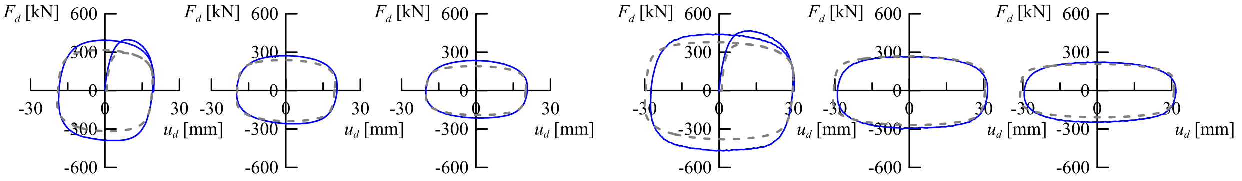


(i) 1 cycle (ii) 57 cycles (iii) 114 cycles

(a) V-5 （T = 2.0 s, u_d = 20 mm, Medium capacity)

(i) 1 cycle (ii) 150 cycles (iii) 299 cycles

(b) V-6 （T = 4.0 s, u_d = 10 mm, Medium capacity）

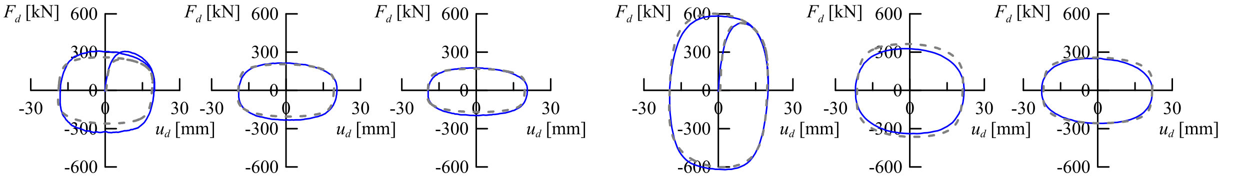


(i) 1 cycle (ii) 75 cycles (iii) 114 cycles

(c) V-7 （T = 4.0 s, u_d = 20 mm, Medium capacity）

(i) 1 cycle (ii) 50 cycles (iii) 99 cycles

(d) V-8 （T = 4.0 s, u_d = 30 mm, Medium capacity）



(i) 1 cycle (ii) 75 cycles (iii) 149 cycles

(e) V-9 （T = 6.0 s, u_d = 20 mm, Medium capacity）

(i) 1 cycle (ii) 225 cycles (iii) 449 cycles

(f) V-10 （T = 4.0 s, u_d = 20 mm, Large capacity）

Figure 2. Comparison of test and analysis results

The accuracy of an analytical model is verified by giving the compulsion displacement of the same sinusoidal wave as the test to a proposed analytical model, and comparing it with the experimental results. Figure 2 shows the examples of the hysteresis (V-5 to V-10) obtained from the test results and the analytical results. Using values from Table 3 [3], α and C_d of the viscous damper were calculated. Here, u_{d0} denotes the displacement amplitude. It can be verified that the analytical result can reproduce the tendency into which the damper property is changed with high accuracy from Figure 2.

Table 3. Approximate values of α and $C_d^{(0)}$

	$\alpha=A_1 u_{d0}^{A2}$		$C_d^{(0)}=A_3 u_{d0}^{A4}$ (kN(s/mm)$^\alpha$)	
	A_1	A_2	A_3	A_4
Medium capacity	0.860	-0.205	24.1	0.319
Large capacity	0.806	-0.156	42.2	0.288

3 Response analysis of the high-rise building considering the performance decrease of the viscous dampers

3.1 Outline of building model

The target building in this paper is a 20-story, 81.7 m high steel building [4], and is modeled by using a 20-mass equivalent shearing model. The natural period of the first mode of the main frame T_1 is 2.69 s. Rayleigh-type damping with 1st and 2nd damping ratios of 1% is used. Since the main of objective of this study was to evaluate the influence of the performance decrease of the damper due to repetition on the building response, a main frame was analyzed using the theory of elasticity.

3.2 Distribution of dampers

The parameters of the viscous damper for the following response analyses are listed in Table 1. The damper and support member are modeled by the series shown in Figure 3, and internal stiffness K_d and support material stiffness K_b are collectively shown by equivalent support member stiffness K_b^* (Table 4) [3]. Figure 4 shows the distribution of the viscous modulus of the viscous damper in the vertical direction.

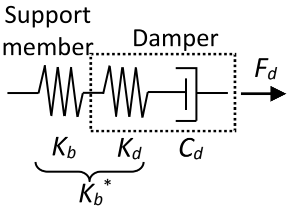


Figure 3. Damper and support member

Table 4. Equivalent support member stiffness

	K_d [kN/cm]	K_b [kN/cm]	K_b^* [kN/cm]
D2-2F	2663	2525	1296.1

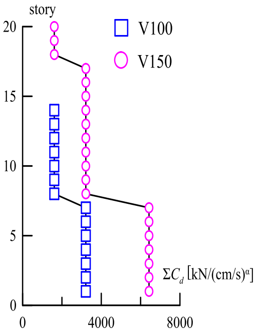
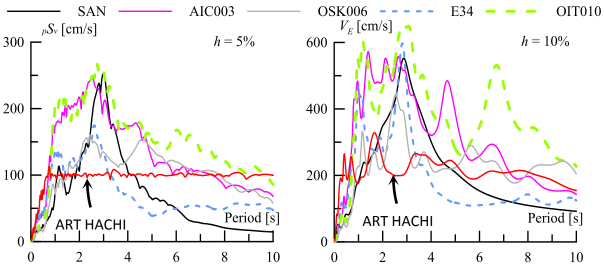


Figure 4. Setting of viscosity coefficient

Two kinds of damper distributions were set: V100 is a damper distribution such that the story drift angle R becomes less than 1/100 under level 2 seismic ground motion; V150 is a damper distribution such that R becomes less than 1/150 under level 2 seismic ground motion [5]. Simulated earthquake motion with a velocity response spectrum pS_V of 100 cm/s after 0.64 s (when the damping ratio h is 5%) is adopted as a level 2 seismic ground motion in this paper. Then, HACHINOHE 1968 EW is used for the phase property, and this simulated earthquake motion is called ART HACHI in this paper. The amount of dampers is designed disregarding the influence of the decrease of damper caused by the bending deformation of the building [6], [7].

3.3 Outline of input earthquake motion

Five waves were adopted as the examined seismic waves in this study: "Sanno-maru wave (SAN)" that is long-period ground motion that assumes the Tokai and Tonankai earthquake in the Tokai area [8], "Tsushima wave (AIC003)", "Sakai wave (OSK006)", "JMA Nagoya wave (E34)", and "Ooita wave (OIT010)" that assume a Nankai Trough 4 linked earthquake [9]. A pseudo-velocity spectrum ${}_pS_v$ (h = 5%) response and spectrum VE (h = 10%) energy are shown in Figures 5(a) and (b) respectively. From Figure 5, it is found that ${}_pS_v$ and V_E have a peak around the first natural period of the frame (2.69 s), and that values are larger than level 2 seismic ground motion (ART HACHI).



(a) Pseudo-velocity response spectrum (b) Energy spectrum

Figure 5. Earthquake spectrum

3.4 Results of time history response analysis

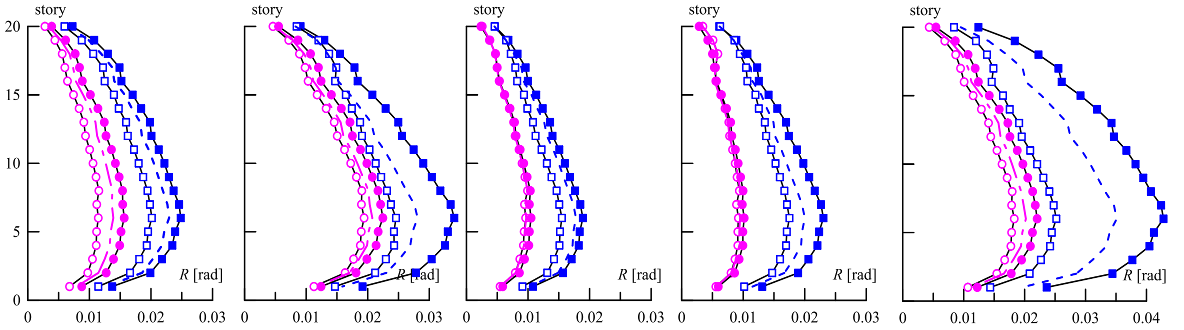
The maximum values of the story drift angle and the absolute acceleration obtained from the time history response analysis are shown in Figures 6 and 7 respectively. In this study, three types of analysis methods are examined and compared, as shown in appendix A.

No-decrease method: The analysis is carried out using a constant initial viscous modulus $C_d^{(0)}$.

Accurate method: The analysis is carried out by decreasing the viscous modulus of each step considering the effect of repetition as shown in section 2.

Simplified method: First, the reduction rate $\lambda^{(n_e)}$ is evaluated from the energy density at the end of the earthquake $\Omega^{(n_e)}$ by the damper of each story obtained from the result of the "No-decrease method" using Equation 2 (Figure 8). After that, the analysis is carried out again using the value $C_d^{(0)}\lambda^{(n_e)}$ obtained by multiplying the initial value of the viscosity coefficient $C_d^{(0)}$ by $\lambda^{(n_e)}$.

	Method		
	No-decrease	Accurate	Simplified
V100	☐	‒ ‒ ‒ ‒	■
V150	○	‒ · ‒	●



(a) SAN (b) AIC003 (c) OSK006 (d) E34 (e) OIT010

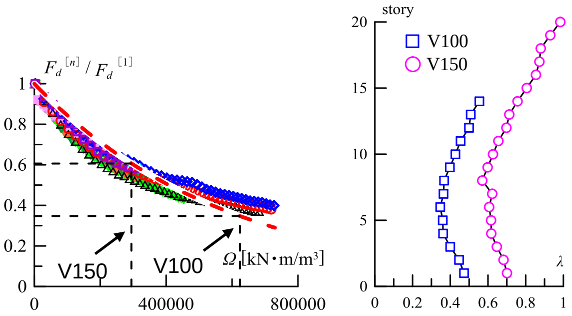
Figure 6. Distribution of story drift angle R

	Method		
	No-decrease	Accurate	Simplified
V100	☐	‒ ‒ ‒ ‒	■
V150	○	‒ · ‒	●

(a) SAN (b) AIC003 (c) OSK006 (d) E34 (e) OIT010

Figure 7. Distribution of absolute acceleration

First, the "No-decrease" and "Accurate" methods are compared. From Figure 6 in SAN, AIC003 and OIT010 of V150, it is found that the story drift angles obtained from the "Accurate" method increase more than the results of the "No-decrease" method because the performance of the viscous damper decreases with repetition. On the other hand, the results obtained using the "Accurate" method are almost the same as those of the "No-decrease" method in case of OSK006 and E34 because the story drift angle had been installed within 1/100. It is verified that the performance of the damper rarely decreases in ART HACHI that uses level 2 as a seismic ground motion because the input energy into the building by the seismic ground motion is smaller than that of other long-period ground motions as shown in Figure 5(b) [10], [11]. In the V100 case with a comparatively smaller amount of dampers, it can be verified that the response of the "Accurate" method increases compared with the response of the "No-decrease" method when the input energy is large as for AIC003 and OIT010. In addition, a similar tendency is verified about the absolute acceleration as shown in Figure 7. The performance decrease of the damper becomes significant because the energy absorbed by one damper increases when the amount of dampers is small. It must be noted that the response to the long-period ground motion may increase when a vibration control building is designed with a small amount of dampers.



(a) Evaluation of decreasing rate λ in sixth layer

(b) Distribution of decreasing rate λ

Figure 8. Decreasing rate – "Simplified" method (SAN input)

Next, the "No-decrease" and "Simplified" methods are compared. From Figure 8 (a), it can be seen that V100 with a small damper amount is greatly reduced as compared with V150, and it can be seen from Fig. 8 (b) that this trend is the same for all layers. It can be verified that the story drift angle and the absolute acceleration obtained from the "Accurate" method lie between the results of the "Simplified" and "No-decrease" methods, as shown in Figures 6 and 7. The "Simplified" method is useful because the response evaluation is possible even when there is no analytical model for the characteristic value of the change of the viscous damper by repetition. However, the response calculated by the "Simplified" method becomes an excessive evaluation when the response is large, as for OIT010 (Figures 6(e) and 7(e)). Moreover, the "Accurate" method can perform more detailed response estimation.

4 Conclusions

This study showed that the decrease in the characteristic value of the viscous damper with repetition can be evaluated using energy density. An analytical model of the viscous damper that considers the performance decrement caused by long-period cyclic loading was proposed, and its accuracy was confirmed by comparing with test results. In addition, the time history response analysis using a 20-story model was performed using an "Accurate" method and it was compared with a "No-decrease" method. It was found that the response caused by the long-period ground motion may increase when a vibration control building is designed with a small amount of dampers. Moreover, the "Simplified" method that simply considers the influence of the performance decrease without using the "Accurate" method was proposed. The "Simplified" method is valuable because the response evaluation is possible even when there is no analytical model for the characteristic value of the change of the viscous damper by repetition. However, the response calculated by the "Simplified" method becomes an excessive evaluation when the response is large. Moreover, the "Accurate" method can perform more detailed response estimation.

The results of the case where the structure was elastic due to limitation of paper width were shown in this paper. A similar trend has been obtained even with non-linear structure [12].

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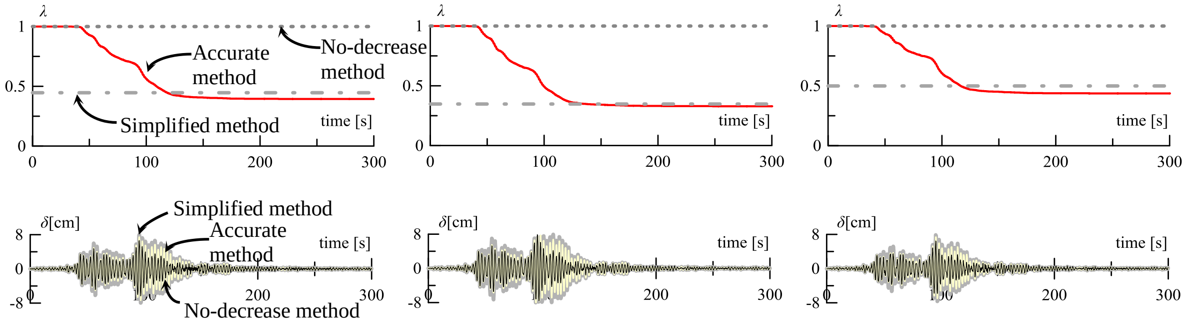
Appendix

Figures A (a)–(c) show the results of comparing the decrease rate of the viscosity coefficient λ (upper row) and the story drift δ (lower row) with the "No-decrease method," "Accurate method," and "Simplified method" at SAN input at V100. From the results, it can be confirmed that λ decreases sharply immediately after the story drift reaches its maximum value. The lowering of the decreasing rate λ of the viscosity coefficient is larger in the 6th layer having the largest story drift. Since the story drift is small when it comes to the upper layer, the decrease of λ is also small. It is understood that the maximum value of the story drift and the subsequent deformation are underestimated in comparison with the accurate method when the characteristic value reduction is not taken into consideration ("No-decrease method").



(a) 2nd story (b) 6th story (c) 12th story

Figure A. Time history of decreasing rate of viscosity coefficient λ *(upper row) and story drift* δ *(lower row);* (*V100, SAN input*)