第18回性能に基づく橋梁等の耐震設計に関する
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Effect of Viscous Damper Capacity on the Seismic Response of Bridges with Reinforced Concrete Columns

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1. INTRODUCTION

Nowadays, there are many existing bridges designed and built according to previous codes which are inadequate for seismic resistance requirement specified in the present code. During an earthquake, these bridges usually have large deformation due to ground motion, and are eventually damaged or collapse. An economical and effective alternative to solve this problem is to retrofit these structures to increase their seismic performance.

One of the retrofit strategies is vibration control such as using viscous damper which is a supplementary device widely used in seismic retrofitting of bridge structures. Kawashima[1)] shows that Shin-Iino-gawa bridge retrofitted with nonlinear viscous dampers, some reinforced concrete (RC) columns were retrofitted with steel jacketing and retrofitted with elastomeric bearings, suffered no damage during the 2011 Great East Japan earthquake.

There are several studies on response of structure retrofitted with viscous dampers. Constantnou[2)] demonstrated that the installation of viscous dampers on bridge structure, reduce isolation system force, column shear force and bearing displacement, and concluded that using viscous dampers is an effective method for reducing seismic response of structures. Kandemir[3)] proposed the simplifying single degree of freedom (SDOF) bridge system can obtain damping coefficient for bridge structure. Moreover, Lee[4)] studied on the control of seismic-excited nonlinear isolated bridges with variable viscous dampers by 2 degree of freedom (2DOF) system. Furthermore, Zhou et al.[5)] proposed a 2 stages of design method for RC structures with viscous dampers. Preliminary stage determines the parameters and configurations of the viscous dampers. In the second stage, deformations, damping ratio and connections are examined. However, vibration control methods for bridge are now developing. The response of bridge structure retrofitted with viscous dampers under severe ground motion is imprecise. Miyamoto[6)] modeled and evaluated limit states and failure mechanisms of viscous dampers and implicated with large ground motions.

In this study, the effect of viscous damper capacity on the seismic response of bridges with reinforced concrete columns, and examine the seismic response of bridge structure with RC columns under strong ground motion by 2 degree of freedom with the consideration of strength ratio of viscous damper yield strength to RC column yield strength.

2. ANALYTICAL MODEL AND CONDITIONS

(1) RC column model

In this study, 8 bridges designed based on 1980 code and accorded to elastic design method. 5 bridges designed with superstructure mass of 650 ton are named as A-series and have structural parameters as listed in **Table 1.**

Table 1 Structural parameters of A-series bridges

		Abbrev.	A-1	A-2	A-3	A-4	A-5
Superstructure	Mass (ton)	m_s	650	650	650	650	650
RC column	Mass (ton)	m_c	413	425	455	451	522
	Yield strength (MN)	P_{cy}	3.01	3.22	3.26	3.52	3.65
	Yield displacement (m)	δ_{cy}	0.040	0.042	0.037	0.044	0.044
	Yield stiffness (MN/m)	k_{cy}	75.1	77.4	88.6	80.0	83.0
	Ultimate displacement (m)	δ_{cu}	0.193	0.214	0.179	0.210	0.187
	Ductility factor	μ	4.82	5.17	4.85	4.76	4.26
Strength ratio (P_{dy}/P_{cy})		R_{Py}	0.08-0.83	0.07-0.77	0.08-0.77	0.07-0.71	0.07-0.68

Table 2 Structural parameters of B-series bridges

		Abbrev.	B-1	B-2	B-3
Superstructure	Mass (ton)	m_s	780	780	780
RC column	Mass (ton)	m_c	451	451	522
	Yield strength (MN)	P_{cy}	3.50	3.62	3.77
	Yield displacement (m)	δ_{cy}	0.035	0.044	0.045
	Yield stiffness (MN/m)	k_{cy}	100.6	81.6	84.7
	Ultimate displacement (m)	δ_{cu}	0.172	0.211	0.189
	Ductility factor	μ	4.95	4.75	4.24
Strength ratio (P_{dy}/P_{cy})		R_{Py}	0.07-0.71	0.07-0.69	0.07-0.66

The other 3 bridges designed with superstructure mass of 780 ton are named as B-series and have structural parameters shown in **Table 2**. In this analysis, Takeda model[7)] is assumed to be force-displacement hysteresis model for RC column. These bridges are significant difference in their yield strength of RC column (P_{cy}) but negligible difference in their yield stiffness of RC column (k_{cy}).

(2) Input ground motion

In this study, ground condition is assumed to be stiff soil. According to Japan Road Association[8)], Kaihoku, Shimizu and Shin-Bansui ground motion record are used as the design ground motion of level 2, type I, and Inagawa, JMA Kobe EW and JMA Kobe NS are used as the design ground motion of level 2, type II.

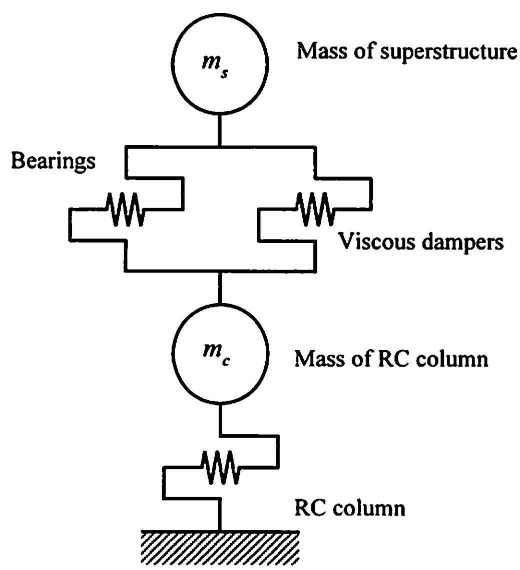


Fig. 1 Analytical model of bridge retrofitted with viscous dampers

(3) Analytical model of bridge

Bridges in this analysis are bridges with RC columns, elastomeric bearings and retrofitted by viscous dampers installed between its column and superstructure, and have been modeled as 2 degree of freedom system shown in **Fig. 1**. In this analysis, Newmark β numerical integration method is used to solve the equation of motion with β = 1/4 and damping coefficient matrix of the structural model is determined by Rayleigh damping where damping ratio of RC column, bearing and viscous dampers are 0.02, 0.03 and 0.00 respectively[8)].

(4) Bearing model

In this analysis, superstructure is supported by 5 elastomeric bearings on each column. Force-displacement relationship of bearing is assumed as linear relationship. These bearings satisfy the present specification[8] even if the bridge has not been retrofitted. The displacement of the bearing is assumed to be same as the displacement of viscous dampers which is equal to the relative displacement between superstructure and column.

(5) Viscous damper model

Characteristics of viscous dampers are assumed as elastic-plastic model as shown in **Fig. 2**. Yield displacement of the viscous dampers (δ_{dy}) is 0.0025 m and yield strength of viscous dampers (P_{dy}) are varied from 0.05 MN to 2.5 MN with step increment of 0.05 MN. Force-displacement hysteresis model for viscous dampers is modeled as bilinear model.

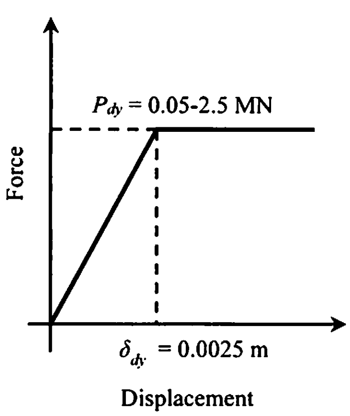


Fig. 2 Force-displacement relationship of viscous dampers

In this study, strength ratio (R_{Py}) is defined as the ratio of yield strength of viscous dampers to yield strength of RC column as shown in Eq. (1).

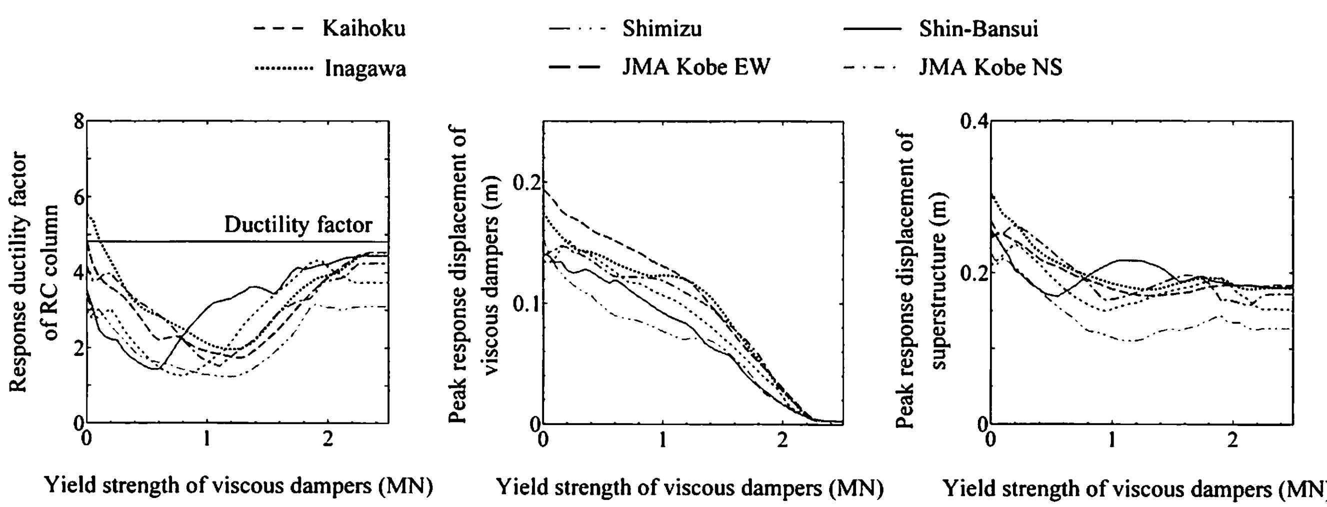
$$R_{Py} = \frac{P_{dy}}{P_{cy}} \tag{1}$$

3. ANALYTICAL RESULTS

From the analytical conditions mentioned above, the relationship between various yield strength of viscous dampers and seismic responses are shown as an example in **Fig. 3**.

The relationship between yield strength of viscous dampers and response ductility factor of RC column in **Fig. 3** (a) represents that for each input ground motion, there is a minimum value of the response ductility factor, yield strength of viscous dampers at this stage is optimum yield strength for the structure which is the most effective parameters for vibration control. Moreover, the response ductility factor at optimum yield strength does not exceed the ductility factor corresponding to ultimate displacement. In case of high yield strength of viscous dampers, the response of RC column increase as the result of the high stiffness and small response displacement of viscous dampers.

The relationship between yield strength of viscous dampers and peak response displacement of viscous dampers in **Fig. 3** (b) shows that as the yield strength of viscous dampers increase, the peak response displacement of viscous dampers decrease. If the yield

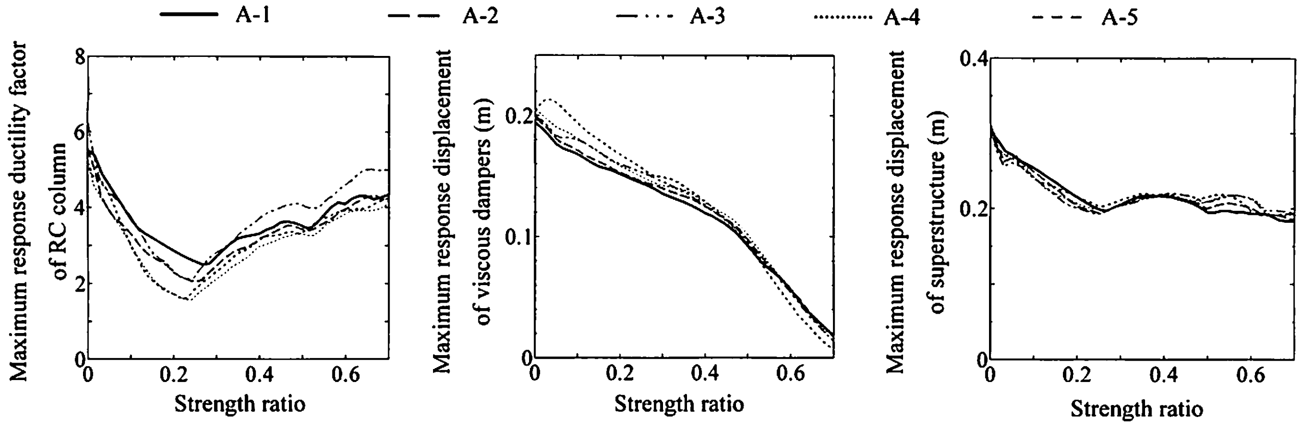


(a) Response ductility factor of RC column

(b) Peak response displacement of viscous dampers

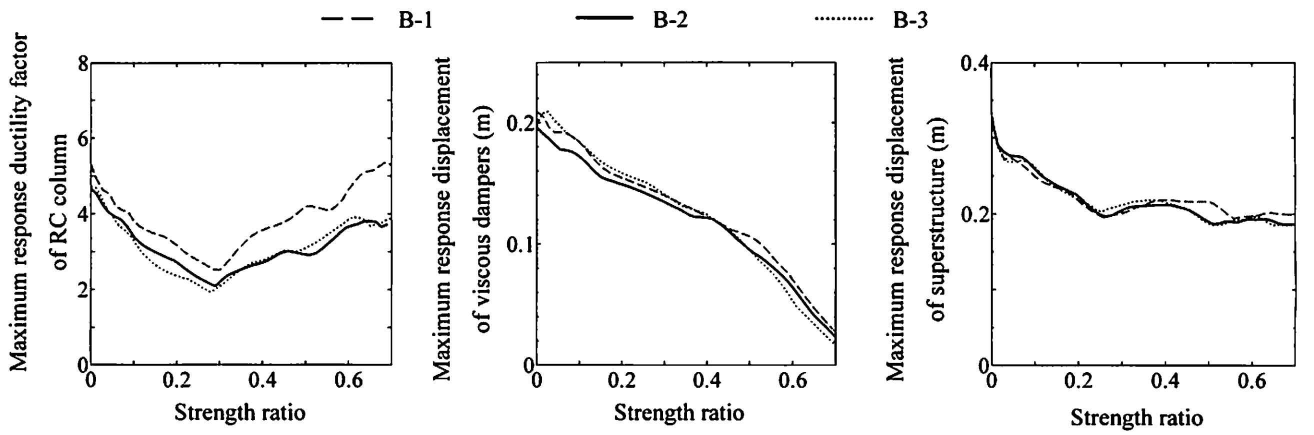
(c) Peak response displacement of superstructure

Fig. 3 Response–yield strength of viscous dampers relationship of bridge A-1



(a) Response ductility factor of RC column (b) Maximum response displacement of viscous dampers (c) Maximum response displacement of superstructure

Fig. 4 Maximum response-strength ratio relationship of A-series bridges under 6 ground motions



(a) Response ductility factor of RC column (b) Maximum response displacement of viscous dampers (c) Maximum response displacement of superstructure

Fig. 5 Maximum response-strength ratio relationship of B-series bridges under 6 ground motions

Table 3 Design of retrofitting with viscous dampers of A-series bridges

	A-1	A-2	A-3	A-4	A-5
Yield strength of RC column (MN)	3.01	3.22	3.26	3.52	3.65
Optimum strength ratio	0.27	0.25	0.23	0.24	0.22
Yield strength of viscous damper (kN)	800	800	750	850	800
Stroke of viscous damper (m)	0.18	0.18	0.20	0.19	0.21

Table 4 Design of retrofitting with viscous dampers of B-series bridges

	B-1	B-2	B-3
Yield strength of RC column (MN)	3.50	3.62	3.77
Optimum strength ratio	0.33	0.32	0.31
Yield strength of viscous dampers (kN)	1050	1050	1050
Stroke of viscous dampers (m)	0.18	0.18	0.19

strength exceeds optimum yield strength, the peak response displacement of viscous dampers instantaneously decrease and approach zero. Since the relative peak displacement is reduced by the viscous dampers, the peak response displacement of the superstructure in **Fig. 3** (c) trends to approach the peak response displacement of the RC column.

The maximum of peak responses from the analysis with 6 input ground motion are chosen in design procedure. **Figs. 4-5** represent a relationship between the maximum response and strength ratio of the bridges.

From the analytical results, the optimum strength ratio chosen from the relationship between maximum responses and strength ratio under various ground motion shown in **Figs. 4** (a)-**5** (a), are shown in **Table 3** for A-series bridges and **Table 4** for B-series bridges. Moreover, the scatters relationship between optimum strength ratio and yield seismic coefficient of RC column are shown in **Fig. 6**. Yield seismic coefficient of RC column (k_{cy}) is defined as the proportion of yield strength of RC column and weight of the superstructure (W_s) as shown in Eq. (2).

$$k_{cy} = \frac{P_{cy}}{W_s} \tag{2}$$

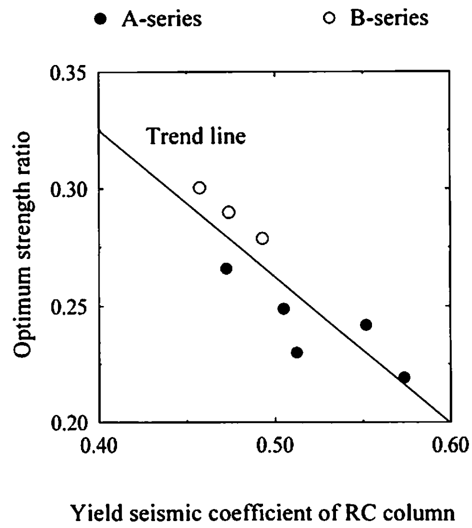
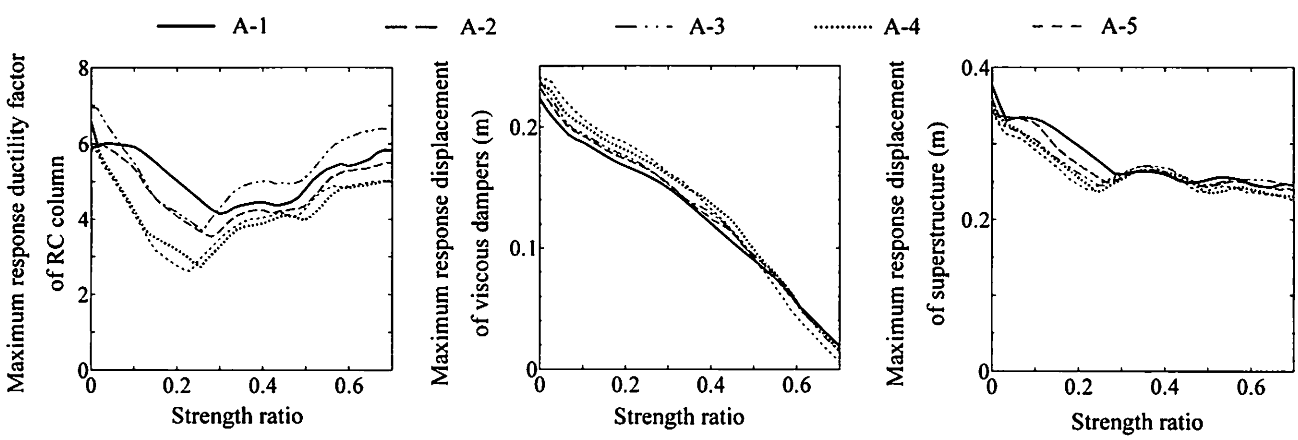


Fig. 6 Optimum strength ratio-yield seismic coefficient of RC column relationship

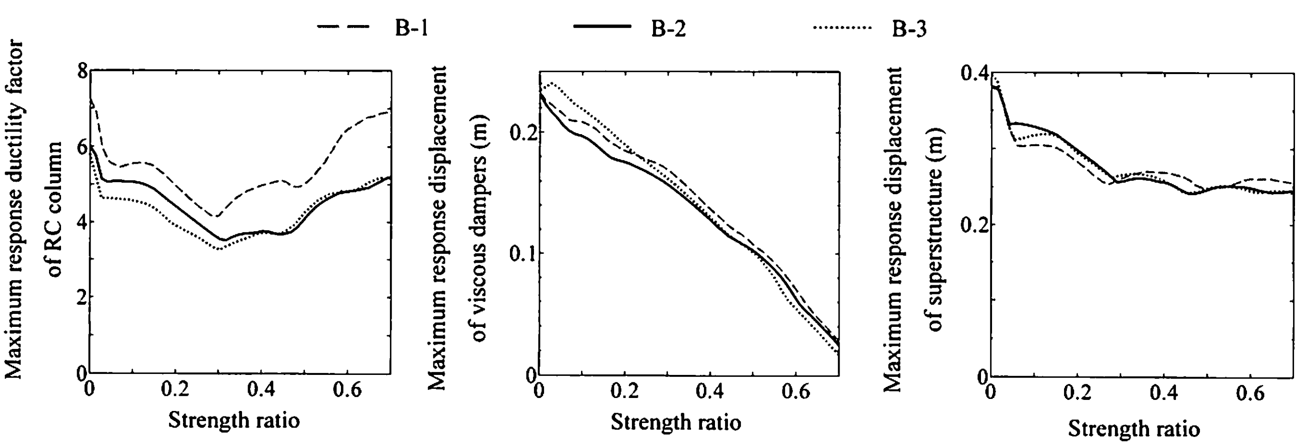


(a) Response ductility factor of RC column

(b) Maximum response displacement of viscous dampers

(c) Maximum response displacement of superstructure

Fig. 7 Maximum response-strength ratio relationship of A-series bridges under 120% amplified 6 ground motions



(a) Response ductility factor of RC column

(b) Maximum response displacement of viscous dampers

(c) Maximum response displacement of superstructure

Fig. 8 Maximum response-strength ratio relationship of B-series bridges under 120% amplified 6 ground motions

Fig. 6 shows that an increment in yield seismic coefficient of RC column decreases the strength ratio as represented by trend line. Furthermore, the optimum yield strength of viscous dampers are designed and be able to use in retrofitting.

From **Figs. 4** (b)-**5** (b) the maximum response displacement of the viscous dampers at optimum strength ratio can be determined. The designed strokes of viscous dampers for bridges are shown in **Tables 3-4** which satisfy the verification with the safety factor of 0.8[9].

Since the bearings of the bridge satisfied the specification[8] without retrofitting with viscous dampers. As retrofitting reduces responses of the bridges, stresses of the bearing during an earthquake are reduced. Therefore the bearings are acceptable.

Figs. 7-8 show the maximum response of these 8 bridges under 6 input 120% amplified ground motions. As the result the maximum response ductility factor in **Figs.** 7(a)-**8**(a) at optimum strength ratio does not exceed the ductility factor of RC column. From **Figs.** 7(b)-**8**(b), the maximum response displacement of viscous dampers at optimum strength ratio does not exceed the designed stroke of viscous dampers shown in **Tables 3-4**.

4. CONCLUSIONS

Based on the result from the analysis of bridges with RC columns retrofitted with viscous dampers, the followings are conclusions,

(1) This study demonstrates that an increment of yield strength of viscous dampers installed to the bridge with RC columns does not always reduce the response displacement of the RC column, but there is an optimum yield strength of viscous dampers or strength ratio which is the most effective in vibration control and most appropriate for these bridges under various design ground motion. As yield strength exceeds optimum yield strength, the response of RC column increase as the result of less inelastic range of viscous dampers. Moreover, these bridges are safe under 120% amplified ground motion.

(2) An increment of yield seismic coefficient of RC column slightly decreases the optimum strength ratio of the structure. However, more analysis is needed for generalization.

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