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NUMERICAL EARTHQUAKE RESPONSE ANALYSIS OF BRIDGE PIER WITH SUPER ELASTIC SEISMIC DAMPERS

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Applicability of the super elastic alloy, which has the ability to restore from more than 10% strain, to the seismic dampers was discussed analytically using the numerical simulations. Seismic behavior of the damper made of super elastic alloy was compared with that of the conventional elasto-plastic damper. As a result, the model with the super elastic damper caused 20% larger response than the elasto-plastic damper. However, the super elastic damper resulted in zero deformation after the earthquake responses while the elasto-plastic damper showed large residual deformation.

***Key Words** : super elasticity, seismic damper, earthquake response analysis, functional alloy*

1. INTRODUCTION

Recent years, many isolated bridges are planed to be constructed and some are already constructed. There are many kinds of isolating devices such as the lead-rubber bearings, the high-damping rubber bearings and the elasto-plastic steel dampers. They elongate the natural periods of the bridges to avoid resonance, or they absorb the earthquake energy to decrease the vibration. The effect of the isolators depends on the characteristics of their material, therefore, it is important to develop and utilize the highly functional material.

This paper discussed the effect of the seismic isolators made of the super elastic alloy. The super elastic alloy has a particular inelastic stress-strain relationship which is quite different from that of the conventional material used in the field of the civil engineering such as steel nor concrete; it absorbs the hysteretic energy through the inelastic response and it also restores from more than 10% of the strain with no residual deformation[1].

In this paper, the seismic response of the bridge pier with the super elastic damper was numerically simulated to investigate the applicability of the super elastic alloy to the seismic isolators.

2. SUPER ELASTICITY

The super elastic alloy softens after its yielding like steel material during the loading procedure, however, it becomes elastic again during the unloading procedure. This material has fine ability to absorb the hysteretic energy, and has no residual deformation at all after the loading and unloading, which is quite different from the conventional material used for the structures.

Fig.1 compares the force-deformation relation among three kinds of material[1),2)]. **Fig.1(a)** shows the conventional elasto-plastic material such as steel; once the material was loaded through O→A→B to the plastic state, the residual deformation remains after unloading process through B→C.

Fig.1(b) shows the force-deformation relationship of the shape memory alloy which has the similar composition to the super elastic alloy. This alloy deforms residually after loading and unloading through O→A→B→C, however, it can regain to the origin (C→O) by heating in certain temperature.

Fig.1(c) shows the relationship of the super

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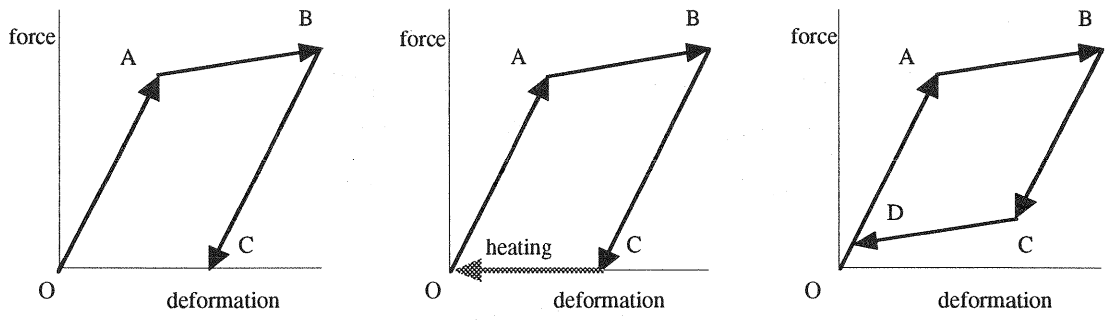

(a) steel (b) shape memory alloy (c) super elastic alloy

Fig.1 Comparison of force-deformation relationship between steel, shape memory alloy and super elastic alloy.

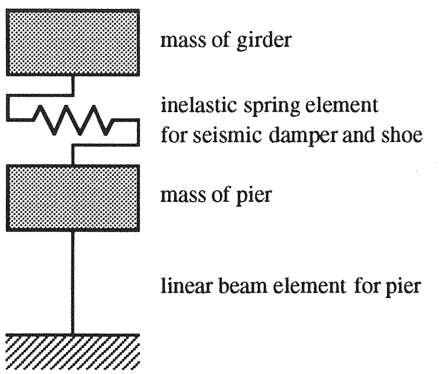

Fig.2 Analytical model used for simulations.

Table 1 Assumed parameters used for the simulations.

Mass of Pier	M_1=3.1 × 10^5 kg
Mass of Girder	M_2=3.7 × 10^6 kg
Yield Point (point-A in Fig.1)	δ_y=1.0 cm
	F_y=1.0 × 10^6 N
Return Point for Super Elastic Model (point-D in Fig.1-c)	δ_o=0.1 cm
	F_o=1.0 × 10^5 N
Initial Stiffness	K_1=1.0 × 10^8 N/m
Stiffness Ratio after Yielding	K_2/K_1=0.2
Initial Natural Period	T_0=1.29 sec
Modal Damping	h=0.05 for all modes

elastic alloy. This alloy deforms to the plastic state through O→A→B on loading and was restored to the origin on unloading through B→C→D→O. The super elastic alloy needs no heating to get rid of the residual deformation unlike the shape memory alloy.

The super elastic alloy and the shape memory alloy have the similar composition to each other. The Ni-Ti (nickel-titanium) alloy shows the shape memory effect in the case of about 50% of nickel, and shows the super elastic effect in the case of more than 50.5% of nickel[1].

The super elastic alloy is already used for the products such as the frame of the eyeglasses, the dental reform wire, and the wire in the women's underwear.

3. EARTHQUAKE RESPONSE ANALYSIS OF BRIDGE PIER WITH SEISMIC ISOLATORS

This chapter compares the earthquake responses of the bridge models with the seismic isolators made of the super elastic alloy and of the conventional elasto-plastic material. They are also compared to the bridge model without any isolators. The inelastic earthquake responses of them were numerically simulated.

(1) Analytical Model

Fig.2 shows the analytical model of a bridge pier and a girder with a seismic damper used for the simulations. A bridge pier was modeled as a linear beam member and a girder was supported with an inelastic spring which represents a damper and a shoe. A viscous modal damping of 5% was also assumed for all modes of this model. The assumed parameters for this two degree-of-freedom system are summarized in **Table 1**.

(2) Input Earthquake Motion

The design earthquake record for the ground condition of the group-1 (tertiary or older) which is

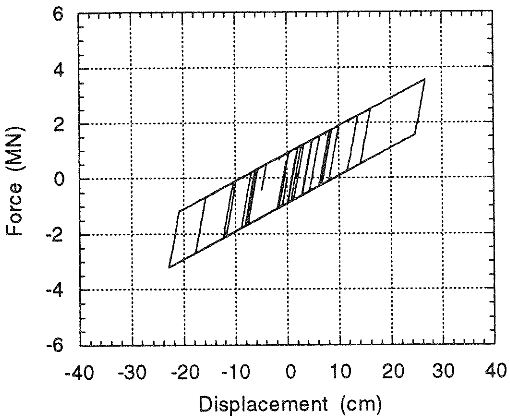

Fig.3 Hysteretic response of bilinear model.

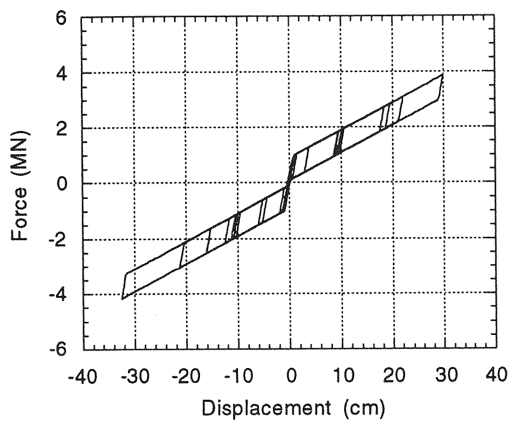

Fig.4 Hysteretic response of super elastic model.

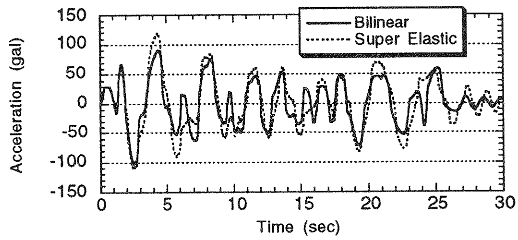

Fig.5 Acceleration responses of girders for both model.

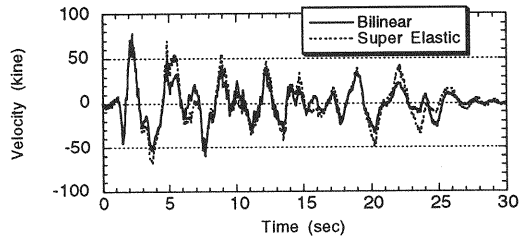

Fig.6 Velocity responses of girders for both model.

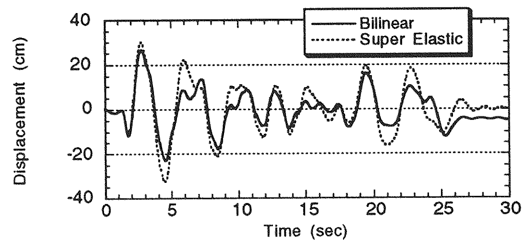

Fig.7 Displacement responses of girders for both model.

recommended in the Japanese seismic design code for the highway bridges[3)] was used for the numerical simulations.

This wave was modified to have the maximum acceleration of 300 gal. This record originally continues for 25 seconds, however, trailing zeros for 5 seconds were added to observe the free vibration of the model after the forced vibration subjected to the earthquake motion. This may enable the evaluation of the residual deformation precisely.

(3) Hysteretic Force-Deformation Relationship

In this study, the conventional elasto-plastic damper was assumed to show the bilinear hysteretic responses. On the other hand, the hysteretic response of the super elastic damper was assumed as the composite of the attached bilinear regions on the both ends of the linear elastic region (shown later in the figure of the hysteretic response).

Note that this hysteretic model does not correspond to the existing specific material. The former studies seldom evaluated the dynamic behavior of the super elastic alloy in the cyclic loading tests, and no provided suitable hysteretic model exists. The simulations in this study were performed assuming that if any material would behaved like this hysteretic model showing the super elastic effect. This study does not attend to evaluate the performance of the existing seismic dampers, but is going to examine the advantage and disadvantage of the super elastic effect for the seismic dampers.

4. EARTHQUAKE RESPONSE RESULTS

(1) Hysteretic Responses

The hysteretic responses of the dampers are shown in **Figs.3** and **4**. **Fig.3** is for the conventional elasto-plastic damper showing bilinear force-displacement behavior. **Fig.4** is for the super elastic damper, which shows the composite response of the bilinear region and the elastic region mentioned before. The displacement response of the super

Table 2 Comparison of responses between bilinear model and super elastic model.

		Bilinear (=A)	Super Elastic (=B)	Ratio (=B/A)
Max. Acceleration (gal)	Pier	471	577	1.22
	Girder	103	118	1.15
Max. Velocity (kine)	Pier	10.2	12.9	1.26
	Girder	73.5	77.9	1.06
Max. Displacement (cm)	Pier	0.616	0.674	1.09
	Girder	26.7	32.6	1.22
Max. Restoring Force (MN)	Pier	2.55	3.03	1.19
	Girder	3.57	4.16	1.16
Residual Deformation (cm)	Pier	0.00	0.00	—
	Girder	4.43	0.00	0.00
Energy (MN·m)	Input Energy	5.03	5.05	1.00
	Hysteretic Energy	3.09	1.92	0.62

elastic damper in **Fig.4** was larger than that of the elasto-plastic damper in **Fig.3** showing the narrow shape of its hysteretic response.

Note that the hysteretic response of the super elastic damper in **Fig.4** always passed the origin point owing to the assumption for the super elastic hysteretic model.

(2) Response-Time Histories

Figs.5-7 compare the response-time histories for the girder of the model with the elasto-plastic (bilinear) damper and that with the super elastic damper; **Fig.5** shows the absolute acceleration responses, **Fig.6** shows the relative velocity responses to the piers, and **Fig.7** shows the relative displacement responses to the piers. Each figure has two lines plotted together to compare the responses for the both models; a solid line is for the bilinear model and a dotted line is for the super elastic model.

From **Figs.5-7**, the model with the super elastic damper shows 10-20% larger response compared to the model with the bilinear damper, however, they have the same vibration phases in the responses.

The displacement-time history of the model with the bilinear damper, the solid line of **Fig.7**, showed the residual deformation at the end of the response for 30 seconds. It was about 5 cm which was more than 4 times larger deformation than the assumed yield displacement of the damper. On the contrary, the model with the super elastic damper resulted in no residual deformation. The super elastic damper would be valuable for the case that the residual deformation is critical.

Note that the first 25 seconds were the forced vibration subjected to the earthquake motion, and the latter 5 seconds were the free vibration. The time to need for convergence of the free vibration after the forced vibration for 25 seconds of the super elastic model was longer than that of the bilinear model as shown in **Fig.7**.

(3) Maximum Responses

Table 2 summarizes the responses for the both models. This table also contains the ratio of the response of the super elastic model to that of the bilinear model. The maximum responses of both the pier and the girder with the super elastic damper showed 10-20% larger responses than those of the bilinear model.

Nevertheless, the effect of the super elastic damper should also be evaluated through the comparison with the model without any dampers. Therefore, the response of the linear one degree-of-freedom system was calculated, which had the single mass corresponding to the composite of the girder mass and the pier mass in the case of the model with a damper previously shown in **Fig.2**.

The model without dampers resulted in the maximum acceleration response of 600 gal. It was almost the same acceleration response as the pier of the model with the super elastic damper. Furthermore, it was 5 times larger than the girder acceleration of the super elastic model. This reduction in the girder acceleration response of 20% is effective enough even if compared to the bilinear model whose reduction ratio of 17%.

(4) Energy Absorbing Capacity

The absorbed hysteretic energy was also evaluated for the both models as shown in **Table 2**. The hysteretic energy absorbed by the super elastic damper was 62% of the energy absorbed by the bilinear damper. Though the super elastic damper absorbed the hysteretic energy only 2/3 of the conventional elasto-plastic bilinear damper, the important thing is that the super elastic damper was able to absorb some amount of the hysteretic energy.

The both models had the identical masses, the identical initial natural periods, and the identical yielding points, therefore, the total input energy subjected to the earthquake motion was almost identical in each model[4].

The less absorbed hysteretic energy of the super elastic damper resulted in the more energy absorbed by the assumed viscous damping compared to the bilinear model. Moreover, the elastic vibrating energy of the super elastic damper at the end of the forced vibration subjected to the earthquake motion was also larger than the case of the bilinear damper, which caused the longer time to stop its free vibration after the forced excitation as mentioned before.

5. CONCLUSIONS

This paper discussed the applicability of the super elastic alloy to the seismic dampers by using the inelastic earthquake response analyses. The main conclusions obtained in this study are as follows.

(1) The maximum earthquake responses, not only for the acceleration response but also the velocity and the displacement responses, of the model with the super elastic damper were 10-20% larger than those of the model with the conventional elasto-plastic bilinear damper. However, the acceleration response of the girder with the super elastic damper was 20% of the model without any dampers. This reduction in the acceleration response of the girder was effective enough even if compared to the value of 17% in the case of the elasto-plastic damper.

(2) The model with the super elastic damper showed no residual deformation after the earthquake response owing to its assumed hysteretic rules. The super elastic damper would be valuable for the case that the residual deformation is critical.

(3) Though the total input energy subjected to the earthquake motion was identical for the super elastic model and the elasto-plastic model, the absorbed hysteretic energy of the super elastic damper was 2/3 to that of the elasto-plastic damper due to the narrower shape of the hysteretic response.

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