EXPERIMENTAL AND ANALYTICAL STUDY ON A NONLINEAR ISOLATED BRIDGE UNDER SEMIACTIVE CONTROL

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ABSTRACT :

The semiactive control system applied to a nonlinear isolated bridge with a magneto-rheological (MR) damper controlled by an improved sliding mode control algorithm is successfully implemented and evaluated through a series of shaking table tests. In the past researches, numerical simulations revealed that structural control systems are effective in mitigating seismic responses for isolated bridges which exhibit nonlinear responses under near-field ground motions. This paper is aimed to show the practical implementation of the semiactive control system to a nonlinear isolated bridge. A two-story shear-type structure model made of steel plates is designed to imitate the nonlinear dynamic behavior of an isolated bridge. In particular, since the column plates are replaceable, next nonlinear test can be continued using the same model by only changing the steel plates. Compared to the control methods based on feedback of displacements and velocities, the used improved sliding mode control based on feedback of velocities and accelerations shows more practical application into real structures, because it is easier to measure acceleration than displacement during earthquakes. Through comparison between analytical and experimental results, the MR damper satisfactorily traces the demanded control force by the control algorithm and the response time histories agreed to each other well. The results verify the feasibility of semiactive control system for a nonlinear structure in practical implementation. Since the results also present that the semiactive control system has outstanding performance, the semiactive control system provides a valuable control method for mitigating seismic responses of nonlinear isolated bridges.

KEYWORDS: Isolated Bridge, Nonlinear Response, Semiactive Control, Sliding Mode Control

1. INTRODUCTION

Seismic isolators are effective in mitigating the induced seismic force of a bridge by a shift of natural period. However, the deck displacement becomes excessively large when a bridge is subjected to a ground motion with large intensity or unexpected characteristics. Kawashima and Unjoh (1994) proposed a semiactive control system by using a variable viscous damper and a displacement-dependent damping model to successfully decrease seismic responses of isolated bridges. Yang et al. (1995) studies the variable viscous damper under sliding mode control for a seismic-excited isolated bridge. Ruangrassamee and Kawashima (2001) adopted a magneto-rheological (MR) damper as the semiactive device in control of an isolated bridge. Recently, Lee and Kawashima (2005, 2006, 2007) extensively investigated the effect of the semiactive control using different devices and control algorithms for isolated bridges which exhibit nonlinear behavior under near-field ground motions. Numerical simulation results have indicated that sliding mode control method achieves excellent control performance.
In this paper, shaking table experimental tests are conducted to verify the effectiveness of semiactive control using a MR damper based on sliding mode control method. A two-story shear-type structure model was designed to imitate the dynamic behavior of isolated bridges. Numerical simulations are performed on the basis of the results of the system identification and the assumption of ideal control situations. Through the comparison between analytical and experimental results, the correlations for the control damping force and the response quantities are satisfactory. The MR damper is mostly capable of tracing the control force demanded by the control algorithm. The results show that the semiactive control system with the sliding mode control method achieved outstanding performance and verify the feasibility of semiactive control in practical implementation.

2. EXPERIMENTAL SETUP AND SYSTEM IDENTIFICATION

A series of experiments of a semiactive control system with a MR damper are conducted on the shaking table at Department of Civil and Environmental Engineering, Tokyo Institute of Technology, Japan. A two-story shear-type structure model made of steel plates is designed to imitate the dynamic behavior of isolated bridges, as shown in Figure 1. In particular, since the column plates are replaceable, next nonlinear test can be continued using the same model by only changing the steel plates. The model did not represent a similitude-scaled replica of a full-scale structure. Rather, the structure model is designed as a small structural system. The mass of about 100 kg is installed on the top level to simulate the bridge deck weight. Most mass of the model is concentrated on the first and second floor levels. There are 85 kg and 200 kg on the first and second floors, respectively. A magneto-rheological (MR) damper with capacity of 2 kN, produced by Lord Corporation, USA, is installed on the second story as the semiactive control device. A load cell (capacity 2 kN) is set between the MR damper and the supporting bracket to measure the force generated by the damper. The acceleration and displacement responses of all floor levels are recorded during experimental testing by using accelerometers and LVDTs. However, only data from accelerometers are utilized for feedback. The displacements are recorded for reference rather than feedback.

Prior to experimental tests, the dynamic properties of the test modal are identified by using free vibration and white noise as input to the shaking table. The first two natural frequencies are 9.2 and 31.0 rad/sec. In order to understand the behavior of the MR damper, the MR damper is excited by a servo-hydraulic actuator under harmonic excitations of 0.5 Hz, 1 Hz, and 2 Hz, with current varying from 0 mA to 1000 mA, shown in Figure 2. The force-displacement behavior of the MR damper is presented in Figure 3.

Two types of MR damper models are herein adopted for experiment and analysis, respectively, shown in Figure 4. In experiment, the used MR damper model consisting of friction damping force and viscous damping force, which are linear functions of current, is constructed (Ruangrassamee and Kawashima 2001) as

$$V_{MR}(t) = f_m(t) + c_m(t)\dot{x}_m(t) \tag{2.1}$$

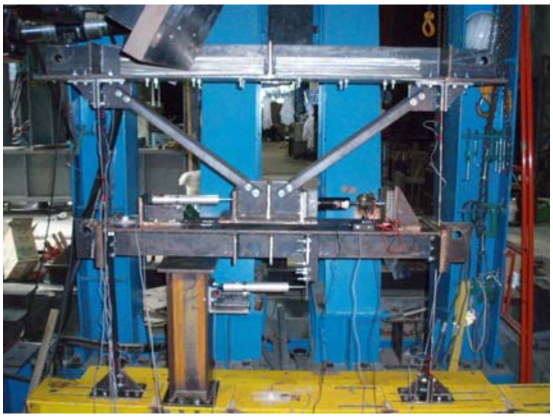

Figure 1 Two-story Shear-Type Test Structure

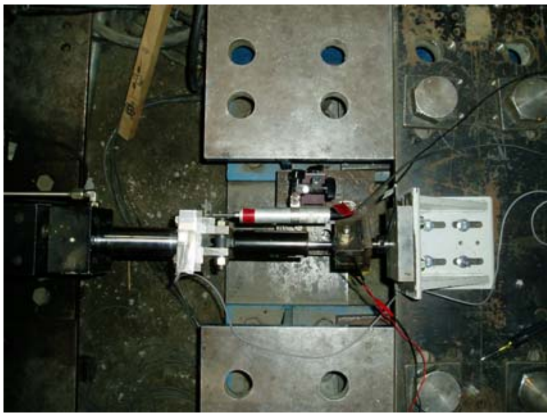

Figure 2 Test set-up for the MR damper

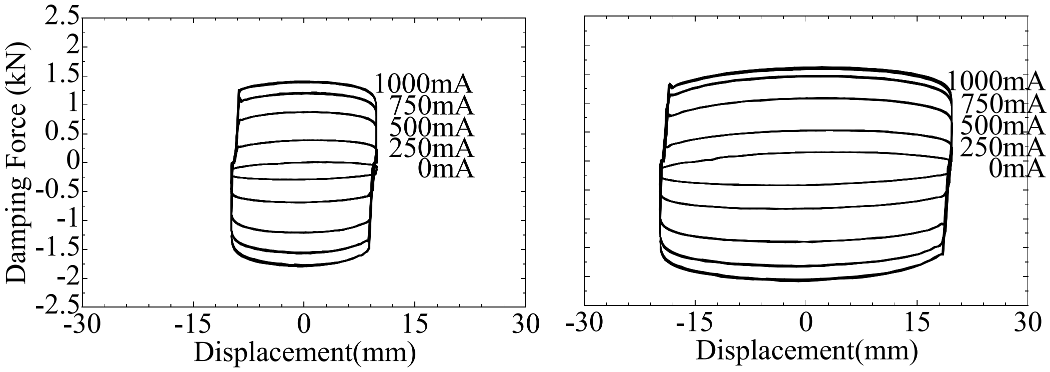

Figure 3 Force-Displacement Response of MR Damper

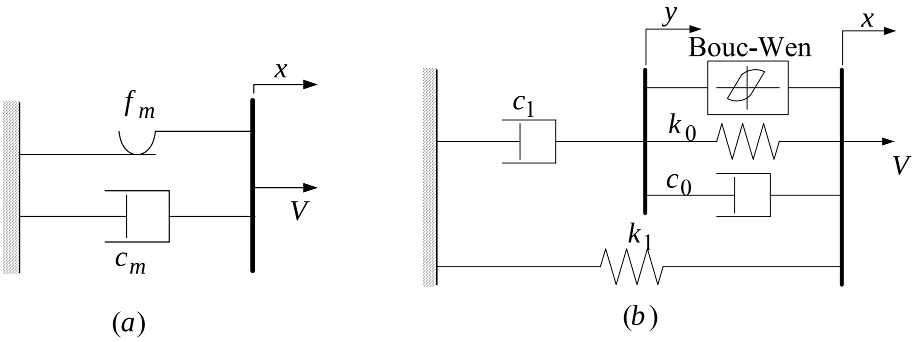

Figure 4 The MR damper models

where $V_{MR}(t)$ is the exerting damping force by the MR damper; f_m and c_m are assumed as the forms of

$$f_m(t) = f_{m1} + f_{m2}I(t)\,; \quad c_m(t) = c_{m1} + c_{m2}I(t) \tag{2.2}$$

It is easy to calculate the demanded current on line by using the above MR damper model once the demanded control force $U(t)$ is given. The friction damping force and viscous damping coefficients of the MR damper with respect to current are shown in Figure 5. Alternative MR damper model proposed by Dyke *et al.* (1996) consisting of friction damping force, viscous damping force and Bouc-Wen hysteresis model is used for analysis as

$$V = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) = c_1\dot{y} + k_1(x - x_0) \tag{2.3}$$

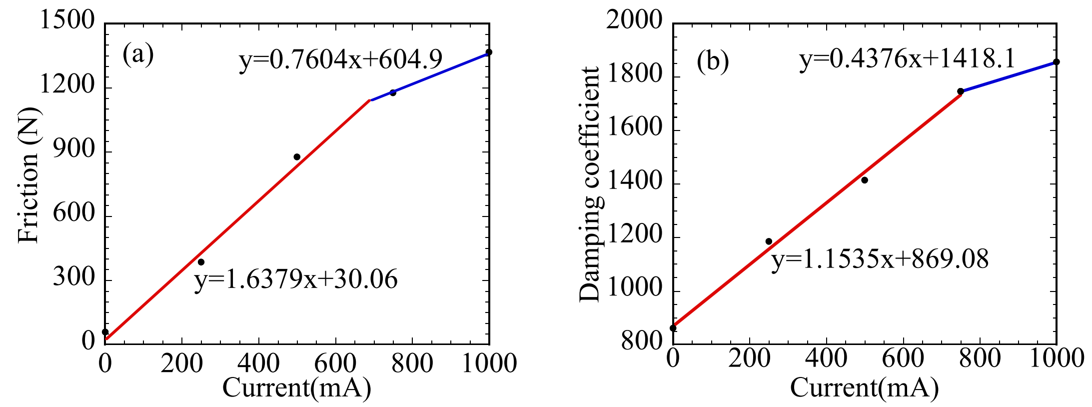

Figure 5 (a) Friction Damping Force and (b) Viscous Damping Coefficient of MR Damper Model

where

$$\dot{z} = -\gamma\left|\dot{x}-\dot{y}\right|z\left|z\right|^{n+1} - \beta(\dot{x}-\dot{y})\alpha z\left|z\right|^{n} + A(\dot{x}-\dot{y}) \tag{2.4}$$

$$\dot{y} = \frac{1}{c_0 + c_1}(\alpha z + c_0\dot{x} + k_0(x-y) \tag{2.5}$$

in which α, c_0 and c_1 are functions of current as

$$\alpha(I) = -\alpha_a I^3 + \alpha_b I^2 + \alpha_c I + \alpha_d \tag{2.6}$$

$$c_0(I) = -c_{0a} I^2 + c_{0b} I + c_{0c} \tag{2.7}$$

$$c_1(I) = c_{1a} I^2 + c_{1b} I - c_{1c} \tag{2.8}$$

The parameters in Eqs. (3) through (8) are obtained by a constrained nonlinear optimization in MATLAB. The optimized parameters fitting the experimental data are given in Table 1. Figures 6 and 7 illustrate the comparison between the estimated results and the experimental data.

3. CONTROL ALGORITHM

Sliding mode control is selected to command the MR damper (Yang *et al.* 1994, 1995). The method of sliding mode control is described briefly in the following. The equation of motion for a lump-mass shear-type structure subjected to an earthquake acceleration $\ddot{x}_g$ can be expressed as

$$\mathbf{M}\ddot{\mathbf{X}}(t) + \mathbf{C}\dot{\mathbf{X}}(t) + F[\mathbf{X}(t)] = \mathbf{H}\mathbf{U}(t) + \boldsymbol{\eta}\ddot{x}_g(t) \tag{3.1}$$

in which $\mathbf{X}(t) = [x_1, x_2, ..., x_n]^T$ is an n-vector with $x_j(t)$ being the displacement of the *j*th mass; $\mathbf{M}$ and $\mathbf{C}$ are $(n \times n)$ mass and damping matrices, respectively, where linear viscous damping is assumed for the bridge; $\mathbf{F}[\mathbf{X}(t)]$ is an n-vector denoting the nonlinear restoring force that is assumed to be a function of $\mathbf{X}(t)$; $\mathbf{H}$ is a $(n \times r)$ matrix denoting the location of r controllers; and $\boldsymbol{\eta}$ is an n-vector denoting the influence of the earthquake excitation.

The equations of motion by Eqn. (9) can be written in a state space formulation as follows

$$\dot{\mathbf{Z}}(t) = \mathbf{g}[\mathbf{Z}(t)] + \mathbf{B}\mathbf{U}(t) + \mathbf{E}(t) \tag{3.2}$$

Table 1 Parameters for the modified mechanics model

Parameter	Value	Parameter	Value
γ, β	36 cm^{-2}	α_c	1182 N/A
A	15	α_d	85 N
k_0	10 N/cm	c_{0a}	4 N s/A^{2}m
k_1	10 N/cm	c_{0b}	13.914 N s/Am
n	5	c_{0c}	8.56 N s/m
x_0	0.1 cm	c_{1a}	10046 N s/A^{2}m
α_a	2729 N/A^3	c_{1b}	10046 N s/Am
α_b	3319 N/A^2	c_{1c}	28017 N s/m

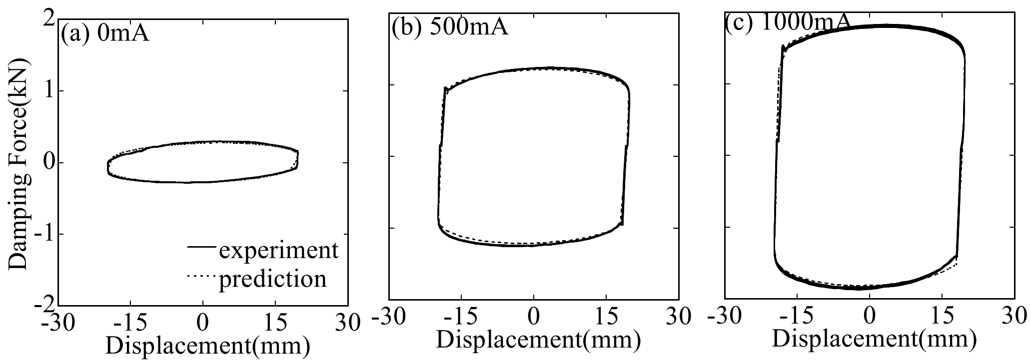

Figure 6 Comparison between experimentally-obtained and predicted displacement v.s. damping force

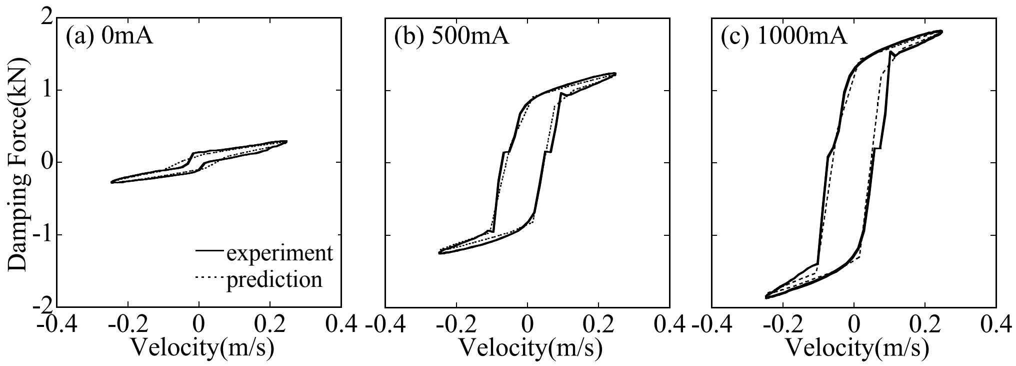

Figure 7 Comparison between experimentally-obtained and predicted velocity v.s. damping force

where $\mathbf{Z}(t)=\left[\mathbf{X}(t)\quad \dot{\mathbf{X}}(t)\right]^T$ is a $2n$ state vector; $\mathbf{g}\left[\mathbf{Z}(t)\right]$ is a $2n$ vector which is a nonlinear function of the state vector $\mathbf{Z}(t)$; $\mathbf{B}$ is a $(2n\times r)$ control force location matrix, and $\mathbf{E}$ is a $2n$ earthquake ground excitation vector, respectively, defined as follows:

$$\mathbf{g}[\mathbf{Z}(t)]=\begin{bmatrix}\dot{\mathbf{X}}(t)\\ -\mathbf{M}^{-1}[\mathbf{C}\dot{\mathbf{X}}(t)+\mathbf{F}[\mathbf{X}(t)]]\end{bmatrix};\quad \mathbf{B}=\begin{bmatrix}\mathbf{0}\\ \mathbf{M}^{-1}\mathbf{H}\end{bmatrix};\quad \mathbf{E}(t)=\begin{bmatrix}\mathbf{0}\\ \mathbf{M}^{-1}\boldsymbol{\eta}\end{bmatrix}\ddot{x}_g(t) \tag{3.3}$$

In sliding mode control, the aim of the control force is to drive the response trajectory toward the sliding surface, where the motion on the sliding surface defined by $\mathbf{S}=\mathbf{0}$ is stable, and then to maintain it on the sliding surface. Define the sliding surface $\mathbf{S}$ as a linear function of state vector $\mathbf{Z}$ such that

$$\mathbf{S} = \mathbf{PZ}(t) \tag{3.4}$$

The sliding surface can be determined using the pole assignment method or the LQR method (Yang 1995). To design the controller, the Lyapunov function $V = \mathbf{S}^T\dot{\mathbf{S}}/2$ is considered. The sufficient condition for the sliding mode to occur is given by

$$\dot{V} = \mathbf{S}^T\dot{\mathbf{S}} \le 0 \tag{3.5}$$

Substituting Eqn. (3.4) in Eqn. (3.5), taking the derivative and using the state equations of motion by Eqn. (3.2), an estimated recursive controller in form of discrete time, which is free of chattering effect, is written as

$$\mathbf{U}(t+\psi) = \mathbf{U}(t) - (\mathbf{PB})^{-1}\mathbf{P}\dot{\mathbf{Z}}(t) - \boldsymbol{\delta}\boldsymbol{\lambda}^T(t) \tag{3.6}$$

where ψ is sampling time; $\boldsymbol{\lambda} = \mathbf{S}^T\mathbf{PB}$; $\boldsymbol{\delta}$ is a ($r \times r$) diagonal positive-definite matrix with diagonal entries $\delta_1, \delta_2, ..., \delta_r$.

It is observed from Eqn (3.6) that the feedback information of the improved sliding mode controller is $\dot{\mathbf{Z}}(t)$ (velocity and acceleration) and $\mathbf{U}(t)$ (current control force) which is much easier than the conventional sliding mode controller to implement the control algorithm because it is more practical to measure acceleration than displacement in application.

4. EXPERIMENTAL AND ANALYTICAL RESULTS

The structural model is tested by using three near-field ground motions recorded at JMA Kobe Observatory and JR Takatori station in the 1995 Kobe, Japan earthquake and Sun-Moon Lake in the 1999 Chi-Chi, Taiwan earthquake, which are scaled in magnitude by the maximum factors of 50%, 30% and 30%, respectively. Based on the results of the system identification and under ideal control situations, numerical simulations are performed for comparison. It is noted that the MR damper model including Bouc-Wen model is used in numerical analysis, which is able to simulate the hysteretic behavior of the MR damper in the vicinity of null velocity. The nonlinear stiffness restoring forces of both stories are also simulated by Bouc-Wen hysteretic model. The initial stiffnesses of the lower and upper stories are 45.5 kN/m and 28 kN/m, respectively. The yielding displacements of the lower and upper stories are 0.036 m and 0.041 m, respectively. The ratio of the post-yielding to initial stiffness is 0.01. The other parameters are A=1, $\beta = \gamma$ =0.5 and n=95 for both stories.

For the sake of limited pages, only the results under 50% of JMA Kobe ground motion are shown herein. Analytical and experimental time histories of the control damping force, applied current, interstory drifts and the displacement at the top floor level are compared in Figure 8. Time delay of 30 ms totally occurs in the control system and is taken into account in analysis. The results demonstrate that the correlations for the control damping force and the response quantities are satisfactory. The MR damper controlled by continuous current traces the control force demanded by the control algorithm well. Figure 9(a) presents the comparison of the hysteretic loop of control damping force and corresponding stroke in MR damper. It is observed that the MR damper model including Bouc-Wen model for analysis is reasonable. Figures 9(b) and 9(c) make a comparison of the hysteretic loops for both stories. It is obvious that the first story undergoes the nonlinear behavior. Consequently, the semiactive control system with the MR damper commanded by the sliding mode control algorithm is feasible for nonlinear structures in practical implementation.

5. CONCLUSIONS

The semiactive control system by using a MR damper with the sliding mode control algorithm for a nonlinear structure is successfully implemented and evaluated through a series of shaking table tests by using a two-story shear-type structure model. Compared to the control methods based on feedback of displacements and velocities, the sliding mode control based on feedback of velocities and accelerations shows more practical application into real structures, especially nonlinear structures, because it is easier to measure acceleration than displacement during earthquakes. Through comparison between analytical and experimental results, the MR

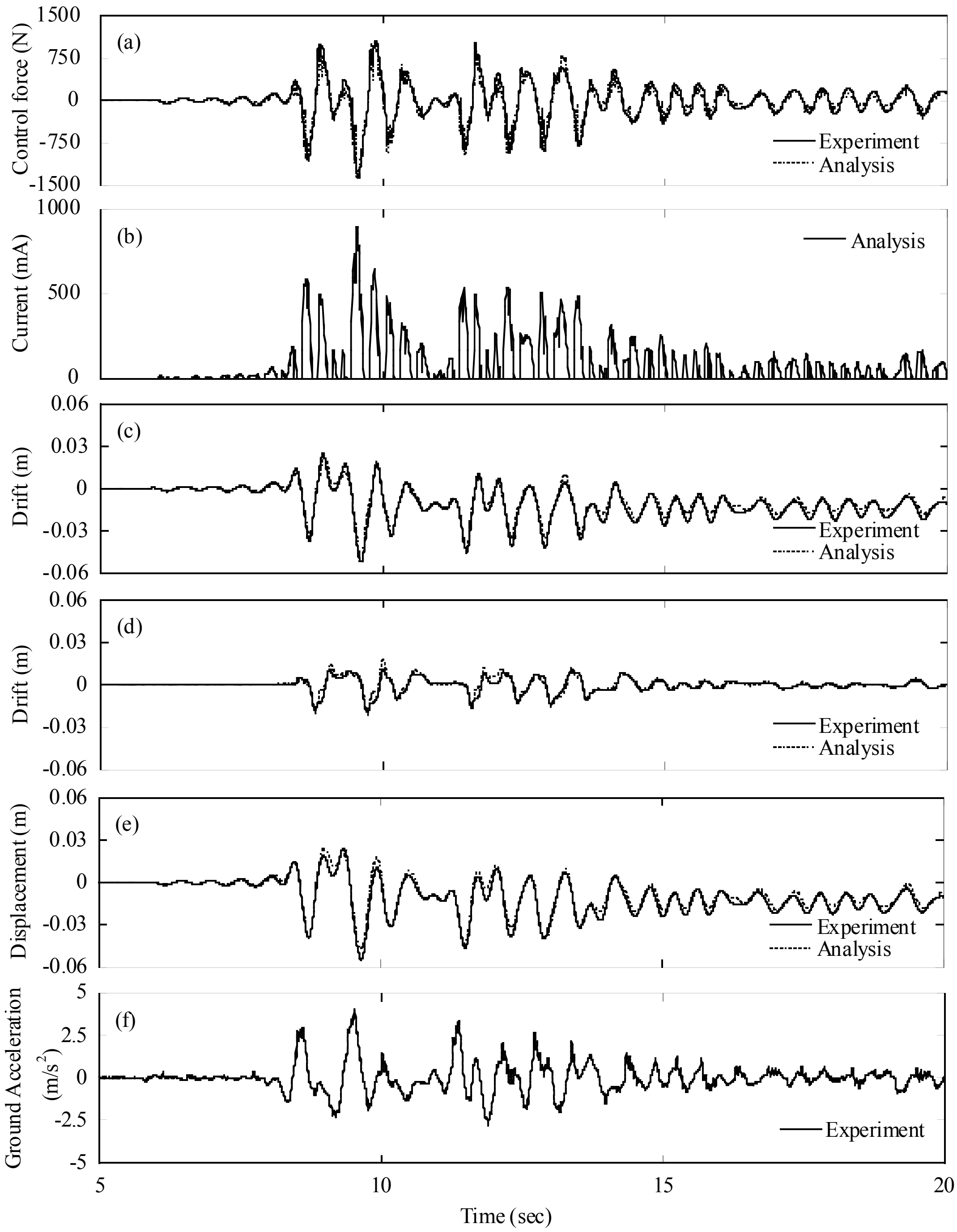

Figure 8 Comparison for (a) control damping force, (b) applied current (c) the first story drift, (d) the second story drift and (e) displacement of the second floor under (f) 50% JMA Kobe ground motion

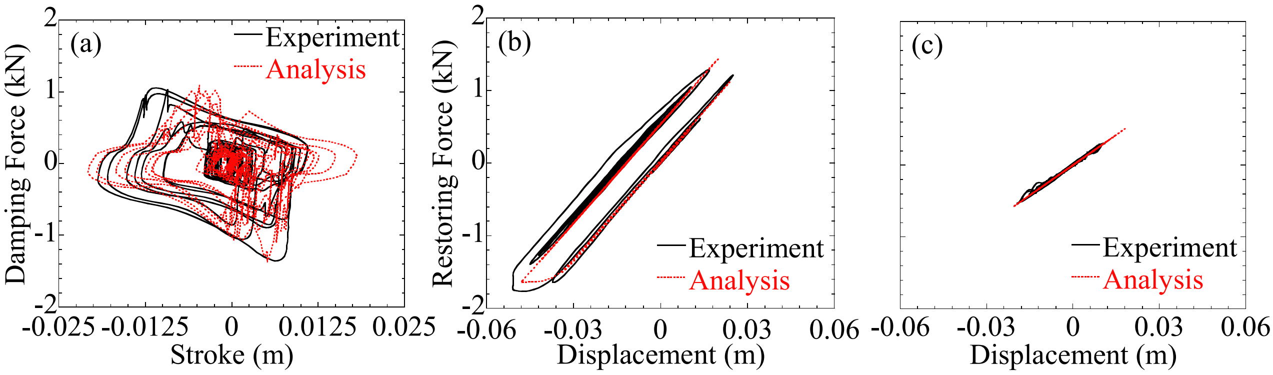

Figure 9 Hysteretic loops of (a) the MR damper, (b) the first story and (c) the second story

damper satisfactorily traced the demanded control force by the control algorithm and the response time histories agreed to each other well. The results verify the feasibility of semiactive control system for nonlinear systems in practical implementation. In addition, since the results both in the past numerical simulation and the present experiments demonstrate that the semiactive control system has outstanding performance, the semiactive control system provides a valuable control method for mitigating seismic responses of nonlinear isolated bridges.

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