DUAL REAL-TIME HYBRID SIMULATION AND SEMI-ACTIVE BASE ISOLATION SYSTEM WITH NONLINEAR BEHAVIOR

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Abstract

Isolated rubber bearings have been used to protect structures from earthquake damage. However, under extreme ground motions such as long-period ground motion and pulse-like ground motion, they can undergo large shear deformation. For shear strain of isolated rubber bearings beyond a certain high level (e.g., 250%), they can then exhibit nonlinear restoring force characteristics (hardening behavior) (Fig. 1). This study verified effects of nonlinear behavior for a control system in an isolated structure. Moreover, this study verified the effectiveness of semi-active base isolation systems with nonlinear restoring force characteristics applying three semi-active control strategies (skyhook control, EF control, and optimal control) using a magnetorheological (MR) fluid damper.

Considering the nonlinear behavior of isolated rubber bearings and uncertainty of a MR damper, the authors developed and conducted the dual real-time hybrid simulation (DRTHS). Real-time hybrid simulation (RTHS) is a seismic response simulation method with a combination of numerical computation and physical specimens tested using an excitation device. This simulation can experimentally assess only the crucially important system components, which complicate validation of the numerical models, while the remainder of the structure is simulated. Therefore, the simulation is a cost-effective means to examine various control strategies. In DRTHS, two specimens are tested using two excitation devices each. For this study, isolated bearings and MR damper were excited using a hydraulic actuator and a shake table (Fig. 2). This report describes the DRTHS experimental setup and explains validation by calculation of the time delay.

Keywords: base-isolated system, isolated rubber bearing, MR damper, real time hybrid simulation, semi-active control

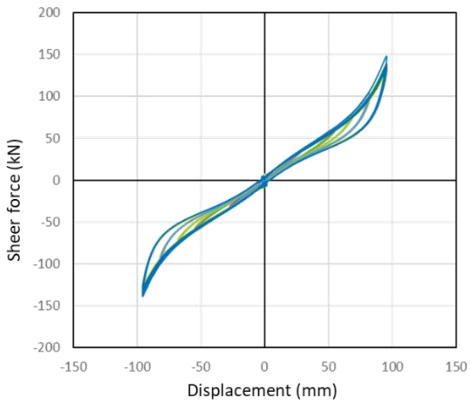


Fig. 1 Shear force – displacement hysteresis loops.

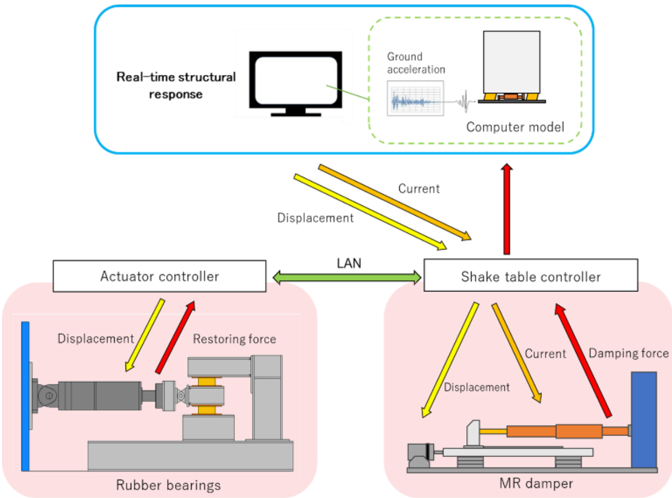


Fig. 2 Schematic of DRTHS.

1. Introduction

Since the Southern Hyogo Prefecture Earthquake in 1995, the use of base-isolated structures has increased rapidly. However, long-period ground motion and pulse-like ground motion cause excessive displacement of the isolation layer. Isolated rubber bearings exhibit hardening behavior while undergoing large shear deformation. The hardening of bearings can increase the absolute acceleration and make it difficult to maintain building safety and functionality.

As described herein, semi-active control using magnetorheological (MR) damping is applied to an isolated structure with nonlinear restoring force of isolated rubber bearings. However, the MR damper and isolated rubber bearings present uncertainties related to velocity-dependent elements and nonlinearity. The uncertainty which accompanies modeling of the MR damper and isolated rubber bearings is a difficulty that is encountered in numerical analysis. Consequently, this research presents dual real-time hybrid simulation (DRTHS), which is an extension of real-time hybrid simulation (RTHS) and which can perform real-time loading of the MR damper and isolated rubber bearings. At the Network for Earthquake Engineering Simulation (NEES), Christenson et al. [1] and Chae et al. [2] worked on an RTHS of the semi-active control of structures using MR dampers. At Kobe University, the RTHS effectiveness was verified by comparison with a shake table test [3]. Fujii et al. [4] worked on RTHS of semi-active control using an MR damper. Yoshida et al. [5,6] performed RTHS of the semi-active control of mid-story isolated buildings using a shake table. Ito et al. [7] also conducted RTHS of structures with TMD using a shake table. For these studies, it is impossible to use multiple excitation devices. DRTHS enables excitement of an MR damper by a shake table and isolated rubber bearings by an actuator. This study verifies the validity of DRTHS.

2. Dual Real-Time Hybrid Simulation (DRTHS)

2.1 Schematic of DRTHS

As a method of testing seismic response, RTHS physically tests only the critical components of the structure while the remainder of the structure is simulated. Dual real-time hybrid simulation was used to test two specimens, rubber isolated bearings and an MR damper, using two excitation devices: an actuator and a shake table (Figs. 3,4). Fig. 2 portrays a schematic diagram of DRTHS. First, earthquake ground motion is input into the building model in the DSP to conduct a time-history response analysis. The relative displacement of the isolation layer is reproduced using the shake table and actuator. The command signal is sent to the actuator from a controller on the shake table through a LAN cable. The restoring force and damping force of the isolation layer, provided by isolated bearings and the MR damper, are put back into a structural model in the DSP to be used for time-history response analysis. The current value assigned to a magnetorheologic (MR) damper is calculated by analysis. These operations are repeated at 500 Hz (0.002 s interval). In this way, real-time hybrid simulation, which considers the damper force by semi-active control and the nonlinear restoring force by isolated rubber bearings, is realized.

Fig. 3 – Actuator and shake table in Kobe University

Fig. 4 – Isolated rubber bearings and MR damper used for DRTHS

2.2 Isolated rubber bearing

Table 1 presents specifications of the isolated rubber bearings used in DRTHS. Fig. 1 shows the hysteresis loop obtained for 0.25 Hz sinusoidal excitation. From Fig. 1, at horizontal displacement about 68 mm, the bearing exhibits a distinct hardening behavior. Total thickness of the rubber layers of the bearings is 27.2 (mm). Therefore, at shear strain beyond about 250%, the bearing stiffness increases. The secondary stiffness was approximately 2.071 times the initial stiffness.

Table 1 – Specifications of isolated rubber bearing

Diameter	φ225
Dimension of rubber	1.6 mm × 17 layers
S_1	35.2
S_2	8.27
Initial horizontal stiffness	526 (kN/m)

2.3 MR damper

Magnetorheological fluid (MR) dampers are semi-active control devices that use MR fluids to produce controllable dampers. The damping force can shift by the volume of electric current, so it can be controlled by a PC. Table 2 shows the specification of the MR damper used in DRTHS.

Table 2 – MR damper specifications

Stroke	±300 (mm)
Maximum force	2 (kN)
Maximum velocity	100 (cm/s)

The MR damper is modelled simply using the Bingham plastic model as shown in Fig. 5. The relation between the damper force (F_{MR} (N)) and the electric current (I (A)) is approximated as Eq. 2.1. In EF control and optimal control, after determining the damper force according to each strategy, the current value to MR damper is calculated using Eq. 2.1.

$$F_{MR} = (-237I^2 + 1484I + 35) \cdot sign(\dot{x}) + 243\dot{x} \quad (2.1)$$

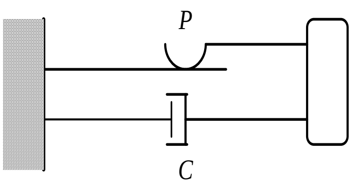


Fig. 5 – Bingham plastic model

2.4 Experiment case

To evaluate the dynamic response when the isolated rubber bearings exhibit hardening behavior, this study relies on the assumption the structure idealized as a 1-DOF base isolated system. Table 3 shows the structure specifications. It is presumed that the structure is set to four isolated rubber bearings and that the natural period is 4 (s). The mass is decided by the stiffness and natural period. Moreover, the number of MR dampers is set as 168 units, which is 4% of the weight of the superstructure.

Table 2 – System specifications

Mass	853 (t)
Stiffness	2104 (kN/m)
Natural period	4 (s)
Units of isolated rubber bearings	4
Units of MR damper	168

Three earthquake ground motions were selected as input waves for DRTH: BCJ-L2, JR Takatori 1995 NS, and Tomakomai 2003 NS. Furthermore, semi-active control, skyhook control, EF control and optimal control were applied. To compare three semi-active controls, a non-control case in which the current value to MR damper is 0 (A) is conducted. In addition, a case in which the maximum amplitude was 60 mm (Case 1) and a case in which the maximum amplitude was 90 mm (Case 2) were performed in DRTH. Case 1 is in the linear range of the bearings. Case 2 is in the nonlinear range. Comparison of Case 1 and Case 2 can verify the effectiveness of semi-active control when hardening behavior occurs.

3. Semi-active Control

3.1 Skyhook control

Skyhook control [8] reduces the response by setting a virtual fixed point for ground motion and by connecting the mass point to it with a viscous element. Therefore, skyhook control is effective at reducing the absolute response. According to the control law of Eq. 3.1, the current value to the MR damper (I(A)) is determined and applied. v is the absolute velocity of base isolation (m/s). Also, $\dot{x}$ represents the relative velocity of base isolation (m/s).

$$\begin{cases} v\cdot\dot{x} \geq 0 & I = 2\ (\mathrm{A}) \\ v\cdot\dot{x} < 0 & I = 0\ (\mathrm{A}) \end{cases} \tag{3.1}$$

3.2 EF control

In EF control [9], the control force (f (kN)) is determined according to the energy function, which is based on the sum of kinetic energy and elastic strain energy (Eq. 3.2). In addition, λ is set to 50 to avoid exceeding the MR damper capacity. Also, m stands for the mass (t), k denotes the stiffness (kN/m), and $\dot{x}$, x spectively express the relative velocity (m/s) and displacement (m). Actually, EF control can evaluate an appropriate control force even at the time of small amplitude or large amplitude.

$$f = \lambda\sqrt{\frac{1}{2}m\dot{x}^2 + \frac{1}{2}kx^2} \qquad (\lambda=50) \tag{3.2}$$

3.3 Optimal control

In optimal control [10], the damping force (u (N)) is determined by performing weighting for minimizing the evaluation function, as shown in Eq. 3.3. Also, x, $\dot{x}$ and $\ddot{x}$ respectively represent the relative displacement (m), velocity (m/s), and acceleration (m/s^2). Furthermore, $\ddot{z}$ denotes the ground acceleration (m/s^2). α_d, α_v, α_a and γ are the respective weight coefficients for displacement, velocity, acceleration and damping force. By increasing each coefficient, the corresponding quantity of state can be made small. For example, by increasing α_d, displacement can be reduced. For this study, α_d ,α_v, and α_a are set to 10^{13}; γ is set to 1. Results confirmed that these values can reduce the structural response acceleration more in preliminary analysis.

$$J = \int_0^{\infty}(\alpha_d x(t)^2 + \alpha_v \dot{x}(t)^2 + \alpha_a(\ddot{x}(t) + \ddot{z}(t))^2 + \gamma u(t)^2)dt \tag{3.3}$$

$$(\alpha_d = \alpha_v = \alpha_a = 10^{13}、\gamma = 1)$$

4. Results of DRTHS

4.1 Stability of DRTHS

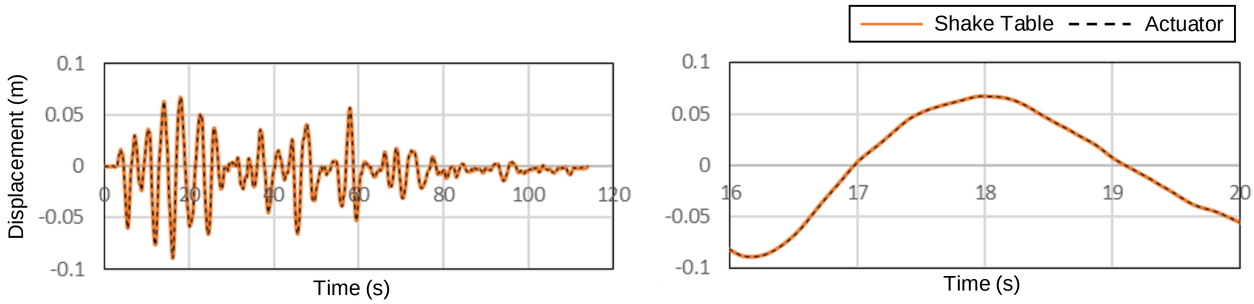
To verify DRTHS stability, time delays of three kinds are calculated, (i) from Shake table command displacement to actuator command displacement, (ii) from shake table command to measured displacement, and (iii) from actuator command to measured displacement. Moreover, regarding (i), (ii), and (iii), the correlation coefficient ρ is calculated. ρ is determined according to Eq. 4.1. N is the number of data, A_i and B_i denote time history data and μ_A and μ_B are the respective averages of A and B. The closer ρ is to 1, the stronger the positive correlation is, and the smaller the phase shift becomes. Table 4 shows the time delay and the correlation coefficient ρ in each case.

$$\rho = \frac{\frac{1}{N-1}\sum_{i=1}^{N}(A_i-\mu_A)(B_i-\mu_B)}{\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(A_i-\mu_A)^2}\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(B_i-\mu_B)^2}} \tag{4.1}$$

In case (i), the time delay is 0.003 (s). The sampling time in DRTH is 0.002 (s). Therefore, the delay of case (i) is only 1 or 2 steps of the sampling time. Moreover, ρ is equal to 1. The time history waveforms of shake table command displacement and actuator command displacement are almost identical (Fig. 6(a)). Therefore, it was judged that there was no problem with the communication speed between the shake table and the actuator through the LAN cable. However, in cases (i) and (ii), the time delays were 0.026 and 0.044. They are much longer than the sampling time. Their correlation coefficients are 0.998 and 0.995. Therefore, compared to case (i), they are more different from 1. In addition, the time history waveforms showed deviation (Figs. 6(b) and 6(c)). Therefore, the delay time found with performance of the actuator and shake table must be regarded as tracking DRTHS results by pure simulation.

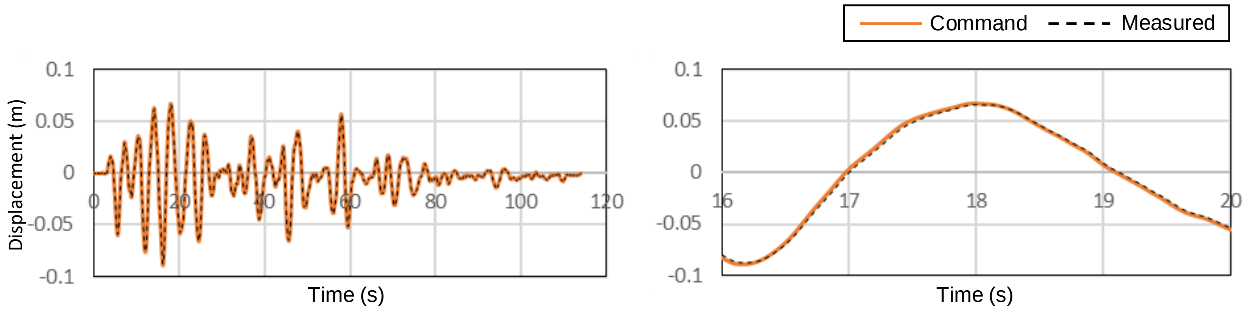
Table 4 – Time delay in DRTHS and the correlation coefficient ρ

	Time delay (s)	Correlation coefficient ρ
(i) From shake table command displacement to actuator command displacement	0.003	1.000
(ii) From shake table command to measured displacement	0.026	0.998
(iii) From actuator command to measured displacement	0.044	0.995



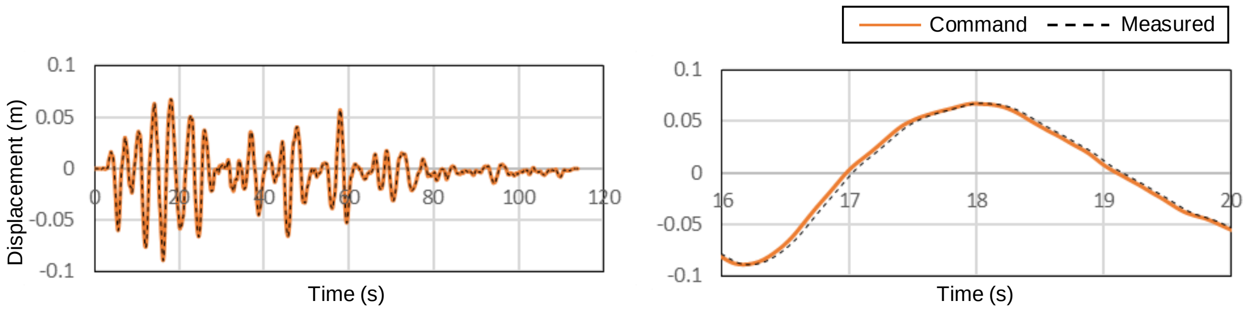
(a) Shake table command displacement and actuator command displacement histories

(BCJ-L2 16%, the current to MR damper is 0A)



(b) Shake table command and measured displacement histories

(BCJ-L2 16%, the current to MR damper is 0A)



(c) Actuator command and measured displacement histories

(BCJ-L2 16%, the current to MR damper is 0A)

Fig. 6 – Displacement histories

4.2 Comparison of semi-active control and non-control

To verify the effectiveness of semi-active control, cases with applied semi-active control were compared with non-control cases for which the current value to the MR damper is 0A. First, when isolated rubber bearings do not exhibit hardening behavior (the maximum amplitude is 60 mm (Case 1)), it is verified that three semi-active control methods of skyhook, EF and optimal control can reduce the response displacement and absolute response acceleration more than non-control. For comparison, reduction rate r_1 is defined as Eq. 4.2.1. For r_1 smaller than 1, semi-active control is more effective than non-control. Table 4 shows r_1. From Table 5, the value of r_1 of maximum response displacement is less than 1 in all cases. Therefore, all three semi-active control methods can reduce response displacement. In BCJ-L2 of about 30–40%, in JR Takatori 1995 NS of about 60%, and in Tomakomai 2003 NS of approximately 20–40%, the response displacement is reduced.

Otherwise, r_1 of maximum absolute response acceleration is not less than 1 in all cases. In JR Takatori 1995 NS, r_1 is much more than 1. Therefore, in pulse-like ground motion such as JR Takatori 1995 NS, the three modes of semi-active control proposed in this study have no effect on reducing absolute response acceleration.

$$r_1 = \frac{(result\ of\ semi\text{−}active\ control\ in\ Case\ 1)}{(result\ of\ non\text{−}control\ in\ Case\ 1)} \tag{4.2.1}$$

Table 5 – Reduction rate with non-hardening

Ground motion		BCJ-L2	JR Takatori 1995 NS	Tomakomai 2003 NS
Reduction rate		r_1	r_1	r_1
Skyhook Control	Max Disp.	0.41	0.60	0.40
	Max Acc.	1.02	1.44	0.83
	RMS Acc.	1.00	1.04	0.71
EF Control	Max Disp.	0.34	0.60	0.26
	Max Acc.	0.88	1.75	0.48
	RMS Acc.	0.82	1.12	0.52
Optimal Control	Max Disp.	0.33	0.60	0.34
	Max Acc.	0.84	1.78	0.49
	RMS Acc.	0.81	1.15	0.47

Second, when isolated rubber bearings exhibit hardening behavior (the maximum amplitude is 90 mm (Case 2)), it was verified that three modes of semi-active control are effective using r_2, which is defined according to Eq. 4.2.2, similarly to r_1. Table 6 shows r_2. From Table 6, in BCJ-L2 of about 30–40%, in JR Takatori 1995 NS of about 60%, and in Tomakomai 2003 NS of approximately 20–40%, the response displacement was reduced. However, the r_2 of maximum absolute response acceleration is much greater than 1 in JR Takatori 1995 NS. These results are similar to those found for Case 1.

$$r_2 = \frac{(result\ of\ semi\text{−}active\ control\ in\ Case\ 2)}{(result\ of\ non\text{−}control\ in\ Case\ 2)} \tag{4.2.2}$$

Table 6 – Reduction rate with hardening

Ground motion		BCJ-L2	JR Takatori 1995 NS	Tomakomai 2003 NS
Reduction rate		r_2	r_2	r_2
Skyhook Control	Max Disp.	0.37	0.58	0.37
	Max Acc.	0.80	0.79	0.73
	RMS Acc.	0.80	0.72	0.59
EF Control	Max Disp.	0.31	0.62	0.20
	Max Acc.	0.66	1.27	0.38
	RMS Acc.	0.75	0.95	0.45
Optimal Control	Max Disp.	0.29	0.58	0.31
	Max Acc.	0.54	1.15	0.46
	RMS Acc.	0.72	0.89	0.42

4.3 Comparison between linear behavior and nonlinear behavior

In the preceding section, Case 1 (with non-hardening) and Case 2 (with hardening) yield the same result. Therefore, in this section, we examine the difference between Case 1 and Case 2. Defining r as Eq. 4.3, one can verify whether the effectiveness of semi-active control differs between that with non-hardening and that with hardening. For r smaller than 1, a greater control effect can be expected for Case 2. Table 6 shows r.

As shown in Table 7, r is equal to or less than 1 in response displacement and absolute response acceleration. Therefore, probably the same or a greater control effect was obtained in Case 1, in which isolated rubber bearings exhibit hardening behavior, as in Case 2, in which they do not.

$$r = {}^{r_2}/_{r_1} \tag{4.3}$$

Table 7 – Reduction rate with hardening

Ground motion		BCJ-L2	JR Takatori 1995 NS	Tomakomai 2003 NS
Reduction rate		r	r	r
Skyhook Control	Max Disp.	0.89	0.96	0.93
	Max Acc.	0.78	0.55	0.87
	RMS Acc.	0.79	0.69	0.83
EFControl	Max Disp.	0.91	1.03	0.77
	Max Acc.	0.75	0.73	0.79
	RMS Acc.	0.91	0.85	0.86
Optimal Control	Max Disp.	0.87	0.96	0.92
	Max Acc.	0.65	0.65	0.94
	RMS Acc.	0.88	0.78	0.89

5. Conclusion

(1) After DRTHS was applied, the time delay associated with DRTHS was calculated. The time delay from shake table command displacement to actuator command displacement was short, indicating no difficulty related to the communication speed between the shake table and the actuator. However, the time delay related to excitation devices is long. Therefore, to reproduce results of DRTHS by pure simulation, this time delay should be considered.

(2) Compared to non-control, semi-active control reduces response displacement in both Case 1 (with non-hardening) and Case 2 (with hardening). However, it cannot suppress the rise of absolute response acceleration in in pulse-like ground motion such as JR Takatori 1995 NS.

(3) For nonlinear behavior of isolated rubber bearings, control effects equivalent to or better than those found for linear behavior were obtained.

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