Research on Hybrid Seismic Response Control System for Motion Control of Two Span Bridge

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Abstract. In this paper, a hybrid seismic response control (HSRC) system was developed to control bridge motion caused by seismic load. It was aimed at optimum vibration control, composed of a rubber bearing of passive type and a MR-damper of semi-active type. The bridge model was built for experiment, a two-span bridge of 8.3 meters in length with the HSRC system put up on it. Then, inflicting El-centro seismic load on it, shaking table tests were carried out to confirm the system’s validity. The experiments were conducted under the basic structure state (without an MR-damper applied) first, and then under the state with an MR-damper applied. It was also done under the basic structure state with a reinforced rubber bearing applied, then the passive on/off state of the HSRC system, and finally the semi-active state where the control algorithm was applied to the system. From the experiments, it was observed that collision rather increased when the MR-damper alone was applied, and also that the application of the HSRC system effectively prevented it from occurring. As a result, the HSRC system was proven to be effective in mitigating responses of the two-span bridge under seismic load.

1. Introduction
When earthquake occurs thus affecting bridges, there may be collision between their upper structure and abutment, and also between upper structures themselves, causing serious damage on them. Two of the most outstanding cases of damage are found in the Loma Prieta (1989) and Kobe (1995) earthquake, where disparate movement of each upper span caused a destruction of whole bridges (Zanardo 2002). Besides, in the 2010 Haiti earthquake, the intermediate supports of a bridge over Momance River were also damaged by collision (DesRoches, 2011). In the 2008 Wenchuan earthquake also, both Gaoyuan and Miaoziping bridges collapsed due to the breakdown of shear key after clash of girders (Han, 2009). Such a structural collision, imposing big flash weight on structure additionally, is very likely to result in initial destruction and deviation (unseating) of upper structure, and then again, of abutments and piers successively (Robert, 1998). For this reason, there have been many studies on bridge collision under seismic load. Among them are analytical and theoretical studies on collision cases, and also preventive ones on the basis of previous analysis and theories. As an analytical type of study on bridge collision, Han et al. (2009) studied the...
damage that the 2008 Wenchuan earthquake did to a bridge on the highway. Zhang et al. (2008) also studied the bridges in California under seismic shaking or liquefaction-induced lateral spreading and found that they were vulnerable to earthquake to each different degree based on their types. As another type of theoretical study on collision, Tanabe et al. (1998) idealized collision of upper structures in terms of nonlinear spring, and proved collision considerably contributed to collapse of an overbridge (a bridge which is continuously pierced on the ground) by performing a time history analysis using the seismic load generated in the 1995 Hyogo-ken Nanbu earthquake. Kajita et al. (1998) simulated inter-girder collision in an element equipped with a linear spring and a damper, and performed a time history analysis to analyze the overbridge response resulted from collision between adjacent upper structures. On the basis of such analytical and theoretical studies, Robert et al. (1998) remarkably analyzed a collision between upper structures of an elevated isolated bridge, due to the spread of seismic load, and proved by means of numerical simulation that bridge collision occurred in proportion to the size of gap between upper structures, while emphasizing the fact that too big or too small size of gap could be a problem, too. Shehata (2009) developed a model for an analysis of expansion joint, carrying out a nonlinear time history analysis on an isolated multi-span bridge with three standard ground motions. Then, he classified the arrangement pattern of restrainer into three types to study which was most effective for collision mitigation. As a result, he proved the bridge was effectively protected from span unseating and collision, but failed to protect two upper structures from colliding each other.

Lately, studies are focused on how to apply MR-dampers to protect the separation layer of existing isolated bridges from collision due to its increasing displacement. The most representative analytical study of this kind was made by Ruangrassamee (2003) et al. After installing four MR-dampers on an analytical model of highway bridge composed of 2 decks (5 spans each), they made an analytical comparison of their performance for response mitigation, using the Kobe seismic load. Li (2006) et al. also studied a method to analyze and control the seismic pounding responses of urban elevated bridges (bridges damaged by earthquake-induced collision). In particular, they tried to control the seismic pounding response of adjacent upper structures using MR-dampers, and theoretically analyzed the performance of the MR-dampers, the one installed at adjacent upper structure and the other put up between the superstructure and piers. Sheikh(2012) et al. studied on the effect of MR-damper to damp collision of a Base-isolated RC Highway Bridge modeled by Matlab & Simulink. However, it was not experimentally verified. The representative experimental study of this kind was made by Guo et al.(2009) who connected two MR-dampers to each span and pier installed with rubber bearings for prevention of collision. But it had some disadvantages when the span was connected to the pier, increasing the shear force and moment for supporting piers (Shehata, 2009). The previous studies have shown that in order to damp relative displacement of nearby structures under seismic load, it was necessary to place a control device between adjacent upper structures rather than between superstructures (Li, 2006; Shehata, 2009). However, even when it happens, that is, a control device is connected to somewhere between adjacent upper structures, the motion of each upper structure may affect others, increasing the shear force on bearings.

For the reasons, this study proposes a hybrid seismic response control (HSRC) System to control structural motion under a huge external impact like seismic load, and verifies its performance experimentally. In it, both MR-damper and rubber bearing work together as a unified control system: that is, a MR-damper as a semi-active device that connects upper structures each other, and a rubber bearing as a passive device whose stiffness was strengthened to resist against increasing shear force caused by application of the MR damper. In order to verify its performance experimentally, a two upper-span bridge model was built, each span made of different size. Also, three control devices were manufactured: a 10kN rubber bearing (RB), and another of 20 KN strengthened for this particular purpose, and an MR-damper of 30KN. Finally, while inflicting El-Centro earthquake load to the structure, its motion under the load was monitored to verify the HSRC system’s control performance. As a result, it was proven effective to mitigate structural motion s under seismic load.
2. Hybrid Seismic Response Control (HSRC) System

A basic structure of two span bridge without any control devices applied, when it is inflicted with some external load, has a double-degree of freedom. Meanwhile, when an MR damper is installed for control between upper layers (MR-damper structure), vibration is controllable to a certain degree, thanks to the different masses of two upper spans as well as to the MR-damper. However, its seat devices get overburdened with too much shear force. It is generally known that when a seismic load is imposed on a bridge laterally, the shear force on bridge seat devices and piers tend to increase. In this case, it is necessary to effectively minimize both the lateral force affecting piers and the shear force on seat devices. For the purpose, an enhanced rubber bearing (E-RB) was installed on the bridge seat device, thereby completing a HSRC system along with a formerly installed MR-damper. This HSRC system is established by integrating a RB, a stiffness-upgraded passive device which was designed to resist the shear force, and also an MR-damper, a semi-active device. The RB on the left is an enhanced RB (E-RB, 20kN) while the one on the right a general type of 10kN.

2.1. Control Algorithm

An MR-damper, a kind of semi-active device, performs its function of control only after a control algorithm is applied. In this study, the clipped-optimal control algorithm was adopted for MR-damper. It is a method of designing an optimum linear controller \( \text{c}K_{\text{s}} \), calculating a control force required for MR-damper, and then finally designing MR-damper itself by using the relation between a required control force and a current control force. A required control force is calculated by Equation (1) on the basis of structural responses.

\[
f_c = L^{-1} \left\{ -K_c(s) L\left\{ y \right\} \right\}
\]

(1)

Where \( L\{\cdot\} \) is Laplace transform. In Equation (1), \( y \) and \( f \) are the measured structural responses and the measured force. To approach a required control force \( f_c \), MR-damper control voltage \( v_i \) should be adjusted. Control voltage \( v_i \) can be calculated by Equation (2), and Eq. (2) is a control law of semi active feedback vibration control system where the Clipped-optimal control algorithm is applied (Dyke et al, 1996).

\[
v_i = V_{\text{max}} H \left( \left\{ f_{c,i} - f_i \right\} f_i \right)
\]

(2)

Where \( v_i \) is a control voltage that should be input into each controller at the moment, and \( V_{\text{max}} \) refers to a max voltage to be flowed into a control device. In addition, \( f_{c,i} \) is a required control force of the \( i^{th} \) MR-damper, and \( f_i \) is a control force observed at the \( i^{th} \) MR-damper. When an MR-damper exerts its required control force, it needs to be provided with the control voltage corresponding to a current structural state. It is not until in the case of \( f_{c,i} = f_i \) that a control voltage signals 0.

2.2. Test Structure

An MR-damper, a kind of semi-active device, performs its function of control only after a control algorithm is applied. In this study, the clipped-optimal control algorithm was adopted for MR-damper. It is a method of designing an optimum linear controller \( K_{\text{s}}(S) \), calculating a control force required for
MR-damper, and then finally designing MR-damper itself by using the relation between a required control force and a current control force. A required control force is calculated on the basis of structural responses. A two-span bridge was built with two spans of different size so as to be unsymmetrical in mass as seen in figure 1 in order to test the HSRC System’s control performance.

![Figure 1. Two Span Bridge](image)

The two-span bridge in figure 1 is structured to have upper structure, lower structure, and abutment. The upper structure is designed with I type girders to support reinforced concrete slabs. The upper span A is a comparatively short one, 2300mm in length and 1476kg in weight, while the upper span B is a longer one that extends 6000mm long and weighs 3492kg. Both upper spans were designed to be 1800mm in width. RBs, a kind of passive control device, while supporting the upper spans, function as a device for control of structural motion under seismic load. The lower structure was designed with mini short beams of I type to minimize the structural influence that the piers exert for their stiffness. Also, abutments were installed to protect the upper spans from falling down. The whole structure was placed on the two shaking tables owned The Seismic Simulation Test Center of Korea as seen in figure 2 to perform shaking table tests.

![Figure 2. Experimental Setup for Shaking Table Test](image)

3. Shaking Table Test
Finally, an experiment was carried out to verify a validity of the HSRC system for control of structural motion. For the experiment, a two span bridge was placed on two shaking tables (60 ton each, available for the 3 degree of freedom experiment under the 30 ton payload condition) which was in
turn put into operation under the El-centro seismic load. The experiment was performed under the following conditions:

Experimental Cases (figure 3)

Case 1. Basic structure condition (Refer to figure 3 (a))
Case 2. MR-damper-applied condition (Refer to figure 3 (b))
Case 3. E-RB-applied condition: RB of span A is replaced with E-RB under the basic structure condition
Case 4. HSRC –applied condition (Refer to figure 3 (c))
Case 5. HSRC & Clip-applied condition: The clipped-optimal control algorithm is applied to the HSRC system.

As an equipment to measure structural responses at various conditions and perform control on the basis of analyzed data, a DS1103 PPC Controller of dSPACE was employed. A PMC 18-3A DC Power Supply of KIKUSUI was also selected as an equipment to flow in electricity to the MR-damper following output voltage from the controller.

4. Test Result
4.1. Motion Control Experiment Result: Case 1, 2

In the Case 1, collision of upper spans is likely to occur under seismic load. To prevent such a collision from occurring, an MR-damper was attached to the basic structure (Case 2), and then an experiment about motion control was carried out to investigate its role and problem. In it, 130% of Elcentro seismic load was excited. The experiment result was compared to displacement between span A and B, relative displacement between the two spans, and acceleration response data of both spans so as to verify the effect of mitigating earthquake responses under each condition.

Figure 4. Comparison of case 1 and case 2
As seen in figure 4, relative displacement was the most conspicuous at Case 1. Accordingly, it is clear that collision between two upper spans is most likely to occur under the basic structure condition as shown on figure 4 (a). As manifested from the acceleration response in figure 4 (a), it is found that the upper spans often clash with adjacent abutment. However, when two spans clash with abutment, their motion energy diminishes, and so two spans themselves did not clash each other.

In the Case 2 as in figure 4, relative displacement between two spans was lower than in Case 1 as predicted in figure 4 (b), but increasing displacement of upper spans also increased impact force between the upper spans and the abutment (a rise of acceleration). In particular, when 3A was supplied to the MR-damper, frequency of collision increased due to increase of its control force. As a result, it was found that the MR-damper was able to mitigate relative displacement by connecting two spans. On the other hand, its strong control force made two spans behave as a single structure, thus imposing excessive shear force on the RB.

### 4.2. Motion Control Experiment Result: Case 3 and 4

Shaking table tests for Case 3 and 4 were taken to verify the HSRC system, using 150% of El-centro 150% seismic load. Acceleration, displacement, and relative displacement of spans A and B, obtained from this experiment, are illustrated in Fig. 10 to show the HSRC system was much more effective in motion control than the MR-damper only applied condition.
As seen in figure 5 the experiment result of Case 3 showed collision between span A and abutment was prevented though it was found in figure 4 (a). However, collision continued to occur between span B only with a RB of 10KN and abutment. Since the HSRC system was applied later, no collision has been observed as seen in figure 5 (a).

Also, the HSRC system reduced relative displacement between upper spans, and also displacement of span B significantly. As for span A, however, its displacement increased even though RB was replaced by E-RB. Such a phenomenon is caused by span B whose motion was not completely dispersed by the MR-damper.

The experiment result of case 4, viewed more closely, says displacement of span A increased by around 3mm at maximum with 0A supplied to the MR-damper, and by around 4mm also at maximum, this time, with 3A to the MR-damper. However, in spite of the increased displacement of span A, displacement of span B is reduced by about 30mm at maximum with 0A supplied to the MR-damper and about 35mm with 3A added to the MR-damper. In addition, relative displacement is also reduced by about 33mm with 0A supplied to the MR-damper and about 38mm with 3A added to the MR-damper, indicating the increased displacement of span A is almost negligible. Therefore, the experiment proved that hybridization of RB (passive device) and MR-damper (semi-active) could perform the best control of structural motion. In addition, comparing each result supplied either with 0A or with 3A, it is shown that displacement response of span A rather increased at the latter. Such an unexpected phenomenon occurred because the MR-damper exerted more control force than needed for structural response, due to excessive supply of electricity. Consequently, it is necessary to adopt a control algorithm by which control force can be sent to the MR-damper after being adjusted to the bridge structure.

4.3. Motion Control Experiment Result: Case 5
Another experiment for the fifth case was performed with a control algorithm applied to the MR-damper of the HSRC system. In figure 6, displacement and relative displacement of the upper spans in Case 3 and 4 are compared to those of Case 5.

As seen in figure 6, the HSRC System where the Clipped-optimal control algorithm is applied was proven more effective for mitigation of displacement and relative displacement of the span B than in Case 3. It also turned out to be effective even when compared to Case 4, especially with 0A supplied to the MR-damper, though a degree of effectiveness may be different. Meanwhile, when compared to the case of 3A supplied to the MR-damper in Case 4, displacement and relative displacement of both spans (A and B) were better mitigated. Table 1 is a quantitative comparison of the values expressed in the graph of figure 6 in terms of max value, min value, and RMS value of all data.

Table 1. Comparison of Displacement Response and Relative Displacement Response (Case 3–5)

| Case     | Span A (mm) |  |  |  |  |  |  |  |  |
|----------|-------------|---|---|---|---|---|---|---|---|
|          | Max  | Min (+) | RMS | Max  | Min (+) | RMS | Max  | Min (+) | RMS |
| Case 3   | 4.42 | 3.97    | 0.75 | 7.52 | 5.72 | 1.12 | 6.50 | 7.70 | 1.48 |
| Case 4. 0A |    |         |    |      |      |     |      |      |     |
| Case 4. 3A |    |         |    |      |      |     |      |      |     |
| Case 5   |    |         |    |      |      |     |      |      |     |

| Case     | Span B (mm) |  |  |  |  |  |  |  |  |
|----------|-------------|---|---|---|---|---|---|---|---|
|          | Max  | Min (+) | RMS | Max  | Min (+) | RMS | Max  | Min (+) | RMS |
| Case 3   | 33.07 | 49.35   | 7.66 | 17.81 | 19.71 | 3.10 | 17.45 | 14.58 | 3.03 |
| Case 4. 0A |    |         |    |      |      |     |      |      |     |
| Case 4. 3A |    |         |    |      |      |     |      |      |     |
| Case 5   |    |         |    |      |      |     |      |      |     |

| Case     | Relative Disp. (mm) |  |  |  |  |  |  |  |  |
|----------|---------------------|---|---|---|---|---|---|---|---|
|          | Max  | Min (+) | RMS | Max  | Min (+) | RMS | Max  | Min (+) | RMS |
| Case 3   | 47.31 | 36.14   | 7.61 | 14.03 | 13.30 | 2.27 | 8.91 | 11.07 | 1.71 |
| Case 4. 0A |    |         |    |      |      |     |      |      |     |
| Case 4. 3A |    |         |    |      |      |     |      |      |     |
| Case 5   |    |         |    |      |      |     |      |      |     |
As seen in Table 1, in Case 5, i.e. displacement of both spans was reduced more than in Case 4 with 3A current supplied to the MR-damper, and relative displacement was reduced more than 30% compared to Case 4 with no current supplied to the MR-damper. In particular, Case 5 is proven to be more effective for reducing displacement and relative displacement of span B than Case 3. In order to verify the effect of control algorithm applied to the system, figure 7 displays acceleration and additional current of both spans, and control force of the MR-damper.

![Figure 7. Comparison of results (HSRC system): Acceleration, Control Force and Current](image)

As seen figure 7, the HSRC system where a control algorithm is applied decelerated the upper spans while reducing current consumption more than in Case 4 with 3A supplied to the MR-damper. In addition, as manifested in the force-displacement graph, the HSRC System was proven to exert an excellent motion control performance, displaying almost the same amount of control force as in Case 4 with 3A supplied. The result in figure 7 can be confirmed from the quantitative result shown on Table 2. Therefore, the HSRC System, where a control algorithm is applied, displayed almost the same amount of control force as in Case with 3A supplied while saving about 50% of electricity.

### Table 2. Comparison of Control Force & Additional Current of HSRC System for Each Condition

| Case     | Force (kN) | Current (A) |
|----------|------------|-------------|
| Case 4. 0A | 8.08 2.11 | 0           |
| Case 4. 3A | 11.53 2.92 | 90003       |
| Case 5.   | 8.43 2.89 | 46218       |

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5. Conclusion
In this paper, the Hybrid Seismic Response Control (HSRC) system was developed to mitigate response of a simple two span bridge under seismic load, and its effectiveness was experimentally verified. For experiments, a two span simple bridge (bridge model) was manufactured, and the HSRC System was applied to this bridge.

As the first step of this experiment, a pretest was done to analyze in advance the problems such as span collision and unseating occurring when rubber bearing only or MR-damper only was used, as discovered in literature review. Then, three kinds of experiment were performed to test the HSRC system to prove its effect for mitigation of response under seismic load. The 1st experiment was done at the E-RB state (with E-RB on span A under the basic structure condition), the 2nd one at the HSRC structure state, and the final one at the state with the clipped-optimal control algorithm applied to the HSRC system. Therefore, the following results were obtained.

- When an MR-damper was used to connect two upper spans of bridge, it contributed to a mitigation of relative displacement of spans to a degree, but it incurred a clash between upper spans and abutment by increasing displacement of spans. That is, in spite of its effectiveness in mitigating relative displacement, the MR-damper, by deforming RB, ended up fixing the upper spans into a single structure and thereby causing clash.

- When the RB of span A was replaced with the E-RB having a stronger stiffness, collision between span A and abutment was remarkably mitigated. Later, an MR-damper was additionally placed on the E-RB equipped structure, and then acceleration response of two spans was reduced even at the passive state (Passive on), and both the displacement of span B and the relative displacement between spans were clearly mitigated. In short, the HSRC system was proven effective for motion control of adjacent structures.

- When a control algorithm was applied to the HSRC System to add semi-active control, the effect for reducing displacement and relative displacement of span B was much stronger than under the passive state of the HSRC system. In summary, the control based on the semi-active performance (with a control algorithm applied) was proven effective while saving energy.

Therefore, the HSRC System was proven to be very effective for motion control under seismic load, solving the previously addressed problems which resulted from connecting adjacent upper spans by means of control devices.

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