Evaluation of Seismic Response Characteristics of Bridges with Rocking Isolation Bearing System (RIBS)

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Abstract. When the earthquake intensity exceeds the design expectation, the conventional rubber-type isolation bearings could generate a higher reaction force transmitted to the substructure with the increase of the bearing displacement, implying difficulties in controlling the maximum response displacement of the substructure. According to past earthquake damage investigation reports, when the rocking motion of the conventional pin bearings, followed by the pulling-out of their anchor bolts, was observed, the damages to the substructure and to the flange of the girder were significantly mitigated. Motivated by this so-called seismic isolation effect, a new rocking isolation bearing system (RIBS) was proposed, in which the maximum horizontal reaction force is adjusted by the height and width of the bearing and the energy is absorbed by the collision at the bottom of the bearing during its rocking vibration.

In this study, the dynamic characteristics and the maximum response control effectiveness of an example bridge featuring such RIBS were analytically investigated. Eighteen ground motions corresponding to the maximum considered earthquake (MCE) in design specifications in Japan and a set of harmonic ground motions with various amplitudes and periods were used as inputs. As for the maximum displacement of the piers, nearly 30~40% reduction under MCE and no obvious resonance peak under the harmonic inputs were observed. The isolation effect of RIBS becomes more significant as the ground condition becomes stiffer. At the moment of the peak pier displacement, a phase difference of nearly 90 degrees between the bearing and pier vibrations was found, implying desirable seismic response control effectiveness.

Keywords: rocking isolation bearing system (RIBS), bridges, seismic response, forced vibration, phase difference

1 Introduction

The application of isolation bearings in bridges has been recognized as an effective seismic response modification technique over the past decades. The seismic isolation effect of these bearings, as a result of the elongated period, allows to significantly reduce the force demand to substructure, while impose an increased displacement demand to bearings. The trade-off relationship between the increased displacement and reduced force can be mitigated by adding energy dissipation devices such as dampers.

Nevertheless, when the earthquake intensity exceeds the design anticipation, conventional rubber isolation bearings could generate increased reaction force transmitted to the substructure as the bearing displacement increases, arising problems in controlling the maximum response displacement of the substructure.

According to past earthquake damage investigation reports, it was found that when the rocking motion of the conventional pin bearings, followed by the pulling-out of their anchor bolts, was observed, the damages to the substructure and to the flange of the girder were significantly mitigated. This can be attributed to the reduction of the inertia forces transmitted from the superstructure to the bearings when the rocking motion occurs. Motivated by the distinctive seismic isolation effect of rocking structures recognized in previous studies [1-3], a new rocking isolation bearing system (RIBS) was proposed in our previous study [4]. The maximum horizontal reaction force of RIBS is adjusted by the height and width of the bearing, and the energy is absorbed by collision at the bottom of the bearing during its rocking vibration. The simulation results showed that by appropriately selecting the two designs parameters of the RIBS (height and width) the seismic performance of the bridge could be significantly improved, namely a reduced pier displacement at an allowable displacement level of the girder.

In this study, the dynamic characteristics and the maximum response control effectiveness of an example bridge featuring such a RIBS were analytically investigated. Eighteen design ground motions corresponding to the maximum considered earthquake (MCE) specified in the design specifications in Japan and a set of harmonic ground motions with various amplitudes and periods were used as inputs. Specifically, the control effectiveness of RIBS on the maximum pier displacement, and the phase difference between the bearing and pier vibration, were focused on.

2 An Example Bridge with RIBS

2.1 Modeling

The newly proposed rocking isolation bearing system, referred to as RIBS, functions as a pin bearing under routine services, while the rocking motion of RIBS under earthquakes is triggered to provide isolation effect to bridges, i.e., elongation of the natural period, see Fig. 1. A model consisting of such RIBS, the rigid body girder supported by the RIBS, and the pier with constant mechanical properties is presented. The structural parameters include the girder mass m_s, the pier mass m_p, the pier natural period T_p at the fixed bearing condition, and the pier damping ratio c_p.

In the context of seismic performance evaluation, the dynamic behavior of the bridge can be represented by two independent generalized variables, namely the angle of the rotation of the rocking bearings θ and the horizontal displacement of the piers u_p. As for the energy dissipated by the collision during the sign-reversal of θ, see Fig. 2, a coefficient of restitution (COR) model that simultaneously conserves the angular momentum and the horizontal momentum of the system was used [1]. The numerical analysis was performed by solving nonlinear differential equations for θ and u_p in MATLAB R2021a.

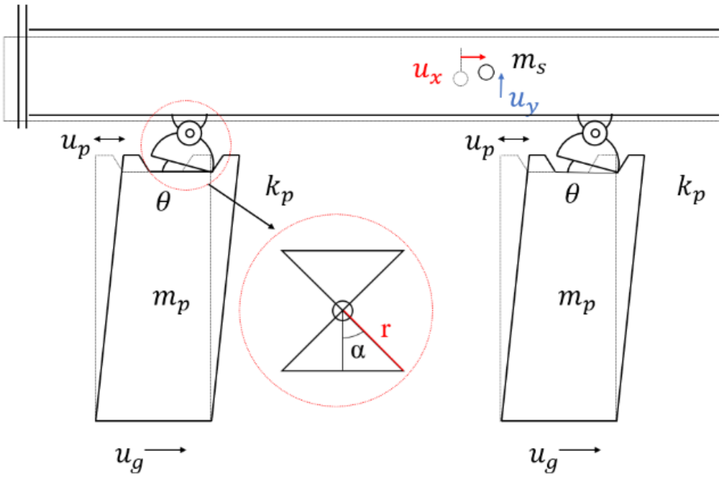

Fig. 1. Analysis Model of an Example Bridge

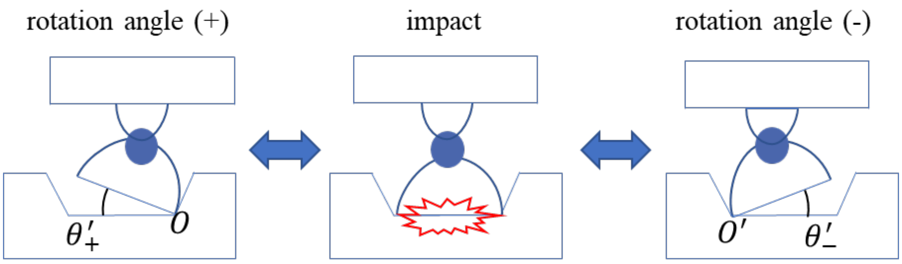

Fig. 2. Energy Absorption due to Collision

2.2 Parameter Setting and Seismic Inputs

The structural parameters of the example bridge were designed as α=35°, r=0.9m, β=5, T_p=0.5sec, and c_p corresponds to a 3% of critical damping ratio, in which β denotes the mass ratio of the girder to the piers. The parameters of RIBS were selected to provide a median level of displacement reduction effectiveness for both the bearing and pier responses, according to our previous parametric study under MCE specified in Japan Road Association (JRA) [5]. All 18 accelerograms (I-I-1, I-I-2,...,II-III-3) corresponding to the MCE for bridge design in Japan, were used as seismic inputs. Specifically, JRA classifies earthquake types into two types. Earthquake Type I corresponds to plate boundary earthquakes with long source-to-site distances. Earthquake Type II corresponds to inland earthquakes. Three types of soil conditions are considered for each earthquake type, i.e., GC1 (stiff), GC2 (medium), and GC3 (soft). Also, 3 accelerograms are provided for each combination of earthquake type and ground condition. An additional set of sinusoidal inputs with varying periods and amplitudes were considered to explore the control effectiveness of RIBS against the two critical factors of the inputs.

3 Seismic Response Characteristics

3.1 Maximum Response for MCE Design Ground Motions

The maximum pier displacements of the bridge model with RIBS are shown in Fig. 3, in comparison with those of the same bridge parameters under fixed bearing conditions. Only in the No. 15 (Type 2, Type II ground) case, the maximum bearing rotation of RIBS exceeds its designed limit α, suggesting a possible overturning consideration.

The maximum response reduction ratio of the RIBS cases from the fixed bearing cases, in terms of its mean value under each earthquake or ground type, is shown in Table. 1. The response reduction ration becomes smaller (i.e., less effective) when the ground type becomes softer (from GC1 to GC3), whereas this value shows little difference between the two earthquake types.

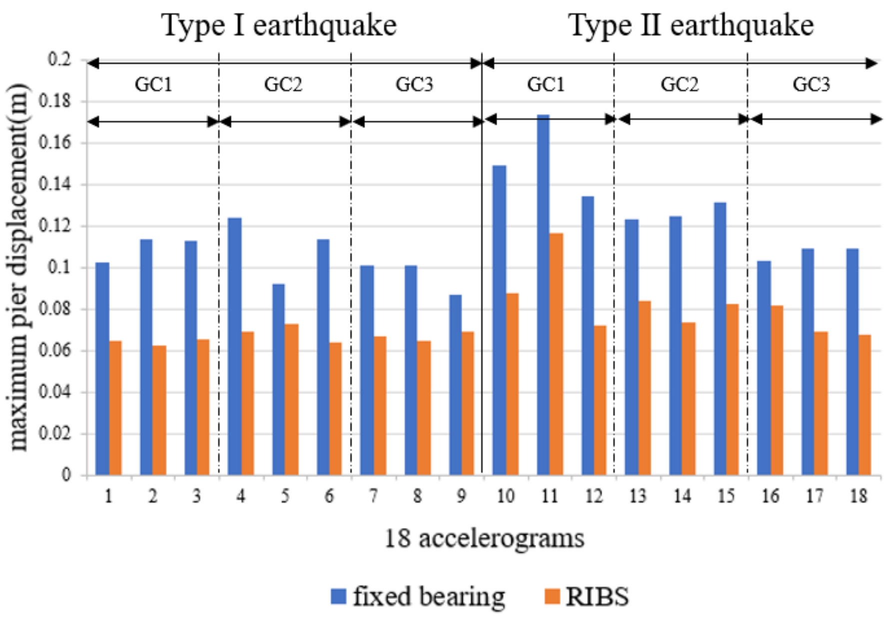

Fig. 3. Maximum Pier Displacement under MCE Design Ground Motion specified in JRA

Table 1. Maximum Pier Displacement Reduction Ratio (%)

ground condition / earthquake type	GC1	GC2	GC3	average
Type Ⅰ	41.2	36.2	30.1	35.8
Type Ⅱ	40.2	36.9	31.9	36.3

3.2 Maximum Response Characteristics depending on the Amplitude and Period of Inputs

In order to evaluate the seismic performance of the bridge and the control effectiveness of RIBS in reducing the pier response, several indices are selected - the maximum bearing rotation angle θ, the ratio of the maximum pier displacement under the fixed bearing condition (referred to as uncontrolled counterpart) to that with RIBS, and the phase difference between the bearing and pier vibration. In particular, the instant phase of the vibration quantity is calculated by the Hilbert transformation as follows:

$$\phi(t) = \arctan\left(\frac{b(t)}{a(t)}\right) \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \quad (1)$$

where a(t) and b(t) are the real and imaginary parts of the so-called analytical signal, i.e., $H\big(x(t)\big) = a(t) + ib(t)$, in which $H(\cdot)$ represents the Hilbert transformation, i is the imaginary unit, and $x(t)$ denote the interested quantity $\theta(t)$ or $u_p(t)$.

At the moment of max$|\theta(t)|$ or max$|u_p(t)|$ in each input case, the phase difference (ϕ) between $\theta(t)$ and $u_p(t)$ is evaluated. This quantity, in terms of its absolute value of nearly 90°, has clearly physical implications in evaluating the maximum response control effectiveness of RIBS, as shown in Fig. 4. A phase difference of nearly 90° at the moment that max$|\theta(t)|$ or max$|u_p(t)|$ is reached indicates that the vibration of the pier displacement $u_p(t)$ or the bearing rotation $\theta(t)$ is approaching its central position rather than simultaneously reaching its maximum. Hence, the resonance of the bridge's seismic response could be effectively mitigated.

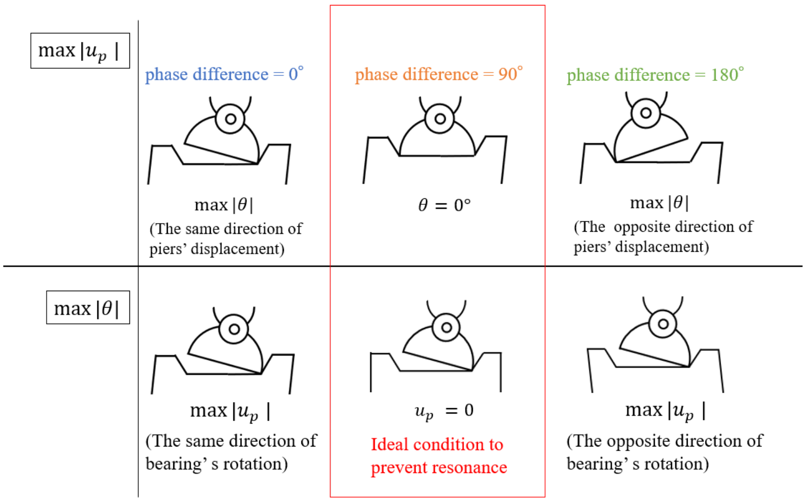

Fig. 4. Implication of Phase Difference and Maximum Response

The abovementioned four performance indices against the period of the harmonic inputs (0.1~2sec) under varying amplitudes of the acceleration (500 gal ~ 1200 gal) were presented in Fig. 5. It can be seen that the bearing rotation in RIBS increases as either the amplitude or the period of the input increases. However, with the growth in period, the bearing could be overturned or back to the fixed bearing condition. The latter is because the inertia force acting on the bearing, associated with the resultant acceleration of the pier and the ground motion, becomes lower than the initiation value of the rocking motion of RIBS. In addition, obvious resonant peaks were not observed in the plot.

As for the maximum pier displacement, the uncontrolled counterpart leads to a substantially higher response (with several folds) than that with RIBS, in particular, at the given natural period of the pier. This is because the RIBS acts as a mechanical fuse so that the maximum pier response only gets slightly increased as the amplitude of inputs increases, as pointed out by our previous study; whereas, in the uncontrolled counterpart cases, the pier response is proportional to the amplitude of inputs and becomes largest at the resonant period.

The phase difference at the moment of $\max|\theta(t)|$ shows large period-to-period variation, whereas the phase difference at the moment of $\max|u_p(t)|$ is always in the vicinity of 90° with the mean value of 80°. This reveals the peculiar control effect of RIBS on suppressing the resonance of the pier response. The RIBS bearing is unlikely to reach resonance when the pier displacement becomes the maximum.

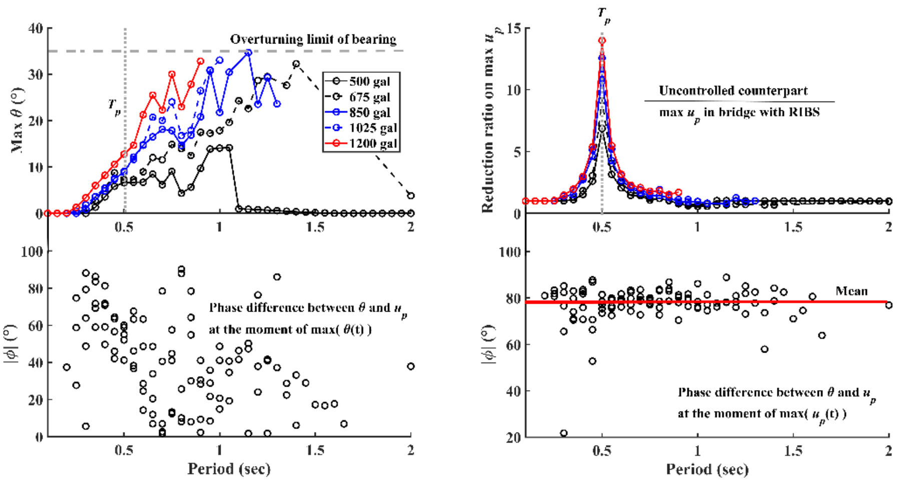

Fig. 5. Maximum Bearing and Pier Responses and Phase Difference against the Period of Inputs (Upper Left: Bearing Rotation Angle, Upper Right: Displacement of Pier, Bottom Left: Phase Difference at $\max|\theta(t)|$, Bottom Right: Phase Difference at $\max|u_p(t)|$)

4 Conclusion

In this study, simulation results demonstrates that the application of the newly proposed RIBS (α=35° and r=0.9m) to an example bridge (T_p = 0.5 sec) can significantly reduce the maximum displacement of piers by about 40% compared with fixed bearings under the maximum considered earthquake for the design of bridges in Japan. The seismic isolation effect, in terms of the pier displacement reduction ratio, was found to be more effective in stiffer ground type earthquakes. On the other hand, under a series of harmonic acceleration input with varying amplitudes and periods, some findings are listed as follows: (1) Even though the intensity of ground motions increases, the increase of pier response is effectively mitigated due to the fuse mechanism of RIBS, which limits the maximum reaction force. (2) By utilizing the rocking mechanism of the bearing, the seismic responses of the bridge show insensitive against various dominant periods of excitations; obvious resonance peak was not observed. (3) At the moment that the pier displacement reaches the maximum, the phase differences between the bearing rotation angle and the pier displacement are always in the vicinity of 90 degrees, implying desirable seismic response control effectiveness.

References

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