CHARACTERIZATION OF BIAXIAL INTERACTION OF SEISMIC ISOLATION FOR BRIDGE STRUCTURES

Hokkaido University　JSPS Fellow, Dr.-Eng.　Shehata E. ABDEL RAHEEM
Hokkaido University　Professor, Dr.-Eng.　Toshiro HAYASHIKAWA

1. Introduction

Special bridges are those curved, skew and long-span bridges that require special considerations in their analysis; design and construction[1), 2)]. Typically, complicated nonlinear time-history analyses are involved in their design, which by itself is a challenge to bridge structural engineers, due to a lack of knowledge about how to design earthquake response modification systems for these special bridges, hence it is difficult to develop standardized design procedures and specification provisions. To address this need, this study seeks to characterize a cost-effective control system for the seismic protection of targeted bridges from destructive earthquake ground motions and provide an additional mechanism to meet multiple performance objectives, particularly in the presence of severe earthquakes. The difficulties that will be confronted in seismic analysis of the isolated bridge will contain how to determine the precise moving trajectories and how to obtain the correct stress conditions of the isolator concerned, so there is an urgent need to investigate bi-directional interaction of bearings in order to understand the behaviour and evaluate the efficacy of the structural control concept. This study objective is to characterize the effects of biaxial interaction on the response of the isolated bridge structures subjected to bi-directional excitations by comparing the system response with and without interaction, and to investigate the influence of bridge dynamic characteristics in both directions on the seismic isolation effectiveness for earthquake design.

The effect of bi-directional seismic excitation is essential for analysis and design of seismically isolated structures[3)~5)], since the bi-directional motion is coupled and that two independent unidirectional models could not accurately describe the bi-directional behavior. The displacement in one direction affects the shear force in both directions; the loading in one direction appears to affect the bearing in the orthogonal direction. Simultaneous seismic excitation along each horizontal axis of a bridge can substantially increase the maximum isolator displacement and modify the unidirectional properties of the isolators. In this study, a bi-directional base isolation strategy is proposed to effectively protect bridge structures against extreme earthquakes; the seismic response of lumped-mass structure model to bi-directional harmonic and real earthquake ground motion is investigated. Adequate modeling of the control devices is essential for the accurate prediction of the behavior of the controlled system, in this study; the biaxial hysteretic behavior of bearings is modeled using the biaxial interaction equations of Bouc-Wen model, the model for biaxial interaction accounts for the direction and magnitude of the resultant hysteretic force.

The response of the system with bi-directional interaction is compared with those without interaction in order to investigate the effects of bi-directional interaction of restoring forces. The analysis varies important parameters including the isolator properties, the characteristics of the harmonic motion such as the excitation frequency, amplitude ratio and phase difference and the substructure dynamic characteristics. Numerical results show that the isolated bridge structure is significantly influenced by the interaction of bearing forces. So the displacement may be underestimated, which can be crucial from the design point of view and the acceleration of the superstructure may be overrated if the bidirectional interaction is neglected. In comparison, loading in one direction while on the bi-directional circular yield surface requires unloading in the other direction. The unidirectional model overestimates the maximum force in the bearing and the hysteretic energy dissipation, particularly in the transverse direction because of the square yield surface; so designs based on uncoupled inelastic springs may not accurately represent the forces transferred to the substructure and hysteretic energy dissipation.

2. Analytical Model Formulation and Equations of Motion

There are many cases of damage of bridges in the past earthquakes all over the world. Due to their structural simplicity, bridges are particularly vulnerable to damage and even collapse when subjected to earthquakes[6)]. The fundamental period of vibration of a majority of bridges is in the range of 0.2 to 1.2 second[7)]. In this range, the structural response is high because it is close to the predominant periods of earthquake-induced ground motions. A simple design procedure for highway bridges aims at optimum balance between the shear forces transmitted to the supports and tolerable deck displacements for isolated highway bridges using the inelastic response spectra approach. How the force-reduction and force-redistribution advantages of seismic isolation could benefit the design and economics of bridges. As the structure also exerts forces on the isolation system, the interaction between the isolation system and structure is essential in the analysis or the design. This interaction cannot be captured by analyzing the components alone.

2.1 Governing equation of motion

The bridge structures shown in **Fig. 1** are modeled as a two lumped mass model with two translational-DOFs system. The general form of the equation of motion for this system with or without a control device is

$$\mathbf{M}\ddot{\mathbf{U}}+\mathbf{C}\dot{\mathbf{U}}+\mathbf{K}\mathbf{U}+\Lambda F_c=-\mathbf{M}\Gamma\ddot{\mathbf{U}}_g \qquad (1)$$

where **M** is the mass matrix; **C** is the damping matrix; **K** is the stiffness matrix; Λ is the location vector for control force, $\mathbf{F}_c$; U is the displacement vector and Γ is the influence vector. The damping mechanism is adapted to the viscous Rayleigh's damping with damping coefficient equal to 5%. In which

$$\mathbf{M}=\begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 \\ 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & m_2 \end{bmatrix},\quad \mathbf{K}=\begin{bmatrix} k_{x1}+k_{x2} & 0 & -k_{x2} & 0 \\ 0 & k_{y1}+k_{y2} & 0 & -k_{y2} \\ -k_{x2} & 0 & k_{x2} & 0 \\ 0 & -k_{y2} & 0 & k_{y2} \end{bmatrix},\quad \mathbf{U}=\begin{bmatrix} x_1 \\ y_1 \\ x_2 \\ y_2 \end{bmatrix}$$

$$\Lambda=\begin{bmatrix} -\mathbf{I}_{2\times2} \\ \mathbf{I}_{2\times2} \end{bmatrix},\quad \Gamma=\begin{bmatrix} \mathbf{I}_{2\times2} \\ \mathbf{I}_{2\times2} \end{bmatrix},\ \mathbf{F}_c=\begin{bmatrix} F_x \\ F_y \end{bmatrix},\ \ddot{\mathbf{U}}_g=\begin{bmatrix} \ddot{x}_g \\ \ddot{y}_g \end{bmatrix},\qquad \mathbf{C}=a\,\mathbf{M}+b\,\mathbf{K} \qquad (2)$$

In the above, m_1 and m_2 are the lumped masses of the pier and deck, respectively; k_{x1} , k_{y1} and k_{x2} , k_{y2} are the stiffness of the pier and bearing in *x*- and *y*- directions, respectively; and x_1 , y_1 and x_2 , y_2 are the pier and deck displacements relative to the ground, respectively.

2.2 Structural system model

In general, base isolated bridges are designed such that the substructure remains elastic and nonlinearities are localized at the isolation level. A mathematical model of a simple isolated bridge structure is utilized[8)], in which, a bridge pier-bearing-deck structure is modeled as two lamped masses model with two horizontal translational degrees of freedom (DOF) system. Based on this model, passive control system using lead rubber bearing is designed for optimal performances. Coupled lateral response with bi-directional interaction effects is accounted for by maintaining two translational DOFs; the isolator is modeled using a coupled-plasticity Bouc-Wen representation. This bridge model is used for a clear understanding of the bidirectional excitation effect on isolation system.

For simulation purposes, mass ratio and damping ratio are set to m_2/m_1 = 5 and 5%, respectively, which are typical values for elevated highway bridges. Considering the bearing stiffness requirement of Japanese code in service condition, which states that an isolated bridge should have approximately twice the natural period of that non-isolated system (Japan Road Association, 1996), the pier stiffness

(a)

(b)

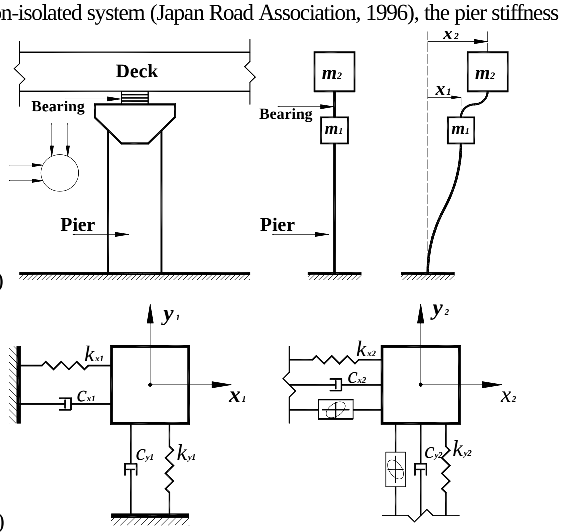

Fig. 1 Bridge model: (a) Two-lamped mass model of bridge pier bearing deck system; (b) Isolation device mathematical model.

k_{x1}, k_{y1} are calculated representing the pier as an SDOF system with mass m_1, the damping ratio and natural frequency of the corresponding system are designated as ζ_1 and w_1. Similarly, the natural period and the damping ratio of the bearing are calculated considering an SDOF system with parameters k_{x2}, k_{y2} and m_2 and the corresponding damping ratio ζ_2 and natural frequency w_2 are found. The damping constant c_{x1}, c_{y1}, c_{x2}, c_{y2} are calculated based on Rayleigh's damping scheme. The LRB is isotropic, implying the same dynamic properties in two orthogonal directions. In the numerical simulations, the mass of the pier is taken as 100 tons and other parameters are calculated accordingly.

2.3 Biaxial Bouc-Wen model of isolation bearings

In a well designed control system, the input energy due to an earthquake is largely dissipated in the lead rubber bearing (LRB) isolation system. Analytical model based on smoothed plasticity, Bouc-Wen is used to characterize the hysteretic behavior of LRB isolation device. The LRB restoring forces F_x and F_y in two directions can be modeled by biaxial interaction model as follow:

$$u_x = x_2 - x_1,\ u_y = y_2 - y_1,\ \mathbf{u}=[u_x\ u_y]^T,\ \mathbf{z}=[z_x\ z_y]^T$$

$$\mathbf{F}_c = c_0\dot{\mathbf{u}} + k_0\mathbf{u} + (1-\alpha)F^{yield}\mathbf{z} \qquad (3)$$

where, z_x and z_y are an evolutionary shape variable, internal state, bounded by the values ± 1; and account for the directional/ biaxial interaction of hysteretic forces. The horizontal nonlinear restoring force is expressed as the sum of three forces acting in parallel given in equation (3), in which, k_0 and c_0 are the horizontal stiffness and viscous damping coefficient of the rubber composite of the bearing. $\alpha = k_0/k_e$ is the post-yield and pre-yield stiffness ratio; F^{yeild} is the yield force from both the lead plug and the rubber stiffness. The properties of the LRB are k_e initial elastic shear stiffness and k_0 post-yield shear stiffness, α = 0.02. The model for biaxial interaction of the resultant hysteretic forces is given as first order differential equation[9)] in general form as follow:

$$\dot{\mathbf{z}}Y = A\dot{\mathbf{u}} - [\gamma + \beta\,\mathrm{sgn}(\mathbf{z}^T\dot{\mathbf{u}})]\,\|\mathbf{z}\|^{\eta-2}\,(\mathbf{z}\mathbf{z}^T)\dot{\mathbf{u}} \qquad (4)$$

In which, A,η , γ and β are dimensionless quantities that control the shape of the Bouc-Wen model hysteresis loop, the values of $A=1$, $\eta=2$, $\gamma = \beta = 0.5$ are used in this study. Y is the yield displacement. The tangent stiffness matrix is

$$\mathbf{K}_t = \begin{bmatrix} \dfrac{\partial \mathbf{F}_c}{\partial \mathbf{u}} & -\dfrac{\partial \mathbf{F}_c}{\partial \mathbf{u}} \\ -\dfrac{\partial \mathbf{F}_c}{\partial \mathbf{u}} & \dfrac{\partial \mathbf{F}_c}{\partial \mathbf{u}} \end{bmatrix} \qquad (5)$$

3. Numerical Simulations and Discussion

The analysis of isolated bridge structure with LRB isolation system is considered. A view of the lumped mass model of the isolated bridge is provided in **Fig. 1.** The dynamic response is computed for harmonic and real earthquake excitations. Isolation bearings and supplemental damping devices can be effective techniques for controlling the forces and deformations transferred from a bridge superstructure to the substructure. Hysteretic energy dissipation in the isolation bearings, with careful design, can limit bearing deformations and overall displacements to acceptable levels. The effects of the bidirectional interaction of the bearing forces are investigated under the variation of important system parameters that include the pier flexibility, input excitation dynamic characteristics and the LRB isolation parameters.

3.1 Response to harmonic base acceleration excitation

Response of bridge system to different harmonic frequencies gives considerable insight into the system dynamic characteristics, which may be useful in interpreting the response to other types of excitation. The harmonic ground accelerations considered in two orthogonal directions are expressed as

$$\ddot{x}_g = A_x \sin(\overline{\omega}_x t)\,, \qquad \ddot{y}_g = A_y \sin(\overline{\omega}_y t + \phi) \tag{6}$$

The interaction between the restoring forces in two orthogonal horizontal directions is duly considered in the response analysis. **Fig. 2** shows the LRB dynamic characteristics subjected to bi-directional excitation with different frequency content ($\overline{\omega}_y / \overline{\omega}_x =$ 0.5), 1 Hz sinusoidal excitation in *x*-direction. Due to the coupled behavior of the isolator response, the contribution of plastic force in the *x*-direction varies due to motion demands in the perpendicular *y*-direction. The unidirectional model also overestimates the hysteretic energy dissipation, particularly in the transverse direction. The coupled model shows considerable interaction effects in hysteresis loops. The unidirectional model overestimates the maximum force in the bearing. The force trajectory for the uncoupled model, approaches bi-directional square yield surface, is different in the details compared to the biaxial interaction model, approaches bi-directional circular yield surface. For harmonic excitation, the peak response is calculated for wide range of input excitation dynamic characteristics including amplitude, frequency ratios and phase difference of *x*- and *y*-directions. **Fig. 3** shows the effect of amplitude ratio (A_y/A_x) on the LRB restoring force, the direction with minor amplitude of excitation is significantly affected, the independent unidirectional model over predict the maximum force in the bearing by more 20% for both directions, this value grows up quickly with amplitude ratio, while resultant force over estimated by more than 10% and reaches 20 %. **Fig. 4** shows input excitation phase difference effect on LRB restoring force, the interaction effect get maximum value of 35% reduction of restoring force in y-direction for phase lag of half input excitation frequency, while approaches minimum value of 15% when the phase lag is 1.5 input excitation frequency. The interaction effect has reduction value of 20% for identical frequency content of bi-directional excitation due to amplification of system response simultaneously; this effect decrease rapidly with frequency ratio, with the variation of the transverse excitation frequency, the biaxial interaction effect is amplified near the system dominant frequencies, as shown in **Fig 5.** The shape factor of the pier section could significantly affect the efficiency of the isolation system in both directions, where the interaction effect reaches about 30% for stiffness ratio (k_{y1}/k_{x1}) of 1.5, moreover, the effect decrease with increase of the pier rigidity, as shown in **Fig. 6**. As the substructure becomes more flexible, the bearing deformation decreases and the maximum displacement increases because of reduced hysteretic energy dissipation in the bearing. This study demonstrates that the designer must consider the input excitation spectral characteristics and the trade-off between bearing and substructure deformation. Designs based on uncoupled inelastic springs may not accurately represent the forces transferred to the substructure and hysteretic energy dissipation.

3.2 Response to real earthquake base excitation

In this section, the seismic response of the isolated bridge model

(a)

(b)

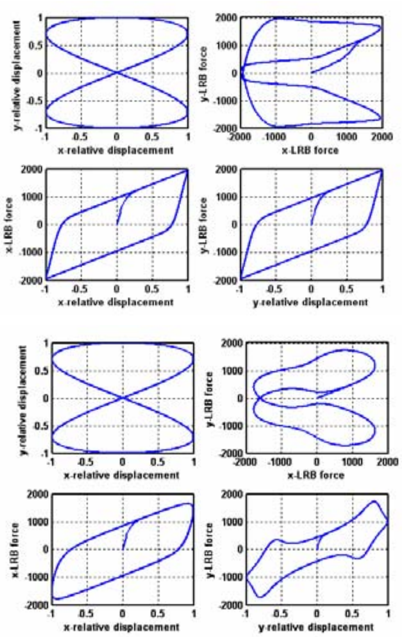

Fig. 2 LRB characteristic under 1 Hz sinusoidal *x*-direction excitation ($\overline{\omega}_y / \overline{\omega}_x$ = 0.5): (a) without, (b) with biaxial interaction

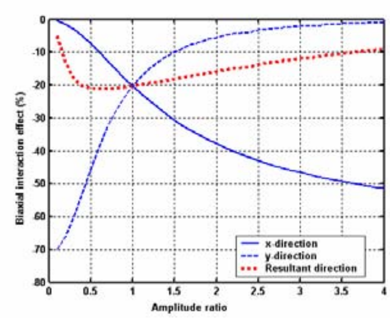

Fig. 3 Input excitation amplitude effect on LRB restoring force

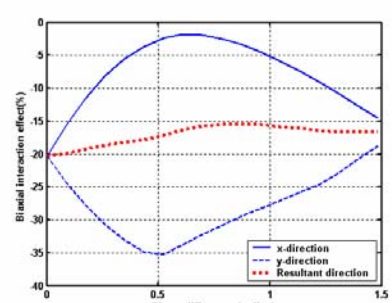

Fig. 4 Input excitation phase lag effect on LRB restoring force

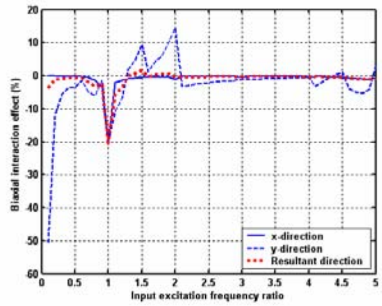

Fig. 5 Input excitation frequency effect on LRB restoring force

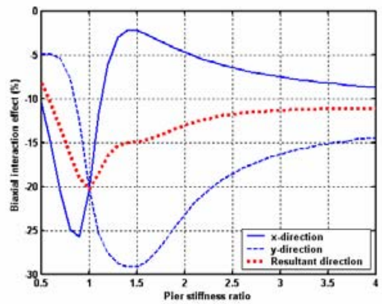

Fig. 6 Pier transverse flexibility effect on LRB restoring force

is investigated under JR Takatori earthquake excitations. Both unidirectional and bidirectional response history analysis is performed considering bridge system, the peak LRB restoring force of this earthquake ground motion is calculated and given in **Table 1**, for three cases, the same wave N-S or E-W component is used in both direction, that clarify the amplitude and frequency content effect on biaxial interaction 13.2 and 6.99%, respectively. The third case, the two different components of the earthquake are used for two directions, the interaction effects is about 4.15% for resultant restoring force, due to phase lag, amplitude and frequency content difference of the earthquake components.

Table 1 LRB restoring force under JR Takatori earthquake motion

Input Excitation	Without interaction	With interaction	Interaction effect (%)
N-S in both direction	845.99	734.25	-13.21
E-W in both direction	626.21	582.46	-6.99
N-S in *x*-direction	845.99	817.71	-3.34
E-W in *y*-direction	626.21	590.93	-5.63
Resultant direction	1052.54	1008.89	-4.15

4. Conclusion

The biaxial interaction between the restoring forces of the LRB bearings in two horizontal directions is considered in the response analysis of simple isolated bridge model. The response with biaxial interaction is compared with those without interaction to investigate the effects of biaxial interaction. The analysis varies important parameters including the isolator properties, the characteristics of the harmonic motion such as the excitation frequency, amplitude ratio and phase difference and the substructure dynamic characteristics. Numerical results show that the isolated bridge structure is significantly influenced by the interaction of bearing forces. The bidirectional interaction of the restoring forces of the LRB has considerable effects on the seismic response of the isolated bridges. If these interaction effects are ignored, then the peak bearing displacements are underestimated the peak bearing restoring forces are overestimated, which can be crucial from the design point of view.

The independent unidirectional models over predict the maximum force in the bearing by more 20% because of the square yield surface, depending on the input excitation, isolation and bridge model parameters. In comparison, loading in one direction while on the bi-directional circular yield surface requires unloading in the other direction. The unidirectional model overestimates the maximum force in the bearing and also overestimates the hysteretic energy dissipation, particularly in the transverse direction. The coupled model shows considerable interaction effects in hysteresis loops. It has been observed that the effect of the biaxial interaction is considerable in the response of bridges isolated by LRB bearing under bi-directional motion. As the substructure becomes more flexible, the bearing deformation decreases and the maximum displacement increases because of reduced hysteretic energy dissipation in the bearing. This study demonstrates that the designer must consider the spectral characteristics of the ground motion and the trade-off between deformation in the bearing and substructure. Designs based on uncoupled inelastic springs may not accurately represent the forces transferred to the substructure and hysteretic energy dissipation.

References

1) Japan Road Association, Specification for Highway Bridges - Part V Seismic Design, Maruzen, Tokyo, 1996.
2) Japan Road Association, Reference for Highway Bridge Design, Specification for Highway Bridges-Part IV Substructures, 1996.
3) Soneji, B.B. and Jangid, R.S., Passive hybrid systems for earthquake protection of cable-stayed bridge, *Engineering Structures*, Vol. 29, No. 1, pp. 57-70, 2007.
4) Jangid, R.S., Seismic Response of Isolated Bridges, *Journal of Bridge Engineering*, Vol. 9, No. 2, pp. 156-166, 2004.
5) Jangid, R.S., Response of sliding structures to bi-directional excitation, *Journal of Sound and Vibration*, Vol. 243, No. 5, pp. 929-944, 2001.
6) Committee of Earthquake Engineering, *The 1995 Hyogoken Nanbu Earthquake, Investigation into Damage to Civil Engineering Structures*, Japan Society of Civil Engineers, 1996.
7) Iemura, H., Taghikhany, T., Takahashi, Y. and Jain, S.K., Effect of variation of normal force on seismic performance of resilient sliding isolation systems in highway bridges, *Earthquake Engineering and Structural Dynamics*, Vol. 34, No. 15, pp. 1777-1797, 2005.
8) Erkus, B., Abe, M. and Fujino, Y., Investigation of semi-active control for seismic protection of elevated highway bridges, *Engineering Structures*, Vol. 24, No. 3, pp. 281–293, 2002.
9) Park, Y.J., Wen, Y.K. and Ang, A.H.S., Random vibration of hysteretic system under bi-directional ground motions, *Earthquake Engineering and Structural Dynamics*, Vol. 14, No. 4, pp. 543-557, 1986.