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# EFFECT OF RUBBER BEARING'S MODELING ON SEISMIC RESPONSE OF BASE ISOLATED HIGHWAY BRIDGE

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**Abstract:** The effects of modeling of isolation bearings on the seismic response of bridges are investigated. To this end, a nonlinear dynamic analysis of a viaduct with natural rubber bearings (RBs), lead rubber bearings (LRBs) and high damping rubber bearings (HDRBs) is carried out. Three analytical models of isolation bearings are considered for comparison: the equivalent linear model, the conventional bilinear model, and the rate-dependent rheology model developed by the authors. The proposed rheology model is able to reproduce the nonlinear viscosity and the elasto-plastic behavior along with strain hardening of bearings. A numerical algorithm for solving the first order governing differential equation of the rheology model has been developed to implement the proposed model into a nonlinear dynamic analysis software. Two level-2 earthquake ground motions, applied in the longitudinal direction, are used in the analysis. The dynamic responses of the isolation bearings and the rotation responses of the plastic hinge in concrete piers are compared for different modeling. Finally, a comparative assessment of the bridge responses shows the sensitivity of modeling of isolation bearings in evaluating seismic responses of the bridge.

## 1. INTRODUCTION

Prior to the Hyogo-ken nanbu (H-k-n) earthquake in 1995, highway bridges were regarded as safe against even the extreme earthquake like the Great Kanto earthquake in 1923 (Kawashima et al. 1997 and Kawashima 2000). However, since the severe damage due to H-k-n earthquake, laminated rubber bearings have been used widely as an isolation system of important structures for the few decades. The base-isolation system with laminated rubber bearings is considered to be an efficient technology for providing mitigation for seismic damage for structures and equipments and has proven to be reliable and cost effective (Kelly 1997).

Three types of laminated rubber bearings are available for the base isolation devices: natural rubber bearings (RBs), lead rubber bearings (LRBs) and high damping rubber bearings (HDRBs). Of these, HDRBs exhibit nonlinear rate-dependent hysteresis (Bhuiyan et al. 2009a and Hwang et al. 2002). On the basis of the experimental observations of HDRBs, an elasto-viscoplastic rheology model has been developed by Bhuiyan et al. (2009a) considering the nonlinear rate-dependence and elasto-plastic behavior. This model is capable of reproducing the above-mentioned mechanical behavior of HDRBs. On the other hand, RBs and LRBs exhibit nonlinear elasto-plastic behavior along with comparatively weak rate-dependence (Robinson 1982 and Bhuiyan et al. 2009b). Robinson (1982) has proposed a bilinear model for representing the hysteresis behavior of LRBs, which is conceptually the same as that recommended for isolation bearings in specification of highway bridges (JRA 1996 and 2002). In the recent years, some other authors have also proposed some analytical models for RBs and LRBs; however, these models cannot reproduce the rate-dependent property (Abe et al. 2004, Kikuchi and Aiken 1997). To improve the performance of the existing models for LRBs and RBs, a rheology model based on experimental investigations has been proposed (Bhuiyan et al. 2009b) by simplifying the earlier rheology model for HDRBs (Bhuiyan et al. 2009a).

The objective of the current study is to evaluate effects of modeling of isolation bearings on the seismic responses by conducting the nonlinear dynamic analysis of a multi-span continuous highway bridge. Three types of isolation bearings, i.e. RB, LRB and HDRB, are considered in this study. The isolation bearings are modeled by the equivalent linear, the bilinear models specified by JRA (1996 and 2002) and the rheology model proposed by the authors (Bhuiyan et al. 2009a and b) for comparison.

## 2. MODELING OF BRIDGE

### 2.1 Physical Model

Figure 1 shows the physical model of a five-span continuous steel-concrete composite girder bridge isolated by laminated rubber bearings. As the laminated rubber bearings, three types of isolation bearings are considered: high damping rubber bearings (HDRBs), lead rubber bearings (LRBs) and natural rubber bearings (RBs). The isolation bearings are installed between the steel girders and the tops of the piers.

The dimensions of this model bridge including rubber bearings are determined by designing in accordance with Japanese Specifications of Highway Bridges (JRA 2002). The superstructure consists of 260 mm thick reinforced concrete slab, covered by 80 mm of asphalt pavement supported on two steel I girders. The depth of the steel girder is 2200 mm. The substructures consist of RC piers and footings supported on pile foundations. The dimensions and material properties of the bridge deck, piers with footings are given in Table 1 and those of the isolation bearings are presented in Table 2.

### 2.2 Analytical Model

The analytical model of the bridge system is shown in Figure 2. The entire structural system is approximated as 2-D frame. The superstructure is idealized as an elastic beam. The plastic behavior of piers is expected to concentrate at the bottom of piers, where plastic hinges are occurred. The plastic hinges of piers are modeled by the tri-linear Takeda model (Takeda et al. 1970). The superstructure, the pier cap, the pier body except the plastic zone, and the footing are modeled using the simple elastic beam elements. The foundation and soil-structure interaction are idealized by a set of linear translational and rotational springs. The superstructure and substructure of the bridge are modeled as a lumped mass system divided into a number of small discrete segments. Each adjacent segment is connected by a node and at each node two degrees of freedom are considered: horizontal translation and rotation. The vertical displacement of the piers is restrained as no significant axial shortening is expected.

In order to describe the mechanical behavior of isolation bearing, two types of analytical models of the bearings are used in the study: the rate dependent rheology model as developed by the authors (Bhuiyan et al. 2009a; 2009b) and the design models including the bilinear model and the equivalent linear model specified in JRA (2002). These two models are briefly discussed in the following sub-sections.

#### 2.2.1 Rheology Model

The rheology model (Bhuiyan et al. 2009a; 2009b) employed in the subsequent numerical analysis is illustrated in Figure 3, where τ and γ are the average shear stress and shear strain of rubber layers, respectively. In this model, the total shear stress is decomposed into three contributions associated with a nonlinear elastic stress, an elasto-plastic stress and finally a viscosity induced overstress. The mathematical description of the model is briefly stated in Eq. (1).

Table 1 Dimensions and material properties of the piers

| Properties | Specifications | |
|---|---|---|
| | Pier S1 & S2 | Pier P1 to P4 |
| Cross-section of the pier cap ($mm^2$) B1 x W1 | 3300x9600 | 2000x9600 |
| Cross-section of the pier body ($mm^2$) B2 x W2 | 3300x6000 | 2000x6000 |
| Cross-section of the footing ($mm^2$) B3 x W3 | 5000x8000 | 5000x8000 |
| Number of piles/pier | 4 | |
| Young's modulus of concrete (MPa) | 25000 | |
| Young's modulus of steel (MPa) | 200000 | |

Table 2 Properties of the isolation bearings

| Dimension | Specifications | | |
|---|---|---|---|
| | RB | LRB | HDRB |
| Length (mm) | 650.0 | 650.0 | 650.0 |
| Width (mm) | 650.0 | 650.0 | 650.0 |
| Total thickness of rubber layers (mm) | 81.0 | 81.0 | 81.0 |
| Material type | G12 | G12 | G12 |

(a) *Rheology model for HDRBs*

$$\tau = \tau_{ep}(\gamma_a) + \tau_{ee}(\gamma) + \tau_{oe}(\gamma_c) \tag{1a}$$

$$\tau_{ep} = C_1\gamma_a \quad \text{with} \quad \begin{cases} \dot{\gamma}_s \neq 0 & \text{for } |\tau_{ep}| = \tau_{cr} \\ \dot{\gamma}_s = 0 & \text{for } |\tau_{ep}| < \tau_{cr} \end{cases} \tag{1b}$$

$$\tau_{ee} = C_2\gamma + C_3|\gamma|^m \operatorname{sgn}(\gamma) \tag{1c}$$

$$\tau_{oe} = C_4\gamma_c \quad \text{with} \quad \tau_{oe} = A\left|\frac{\dot{\gamma}_d}{\dot{\gamma}_o}\right|^n \operatorname{sgn}(\dot{\gamma}_d) \tag{1d}$$

$$A = \frac{1}{2}\left(A_l \exp(q|\gamma|) + A_u\right) + \frac{1}{2}\left(A_l \exp(q|\gamma|) - A_u\right)\tanh(\xi\tau_{oe}\gamma_d) \tag{1e}$$

where $C_i$ ($i$ = 1 to 4), $\tau_{cr}$, $m$, $A_l$, $A_u$, $q$, $n$, and $\xi$ are parameters of the model to be determined from experimental data, and $\dot{\gamma}_o = 1/\text{sec}$ (Bhuiyan 2009a).

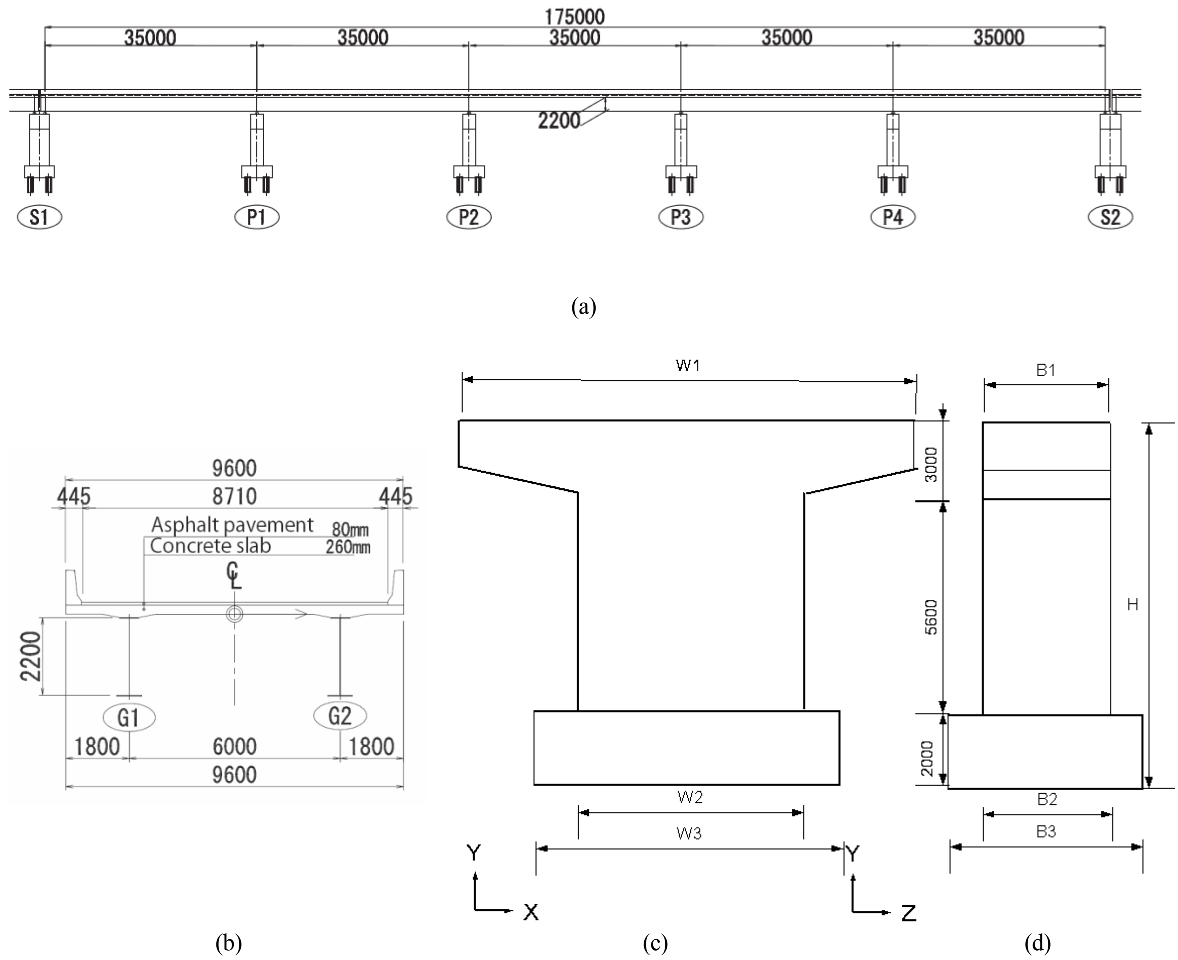



Figure 1 Description of the bridge (a) Longitudinal view (b) Transverse section of the superstructure (c) Transverse section of a typical pier (d) Longitudinal section of a typical pier; all dimensions are in mm.

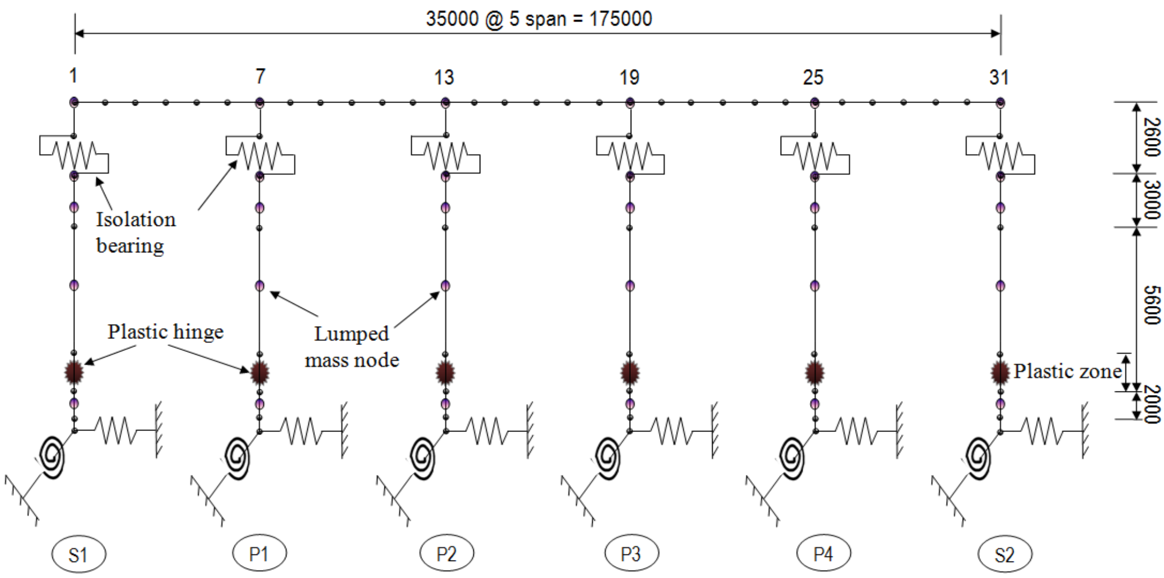



Figure 2 Analytical model of a complete bridge.

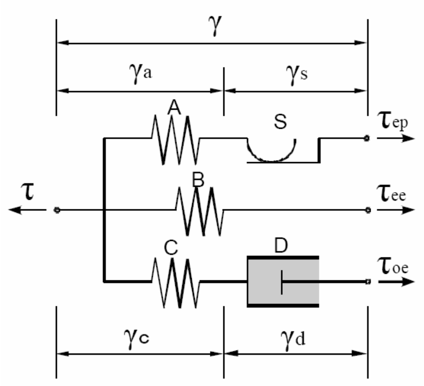



Figure 3 Rheology model structure of the isolation bearing

*(b) Rheology model for LRBs and RBs*

For the rheology model LRBs and RBs, the parameter $A$ in Eq. (1d) is assumed to be constant on the basis of experimental results (Bhuiyan et al. 2009b). The other equations are the same as those for HDRs. The values of the parameters for HDR, LRB and RB used in the numerical analysis are listed in Table 3 and 4 respectively.

Table 3 Rate-independent parameters for the bearings

| Type of Bearing | $C_1$ MPa | $\tau_{cr}$ MPa | $C_2$ MPa | $C_3$ MPa | $C_4$ MPa | $m$ |
|---|---|---|---|---|---|---|
| HDR2 | 2.50 | 0.247 | 0.653 | 0.006 | 3.25 | 6.62 |
| LRB1 | 4.25 | 0.190 | 0.710 | 0.003 | 2.35 | 8.42 |
| RB2 | 2.05 | 0.112 | 0.883 | 0.006 | 0.40 | 7.23 |

Table 4 Viscosity parameters for the bearings

| Type of Bearing | $A_l$ MPa | $A_u$ MPa | q | $n$ | ξ |
|---|---|---|---|---|---|
| HDR2 | 0.351 | 0.272 | 0.344 | 0.224 | 1.252 |
| LRB1 | 0.302 | 0.302 | ----- | 0.272 | ----- |
| RB2 | 0.075 | 0.075 | ----- | 0.243 | ----- |

### 2.2.2 Bilinear Model

It is recognized that the isolation bearing has generally nonlinear inelastic hysteretic property. Some specifications have specified guidelines for using the bilinear model in order to represent the nonlinear inelastic hysteretic property of the HDRB and the LRB (AASHTO 2000; JRA 2002). In this case, three parameters are required to represent the hysteresis loop of HDRBs and LRBs: initial stiffness $k_1$, post yield stiffness $k_2$ and the yield strength of the bearings $Q_d$ as shown in Figure 4. In the subsequent numerical study, these parameters are assigned for HDRB and LRB in accordance with the manual of bearings for highway bridges(JRA 2004).

### 2.2.3 Equivalent Linear Model

From experimental observations of RBs, it has been found that the force-displacement hysteresis loop of RBs can be approximated by the equivalent linear model (JRA 2002). Accordingly, the equivalent linear model is employed for RBs in the numerical analysis. The equivalent stiffness of the RB can be evaluated based on the nominal shear modulus $G_e$ of the rubber material and the damping constant of the bearing is set to be 3.0%.

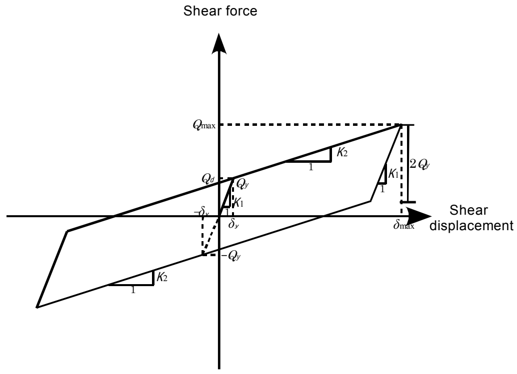



Figure 4 Bilinear relationship of the horizontal shear force-displacement of isolation bearing.

## 3. STRUCTURAL DAMPING

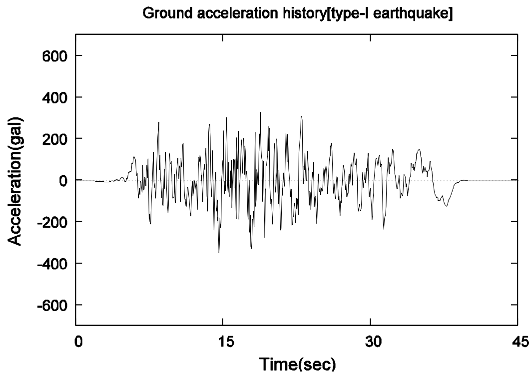
The damping constant matrix $\mathbf{C}$ for the bridge system is evaluated using the stiffness proportional damping model. The damping constant matrix is calculated by summing all the elements' damping constants. The damping constant matrix is determined by using the elemental damping constant $h_j$ and the first natural circular frequency of the system $\omega_1$. The damping constant matrix $\mathbf{C}$ can be written as

$$\mathbf{C}=\sum_{j=1}^{N}\frac{2h_j}{\omega_1}k_j \tag{4}$$

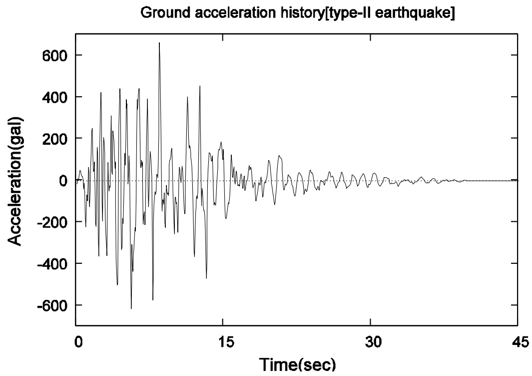
where $h_j$ and $k_j$ are, respectively, the damping constant and stiffness matrix of the $j^{th}$ element and $N$ is the number of elements of the bridge system. The elemental damping constants for the steel girder are taken as 0.02, for the concrete part and the foundation soil taken as 0.05 and 0.2, respectively (JRA 2002).

## 4. EARTHQUAKE GROUND MOTIONS

The designed earthquake waves for level-2 type-I (1-2-1) and type-II (2-2-1) specified by JRA (2002) are applied to the model bridge in the longitudinal direction. Figure 6 shows the ground acceleration time history of these seismic waves.




(a)




(b)

Figure 6 Ground acceleration histories used in the seismic response analysis (a) type-I (1-2-1), (b) type-II (2-2-1) earthquake ground motions.

## 5. SEISMIC RESPONSES OF BRIDGE

Before conducting nonlinear time history analysis of the bridge system, an eigenvalue analysis has been carried out to compute the vibration properties (natural frequencies and mode shapes of the bridge). Using the first natural frequency properties of the system, the damping matrix in Eq. (4) is obtained.

A proposed solution algorithm for the rheology model has been successfully implemented in commercially available software (Kozo Keikaku Eng. Inc., 2006). Due to symmetry of the bridge structure shown in Figure 1(a) and due to space limitation, only one pier's results P1 (=P4) using three isolation bearings (HDR2, LRB1 and RB2) are graphically presented and discussed herein. Figures 7, 8 and 9 represent the moment-rotation relations of the plastic hinges of the pier for level-2 type-I and type-II earthquakes, respectively. The similar trend of the responses is obtained from the shear stress-strain relations of the bearings as shown in Figures 10, 11 and 12. The effect of modeling of isolation bearings on the responses of the bridge have been clearly appeared in the comparisons of maximum shear strain ($\gamma_{max}$) occurred in the isolation bearings and the ratio of the maximum rotation to the allowable rotation ( $\theta_{max}/\theta_a$ ) of the plastic hinge experienced for type-I and type-II earthquakes waves respectively are shown in Table 5 and 6.

Table 5 Seismic response of bridge for type-I earthquake

| Type of Bearing | Type of Model | $\gamma_{max}$ (Bearing) | $\theta_{max}/\theta_a$ (Plastic hinge) |
|---|---|---|---|
| HDR2 | Rheology | 1.51 | 0.43 |
| | Bilinear | 1.49 | 0.57 |
| LRB1 | Rheology | 1.71 | 0.46 |
| | Bilinear | 1.18 | 0.65 |
| RB2 | Rheology | 1.87 | 0.62 |
| | Eq. linear | 1.89 | 1.17 |

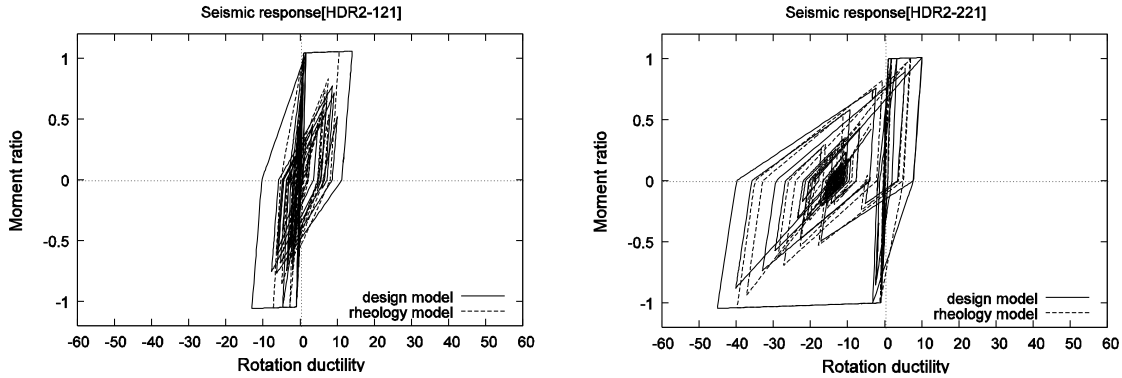
Table 6 Seismic response of bridge for type-II earthquake

| Type of Bearing | Type of Model | $\gamma_{max}$ (Bearing) | $\theta_{max}/\theta_a$ (Plastic hinge) |
|---|---|---|---|
| HDR2 | Rheology | 1.69 | 0.76 |
| | Bilinear | 1.72 | 0.86 |
| LRB1 | Rheology | 1.74 | 0.80 |
| | Bilinear | 1.35 | 0.87 |
| RB2 | Rheology | 1.97 | 0.78 |
| | Eq. linear | 2.05 | 0.87 |

## 6. CONCLUDING REMARKS

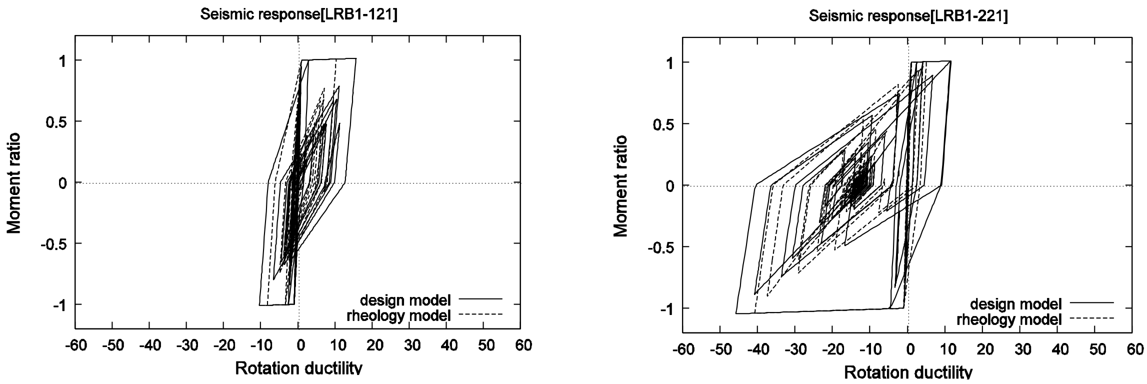
Effect of modeling of bearings on the seismic responses of the isolated bridge is evaluated by conducting nonlinear dynamic analyses. Two different analytical models of the isolation bearings are used in the study for conducting a comparative assessment of the seismic responses of the isolated bridge system. These two models are design model specified in manual of bearings for highway bridges (JRA 2004) and the proposed rheology model. As the design model, the bilinear model is employed for modeling LRB and HDRB; and, the equivalent linear model for RB.

It should be noted that a set of parameters corresponding to design models are estimated using the design equations as specified in JRA (2004), whereas the parameters of the proposed rheology model are estimated using experimental data conducted by the authors. In this



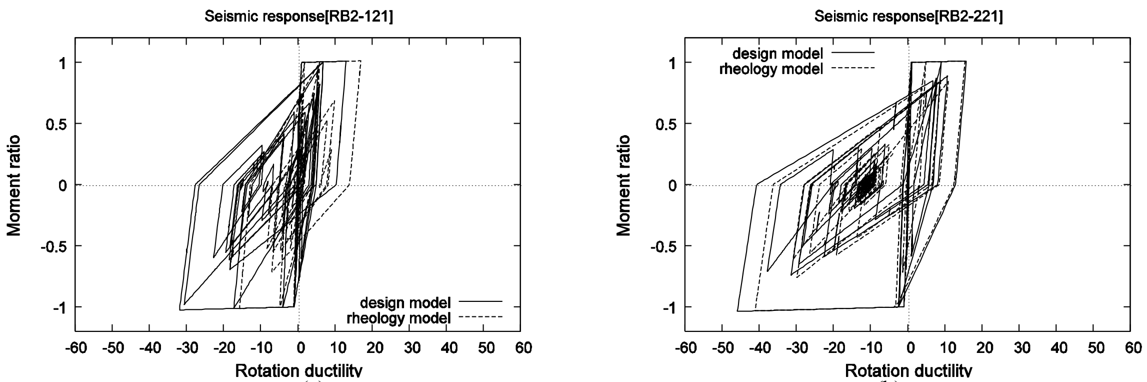

(a) (b)

Figure 7 Moment-rotation relationships at plastic hinge of the pier P1 (=P4) as obtained for HDR2 bearings due to level-2 (a) type-I and (b) type-II earthquake ground motions; moment ratio ($M/M_y$) is the bending moment (M) at the level of plastic hinge divided by the yield moment ($M_y$) and rotation ductility is the rotation occurred at the plastic hinge level divided by the yield rotation.



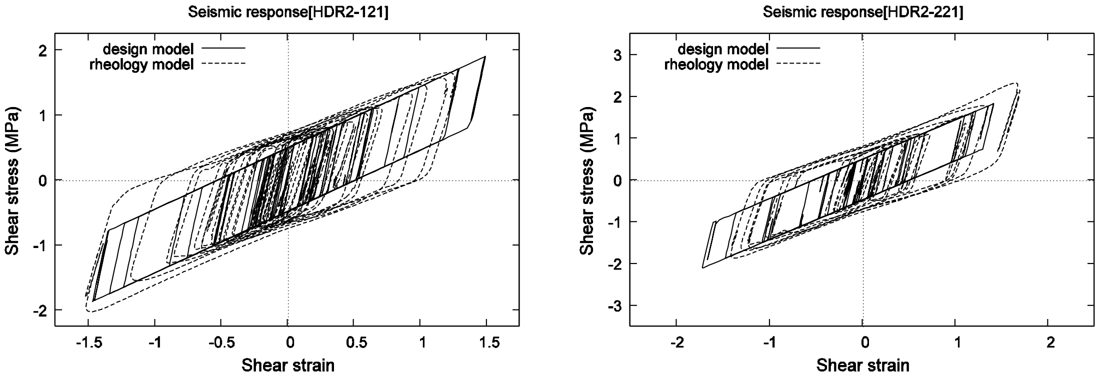

(a) (b)

Figure 8 Moment-rotation relationships at plastic hinge of the pier P1 (=P4) as obtained for LRB1 bearings due to level-2 (a) type-I and (b) type-II earthquake ground motions; moment ratio ($M/M_y$) is the bending moment (M) at the level of plastic hinge divided by the yield moment ($M_y$) and rotation ductility is the rotation occurred at the plastic hinge level divided by the yield rotation.



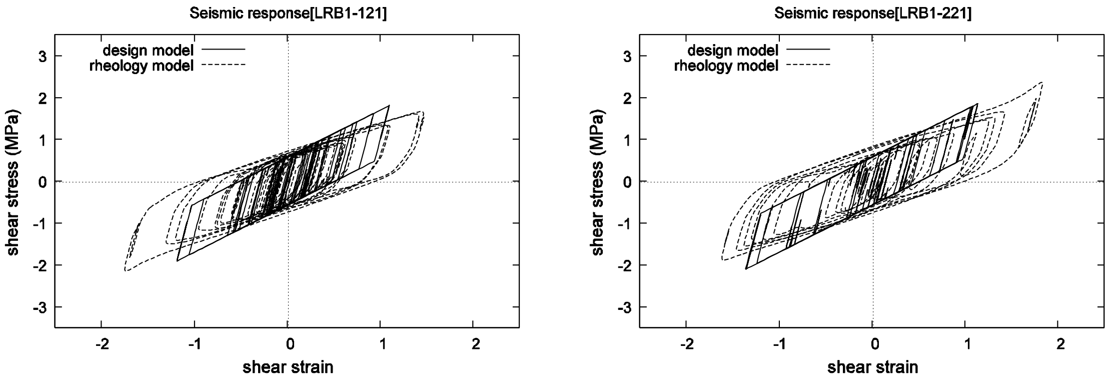

(a) (b)

Figure 9 Moment-rotation relationships at plastic hinge of the pier P1 (=P4) as obtained for RB2 bearings due to level-2 (a) type-I and (b) type-II earthquake ground motions; moment ratio ($M/M_y$) is the bending moment (M) at the level of plastic hinge divided by the yield moment ($M_y$) and rotation ductility is the rotation occurred at the plastic hinge level divided by the yield rotation.



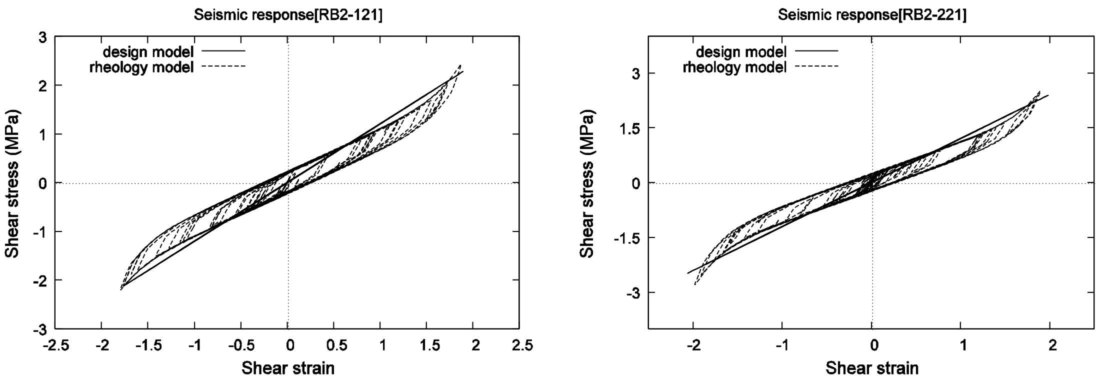

(a) (b)

Figure 10 Shear stress-strain relationships of the isolation bearing (HDR2) located at the top of the P1 (=P4) piers due to level-2 (a) type-I, (b) type-II earthquake ground motions.




(a) (b)

Figure 11 Shear stress-strain relationships of the isolation bearing (LRB1) located at the top of the P1 (=P4) piers due to level-2 (a) type-I, (b) type-II earthquake ground motions.




(a) (b)

Figure 12 Shear stress-strain relationships of the isolation bearing (RB2) located at the top of the P1 (=P4) piers due to level-2 (a) type-I, (b) type-II earthquake ground motions.

paper, the bridge responses are discussed in terms of the moment-rotation relations of the plastic hinges and the shear stress-strain relations of the bearings, since these responses are very crucial for seismic design of bridge systems. The effect of modeling the bearings is significantly observed in the responses indicating that a careful selection of the models of isolation bearings is very important for seismic design of an isolated bridge system.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