Study on Effect of Different Models of Lead Rubber Bearings on the Nonlinear Dynamic Response of Curved Viaduct under Great Earthquake

Hokkaido University	Researcher	Waleed A. MOHAMED
Hokkaido University	Assoc. Prof.	○ Toshiro HAYASHIKAWA
Assiut University	Prof.	Aly Gamal ALY
Assiut University	Assoc. Prof.	Mohamed Hamed HUSSIEN

1. INTRODUCTION

In recent years, the concept of base isolation has gained wide acceptance in the seismic design of bridges, which lend themselves quite naturally and economically, to this innovative approach. Base isolation of bridges can be afforded through flexible bearings capable, to a variable extend, of decoupling the motion of the superstructure from that of the piers 1) . Many devices can be used for isolation, however elastomeric and lead rubber bearings introduce a simple and inexpensive solution. The response of such elastomeric bearings can be modified by placing a lead plug to produce hysteretic damping. The selection of the lead material is attributed to that in shear, lead yields at low stress, it is available at high purity with a predictable mechanical properties and it has good fatigue properties under cyclic load. Laminated rubber layers are capable of supporting high load in compression as well as accommodating one or more movement in shear [2]. The rubber that the isolator will be made from is a highly filled natural rubber which has mechanical properties that it make it ideal for base isolation systems. The shear stiffness of rubber is considered high for small strains but decreases by a factor of four or five as strain increases, this stiffness will reach a minimum value at a shear strain of 50%. For strains greater than 100% the stiffness begins to increase again [3].

Existing bilinear analytical models have been extensively applied for the dynamic analysis of base isolated structures using lead rubber bearings. However, experimentally obtained shear force displacement relationships for elastomeric bearings show nonlinearities and stiffening dependent on the shear strain magnitude which may not be possible to be represented by such models [4].

Of the ways that control the large bearings deformation is to provide additional viscous damping but this will be at the expense of increasing the acceleration. The solutions to this dilemma is to design a system that is very stiff at low input shaking, softens with increasing input motion till reaching a minimum at the designed earthquake and then stiffens again at higher levels of input motion. For elastomeric isolators it requires using the increased stiffness and increased damping that is associated with the strain-induced crystallization that occurs in the elastomer at high strains 5).

The purpose of this study is to evaluate the nonlinear seismic response of four spans base isolated curved highway viaduct, which can suffer severe damage under earthquake excitation [6]. The investigation is focused on studying the efficacy of controlling the high deformations that may result of using flexible lead rubber bearings by considering either hardening of the bearings or the external stopper. Three different models for lead rubber bearings, bilinear model as an original case, trilinear model that takes into consideration the effect of hardening and a trilinear model which permits the application of an external stopper are applied. A parametric study is carried out to investigate the effect of both beginning of hardening or stopper effect and the stiffness of the hardening region.

It is found that hardening model with small clearance ratio can effectively control the high deformation of both deck and bearings without excessive increase in the response of forces.

2. DESCRIPTION OF VIADUCT SYSTEM

2.1 Viaduct deck and piers

The curved viaduct has four spans continuous steel deck of total length equal 160 m (40 m each span) and radius of curvature equal 100 m. The height of all steel piers is 20 m. Radial configuration for piers and bearings is adopted. The general view and configurations for bearings and piers are shown in Figs. 1 and 2.

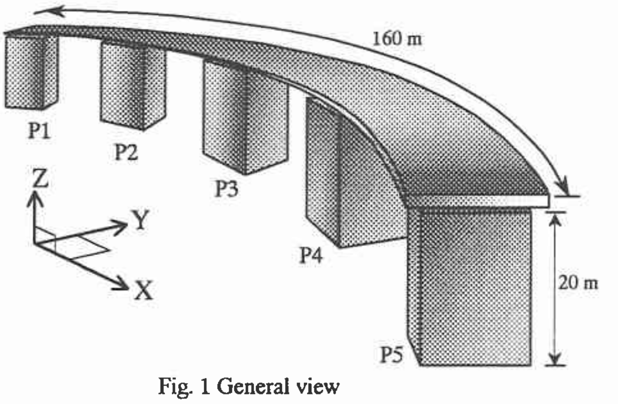

Fig. 1 General view

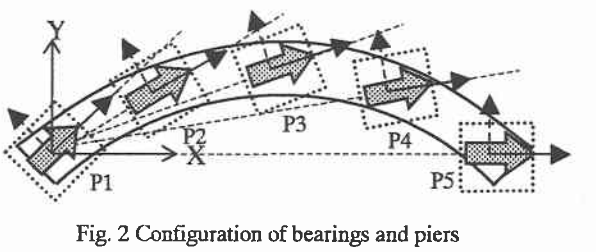

Fig. 2 Configuration of bearings and piers

2.2 Bearings

The studied viaduct is isolated using Lead– rubber bearings (LRB) which have found wide application in highway bridges. Lead–rubber bearings are elastomeric bearings with a lead core at its center extends over the full depth of the bearing. Under low (service) load the lead core provides elastic stiffness K_1 up to the shear yield force F_y. Beyond this point the lead core provides energy dissipation during the cycling of a seismic event. The rubber/steel laminated bearing surrounding the lead plug carries the weight of the structure and provides a restoring force for the device. Energy dissipation and damping are provided through material hysteresis. In this study three different models of LRB are investigated. The first one, original case, is idealizing the behavior of LRB as a bilinear hysteresis element in the three dimensions as shown in Fig. 3(a) in which K_1 is a property of the material of bearing, K_2 is proportional to the bearing size and inversely proportional to the rubber height. F_y is proportional to bearing size and lead radius. The second model is a trilinear model which takes into consideration the effect of hardening of rubber. Force and displacement at the beginning of the hardening region are denoted F_h and d_h while the hardening stiffness is denoted K_3 as shown in Fig 3 (b). The third model is a trilinear model to enable the provision of a steel stopper. The effect of steel stopper is represented by K_3, force and displacement at the beginning in the hardening stage are denoted F_s and d_s as shown in Fig as shown in Fig. 3 (c). An extensive study is carried out to investigate the effect of both the distance at which hardening begins and the stiffness at the hardening region. This studied clearance d_h is taken as a ratio of the yield point d_y, ($r = d_h / d_y$), r is ranged from 2.5 to 15 with a step of 2.5. The stiffness of the hardening part K_3 is taken as a ratio (R) to the initial stiffness K_1 and is equal to 2, 3 and 4. The clearance of the stopper is studied to be the same as the beginning point of hardening while its stiffness is taken equal to 500 MN/m. The initial stiffness and post yield stiffnesses are taken the same for the three models as a reason for the comparison between their behavior. The initial stiffness is determined to be equal to $1\text{x}10^{-3}$ of that installed in a viaduct to give the same response as the nonisolated one. The strain hardening ratio is nominally equal to 0.15 . F_y is chosen as a ratio of K_1, to be equal to 0.02 and the yield displacement is equal to .02 m.

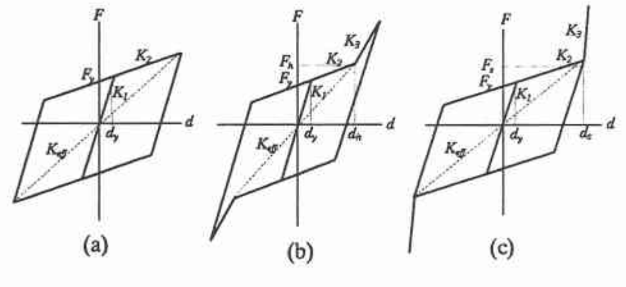

Fig. 3 Different models of LRB

3. FINITE ELEMENT ANALYSIS

A three dimensional nonlinear time history analysis is carried out using the Newmark β method. While both girders and piers are modeled as flexural fiber element, spring elements are used to model the bearings. An elasto– plastic constitutive model with strain hardening ratio in the plastic range equal to 0.01 is adopted to model the material behavior. The yield stress and the elastic modulus are equal to 240 MPa and 200 GPa, respectively. Damping of the structure is taken as Ryleigh damping for the first two modes of natural period with damping ratio equal 2%. The earthquake input motion adopted in this study is the three components (E–W, N–S, U–D) of the JR Takatori wave during Hyogoken-Nanbu earthquake 1995. These components are arranged in the longitudinal, transverse and vertical directions of the viaduct, respectively.

4. NATURAL VIBRATION ANALYSIS

Natural vibration analysis is carried out using consistent mass method to determine the values of the natural period for the studied cases. For a typical viaduct isolated with LRB the effective stiffness is used in the analysis regardless of the effect of the hardening region or stopper. The results of the natural period for the first mode of vibration for different clearance ratios are illustrated in Fig. 4. From which it can be concluded that the obtained results of natural vibration is proportional to the clearance ratio. The percentage of reduction in the values of natural vibration with respect to the original case ranges between 3% and 30%.

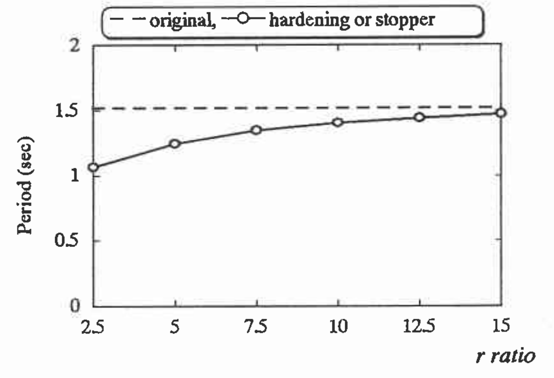

Fig. 4 Natural period of first mode

5. MAXIMUM RESPONSE ANALYSIS

5.1 Force-displacement of bearings

The bearings of the original case exhibit different behavior according to their position on the piers and the direction of response, in plane and out of plane. Bearing forces and displacement are much higher for the out of plane response. For the in plane direction the bearing of P5 suffers the highest deformation due to its arrangement in the radial direction with zero angle, while for the out of plane direction the middle pier suffers the highest deformation as shown in Fig 5.

The behavior of bearings with maximum response for cases of hardening model with R= 3 is shown in Fig 6, from which it is clear that while the maximum displacement gradually increases as the clearance of bearings increases the corresponding bearing forces increases as the clearance increase reaching its highest value then the response gradually decreases. The best response is obtained for case of clearance ratio equal 2.5 which achieves reduction in the maximum displacement equal to 40% and 50% for the in plane and out of plane directions, respectively while the percentage increase in the values of forces did not exceed 25%.

While the external stopper highly restricts the displacement of the bearings it results in high force response, for the same clearance ratio, ratio of 2.5, it is 102% and 45% for the in plane and out of plane, respectively as shown in Fig. 7.

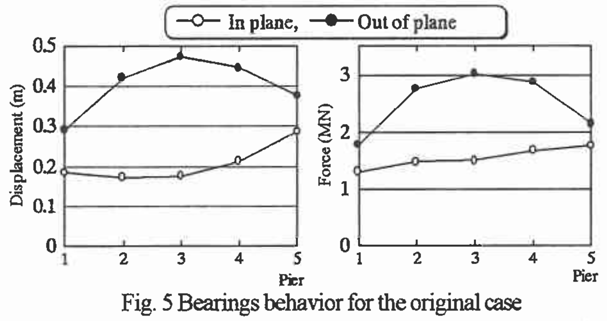

Fig. 5 Bearings behavior for the original case

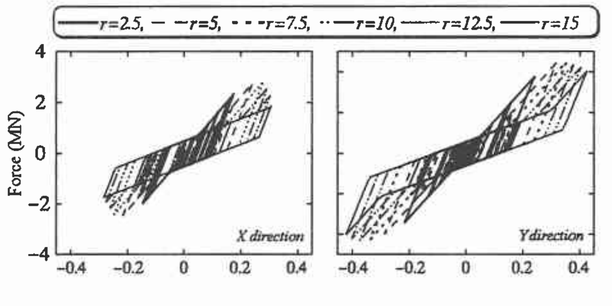

Fig. 6 Maximum bearing behavior for the hardening model

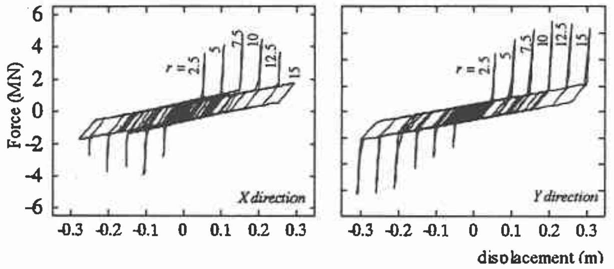

Fig. 7 Maximum bearing behavior for the stopper model

5.2 Deck displacement

Appling hardening or external stopper models is effective in reducing deck displacement achieving reduction ratio for the in plane motion up to 35% and 62%, respectively and for the out of plane it is 47% and 64%, respectively. Only hardening models with small clearance ratio equal to 2.5 and 5 are capable of achieving reduction in the values of in plane displacement while the ratio extends beyond this for effective out of plane reduction in the response as shown in Fig. 8. This behavior can be attributed to the behavior of bearings for the original case which results in higher response for the out of plane response than that of the in plane.

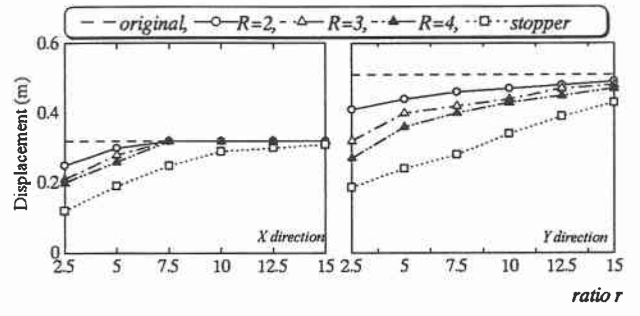

Fig. 8 In plane and out of plane deck displacement

5.2 Deck acceleration

It is clear from the behavior of deck acceleration shown in Fig. 9 that all cases of hardening model exhibit reasonable values of in plane and out of plane acceleration and so close to the behavior of the original case without hardening. Using an external stopper results in high values of this response that the ratio of increase in exceeds 300% for both directions due to the sudden collide of the bearings with the high stiffness stopper.

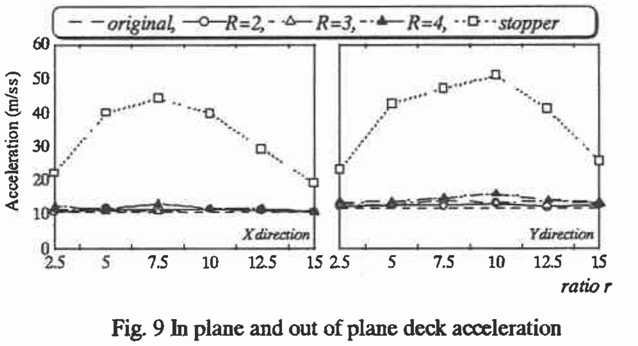

Fig. 9 In plane and out of plane deck acceleration

5.4 Bending moment

The behavior of base of piers maximum bending moment is shown in Fig. 10 from which it can be observed that the in plane response is better than that of the out of plane response, all values are within the elastic limit. The stiffness of the hardening region has a pronounced effect on the response especially for the out of plane, as the stiffness increases the response of bending moment increases. Of the cases with effective deck displacement reduction, bearings with clearance ratio equal 2.5 and with hardening stiffness ratios equal to 2, 3 exhibit the best response, the percentage increase in the in the values of moment did not increase 5% and 20% for the in plane and out plane directions respectively. All cases of external stopper result in high out of plane plasticity which is much higher than the corresponding values of the hardening model.

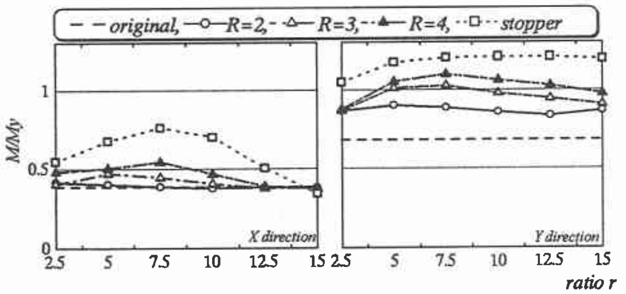

Fig. 10 Maximum bending moment at base of piers

6.TIME HISTORY ANALYSIS

Relying on the previous analysis of maximum values for deformation and forces for the different cases it can be observed that for both hardening and external stopper models, clearance ratio equal to 2.5 and stiffness ratio for the hardening region equal to 3 give satisfactory results among the studied cases of each model. Examples of time history response for these tow cases in comparison with the original case are shown in Figs. 11 through 14 from which it is clear that the hardening and stopper models with the above mentioned rations are effective in reducing the deck displacement, applying hardening results in reduction ratio equal to 34% and 38% for in plane and out of plane response respectively while applying the external stopper results in reduction ratios equal to 62% and 64% respectively. The percentage increase in the response of bending moment, hardening model, at the base of piers did not exceed 5% and 27% for in plane and out of plane directions respectively. The case of external stopper is suffered high response of bending moment, the percentage increase for the bending moment is 42% and 54% for in plane and out of plane response respectively.

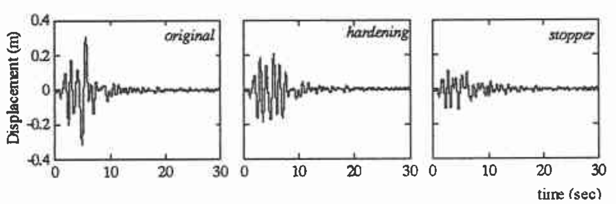

Fig. 11 Time history of maximum in plane deck displacement

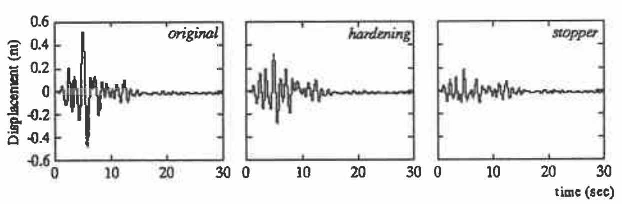

Fig. 12 Time history of maximum out of plane deck displacement

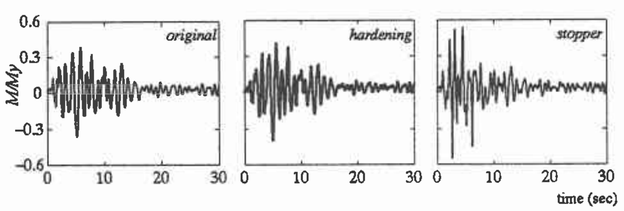

Fig. 13 Time history of maximum in plane bending moment

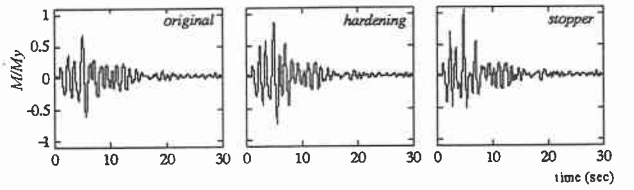

Fig. 14 Time history of maximum out of plane bending moment

7. CONCLUSIONS

From studying the efficacy of both hardening and stopper models in comparison with the original case, the following conclusions can be drawn out

(1) The application of the hardening and stopper models are effective in controlling the high deformation associated with the bearings of the original case.

(2) Due to the nature of the curved viaduct and the adopted excitation only models with small clearance ratios can achieve enhancement in the response of deck displacement.

(3) All the studied cases of hardening model result in acceleration response close to that of the original case with percentage increase did not exceed 7% while using the stopper results in high acceleration response with a ratio more than 300%.

(4) All cases of external stopper result in high out of plane response for bending moment with high plasticity while hardening model only cases with stiffness ratio equal 4 exhibits such plasticity.

(5) For both hardening and external stopper models, clearance ratio equal to 2.5 and stiffness ratio for the hardening region equal to 3 give satisfactory results among the studied cases of each model.

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