Nonlinear Seismic Dynamic Behaviour of Highway Viaducts with Various Support Conditions

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1. INTRODUCTION

The Hyogoken-Nanbu earthquake, occurred on 17 January 1995, caused destructive damage to many highway bridges [1-2]. The severe and extensive seismic damage to highway viaducts that resulted from inadequate performance of bearing supports indicates the need to evaluate carefully the role of bearings as important bridge structural elements [1]. Base isolation is actually considered an important measure for earthquake protection of bridges [3]. Responses of isolated bridges are reduced during an earthquake by introducing flexibility and energy dissipation capabilities. Due to the installation of isolation bearings, piers are protected, however, maximum design displacements of deck can exceed the usual values, resulting in the necessity to install large expansion joints which cause serviceability and maintenance problems to the viaduct [4].

Four different types of bearing systems are previously studied, to obtain optimal values of their design parameters which ensure the most adecuated seismic performance of the model of viaduct. Parametric studies are conducted to determine the most appropriate values for the distance to stoppers of steel roller and laminated rubber bearings, damping characteristics of lead-rubber bearings, and friction coefficient of the Electricite de France system [5]. Trilinear analytical model has been also considered for lead-rubber bearings in order to evaluate the influence of hardening behaviour at large strain levels, due to geometrical effects, in the seismic behaviour of the bridge [6].

The objective of this analytical study is to evaluate the seismic performance of highway viaducts under different bearing support conditions. For this purpose, nonlinear dynamic analysis of a two-dimensional model of highway viaduct is carried out. The dynamic response of the same model of viaduct, under the same input earthquake wave, is compared when steel, laminated rubber, lead-rubber and elastomeric-sliding bearing supports are considered. Overall structural performance of the bridge is compiled, systematically compared and discussed for aseismic performance of multi-span continuous viaducts in this study.

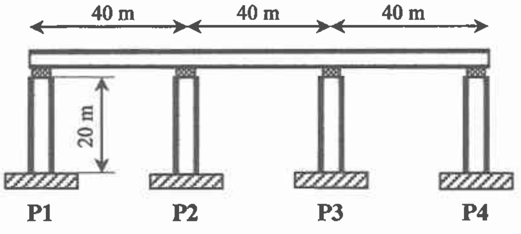

Fig. 1 Model of three-span continuous highway viaduct

Table 1 Structural properties of cross section

	b (m)	t (m)	A (m^2)	I (m^4)
Pier 1	2.20	0.05	0.4300	0.3314
Pier 2	2.30	0.05	0.4500	0.3798
Pier 3	2.30	0.05	0.4500	0.3798
Pier 4	2.20	0.05	0.4300	0.3314
Deck	1.61	0.082	0.5013	0.1963

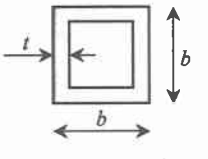

Fig. 2 Cross section of piers and deck

2. ANALYTICAL MODEL OF VIADUCT

2.1 Superstructure and Substructure

The lateral side view of a highway viaduct used in dynamic analysis is shown in **Fig. 1**. The model is a three-span continuous viaduct having equal spans of 40 m, and supported on four steel piers of 20 m of height. The dead load of the steel reinforced concrete deck, assumed to be uniformly distributed, is 8.84 MN. Characteristics of cross sections of piers and deck superstructure are shown in **Table 1** and **Fig. 2**.

2.2 Models of Bearing Supports

Four different types of bearing systems, installed between the top of bridge piers and beneath the deck structure, have been considered in the analysis.

(a) **Steel bearings (SB)**: The model supported on steel bearings is constituted by one pier, P2, with fixed bearing support (**Fig. 3-a**), whereas roller bearings (**Fig. 3-b**) are used for the other three piers. Friction force is taken into account for roller bearings, and lateral stoppers, with a clearance of 12.5 cm, are placed at each side of these bearings in order to prevent excessive longitudinal deck displacements.

(b) **Laminated rubber bearings (RB)**: A laminated rubber bearing consists of horizontal rubber layers bonded and alternated by rigid steel plates. RB bearings are capable to support high loads in compression and large displacements in shear, but their energy dissipation capacity is small. Laminated rubber bearing system is modeled with the bilinear element represented in **Fig. 3-c**. Horizontal stiffness of rubber material is set to 24.5 and 29.4 MN/m for outer and inner piers, respectively. RB bearings can move a maximum of 3.5 cm in the longitudinal direction of the bridge because they are restrained by two side stoppers to limit the deck displacements.

(c) **Lead-rubber bearings (LRB)**: To increase the damping capacity of RB bearings, a lead plug is inserted to provide hysteretic energy dissipation. A yield force of 15% of deck weight, and a pre-yield to post-yield stiffness ratio of 10 are chosen as design parameters for the LRB bearings, according to the type of viaduct and the input earthquake, to achieve maximum seismic energy dissipation concentrated in the bearings, and to control maximum bearing deformation. LRB bearings are usually characterized with bilinear force-displacement hysteretic loop (**Fig. 3-d**), but if hardening effect is considered, trilinear model is used (**Fig. 3-e**).

(d) **Electricite de France (EDF) system**: The Electricite de France system is an innovative base isolation system which consists of a laminated rubber bearing with a top friction sliding plate. For small loads the system behaves like a RB bearing, but if a big load is applied the system allows a relative displacement between the top plate of the bearing and the superstructure to dissipate seismic energy by friction. EDF system is represented with bilinear analytical model (**Fig. 3-d**) with a friction coefficient of 0.25 and yield displacement fixed to 5 cm.

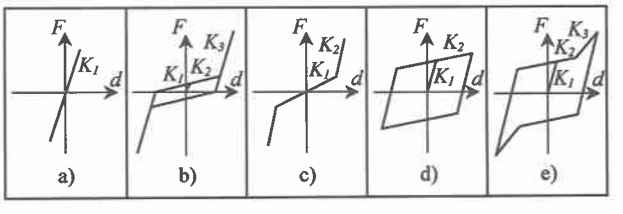

Fig. 3 Analytical models of bearing supports

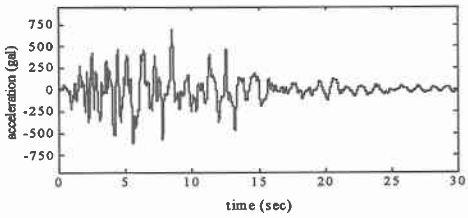

Fig. 4 Acceleration-time history of input earthquake wave

3. METHOD OF ANALYSIS

The analytical method is based on the elasto-plastic finite displacement dynamic response analysis composed by finite element, Newmark β and Newton-Raphson methods. Finite element method considers the beam-column element with material yield and geometrical nonlinearity. The tangent stiffness matrix, considering geometric and material nonlinearities in-plane of bending deformation, is adopted in this study, and cross-sectional properties of the nonlinear elements are prescribed using fiber elements. The stress-strain relationship of the beam-column element is modeled as a bilinear type. The yield stress is 235.4 MPa, the elastic modulus is 200 GPa and the strain hardening in plastic area is 0.01. The damping of the structure is supposed a Rayleigh type, with a damping coefficient to the first two natural modes of the structure of 2%. The number of divisional elements of the bridge is 40.

To assess the performance of the multi-span continuous bridge, the nonlinear model is subjected to the action of the "Standard Earthquake Wave, Ground Type II", represented in **Fig. 4**, and characterizated by a peak ground acceleration of 686.8 gal and a dominant period of 1.0 sec.

4. NONLINEAR DYNAMIC RESPONSE

4-1 Comparative Performance of Bearing Systems

A comparison of seismic responses for the model of viaduct supported on four different bearing systems is carried out. Shear force-displacement relationship at bearing supports and bending moment-curvature relationship at base of piers are given in **Figs. 5** and **6**, respectively.

For the models with steel and RB bearings, stoppers are installed to bearing supports, as unseating prevention devices, to limit unusual large displacements of the deck. Due to the limitation of displacements imposed by the lateral stoppers, large inertial force of the superstructure is applied directly on the top of piers, causing extensive bending damage by plastic hinge at the bottom of piers. For the model supported by steel bearings, this damage is specially concentrated on P2 because the three-span viaduct is configurated with one pier with fixed bearing which resists the entire longitudinal seismic force from the superstructure. Bending damage at base of an inner pier (P3) is shown for other models because, even seismic force is distributed by the bearings, inner piers support double weight from the superstructure and consequently, the most severe seismic response is found in this structural member. In the case of model with RB bearings, the behaviour of the piers exceeds the linear range and moderate damage can be observed. The effect of the base isolation system using LRB bearings is that the lateral seismic force acting on the bearing supports is greatly reduced, and the linearity between bending moment and curvature is observed at base of piers. On the other hand, bearing deformation is moderately large and hardening behaviour when trilinear model is used can be observed. Maximum shear force acting on the EDF system is fixed and predeterminated by the friction coefficient of the top plate. A sliding occurs in the friction plates when the frictional resistance is exceeded and therefore, a predictable bending moment at the base of piers is originated. Consequently, piers are protected remaining under elastic range during the seismic event.

The displacement responses to the input earthquake wave are computed for the first 30 sec of the input ground motion, and deck superstructure displacement-time history responses are presented in **Fig. 7**. It is found that absolute maximum deck displacements vary in the interval 20.0-25.0 cm, depending on the type of bearing supports. These moderate values are within the tolerance range that allows the construction of standard expansion joints for bridges. It is also noted that the model with EDF system experiences a small deck residual deformation in the friction surface of 4 cm at the conclusion of the earthquake.

4-2 Optimal Parameters of Bearings

To obtain the optimal parameters which determine better performance of the model of viaduct under the action of the input earthquake wave for each bearing system type, two response factors have been analyzed. One is the ratio of maximum to the yield bending moment at base of piers, because this factor indicates structural damage. The other is the absolute maximum deck displacement, related to the serviceability of the bridge.

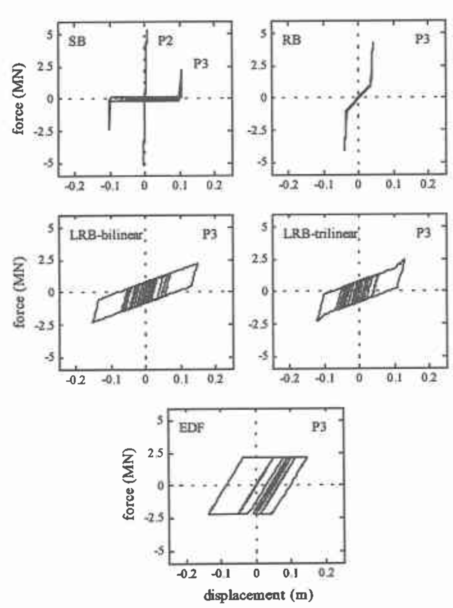

Fig. 5 Shear force-displacement response at bearing supports

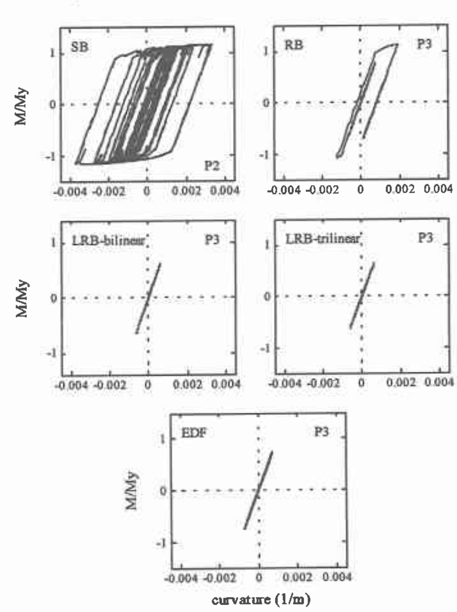

Fig. 6 Moment-curvature response at base of piers

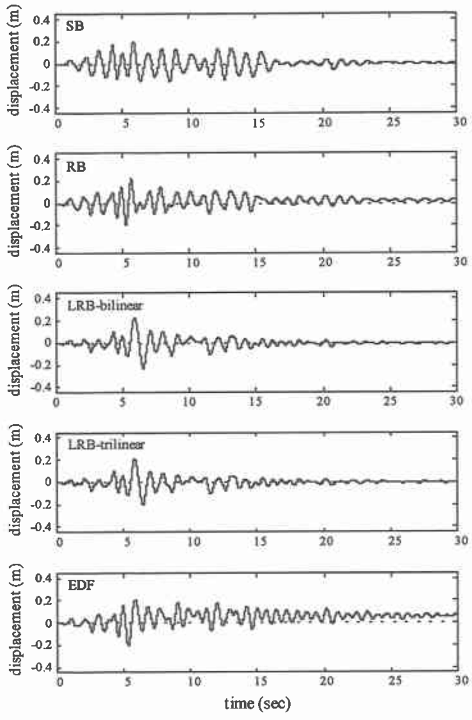

Fig. 7 Displacement-time history of deck superstructure

(a) **Distance to stoppers of roller SB bearing supports**: Positioning of stoppers of steel roller bearings has been extensively studied to obtain an optimal value which ensure appropriate distribution of seismic forces between piers with fixed and roller bearing supports, and to limit maximum displacements of the deck, as it is shown in **Fig. 8**.

Adverse effects to the seismic behaviour of the viaduct are observed when unsuitable values of distance to stoppers of roller bearings are selected. If the clearance to stoppers is small, displacements of deck are sensibly reduced. However, reaction forces acting on bearings reach high values, all piers are heavily damaged, and the possibility of bearing breakage is increased. It is also noted that, in this interval of small distance to stoppers, both responses are amplified due to the effect of the violent collisions to the stoppers of bearings. For large values of clearance, piers with roller bearings are protected, because the intensity of the impacts to stoppers is reduced. In contrast, large deck displacements are originated, and considerable damage to pier with fixed bearing is caused because this pier is assembled to the deck superstructure. A clearance of 12.5 cm is considered optimal because moderate damage to pier with fixed bearing and elastic behaviour for piers with roller bearings are achieved, and a reasonable value of maximum displacement of deck is obtained.

(b) **Distance to stoppers of RB bearing supports**: Stoppers are also provided to laminated rubber bearings to limit the maximum displacements of deck. If bearings are not restrained in the longitudinal direction of the bridge, large deck displacements of more than 35.0 cm are observed. To investigate the effect of distance to stoppers of RB bearings the response factors are examined, and results are given in **Fig. 9**. Parametric study has been carried out to determine that a distance to stoppers of 3.5 cm achieves the most appropriate seismic performance of the model of viaduct.

For values larger than 3.5 cm, a significative increment of peak deck displacement is not recommended. And also, large values of reaction forces at bearings are originated because the flexibility of the rubber material acts as a strong spring, hitting with special violence the stoppers of bearings, transmitting large inertial force to top of piers, and causing an increment of bending damage at base of the piers. When the distance to stoppers is extremely small, following the same trend as the case of stoppers of steel bearings, both responses are undesirably incremented due to violent collisions to stoppers.

(c) **Damping characteristics of LRB Bearing Supports**: In the design of lead-rubber bearing for this study, the influence of two parameters is considered: the lead plug yield force expressed as a fraction of the deck weight *(W)*, and the pre-yield to post-yield stiffeness ratio α $(\alpha=K_1/K_2)$. **Fig. 10** shows the effect of design parameters of LRB to response factors. The results are given as a function of the yield force ratio $F_1/W(\%)$ for several values of stiffness ratio α.

The linearity between bending moment and curvature is observed for most of cases, and piers remain under elastic range. However, isolators with unsuitable characteristics such as very low and very high levels of damping may generally induce inelastic pier behaviour. At very low damping levels, the energy dissipation capacity is small and the isolation system displacement tends to be large. At a very high level of damping, bearing displacements are reduced, but hysteretic damping provided through the yielding of the lead core is small, and the structure behaves like a non-isolated bridge. Peak deck displacement is reduced for values of stiffness ratio α equal or greater than 10. If the pre-yield stiffness of the bearing K_1 is low ($\alpha = 5$), isolation bearing deformation tends to be large, resulting in extremely large peak deck displacements. The influence of the yield force parameter can be especially observed for values of F_1 less than 10% of the weight of deck. The lead core yields at a relatively low force level, and the flexibility of rubber causes large peak displacement of the deck. The optimal LRB design parameters are defined as the combination which allows piers to remain under elastic range while providing acceptable displacements of deck superstructure. Based on the results from this study, a lead-rubber bearing with yield force ratio F_1/W=15% and stiffness ratio α =10 is chosen for the model of viaduct, because it is observed to perform well for this type of earthquake wave.

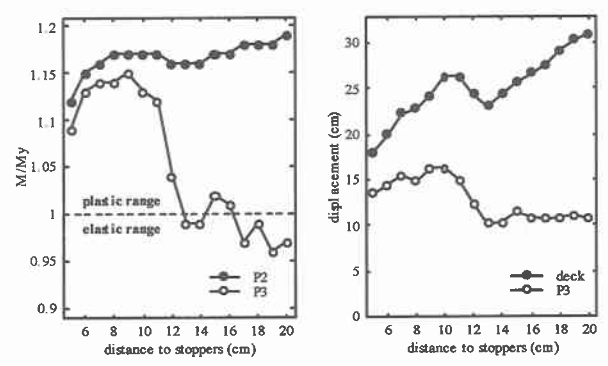

Fig. 8 Response variations with distance to stoppers of steel bearings

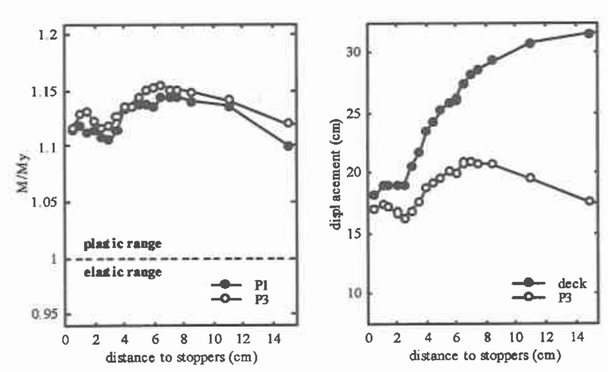

Fig. 9 Response variations with distance to stoppers of RB bearings

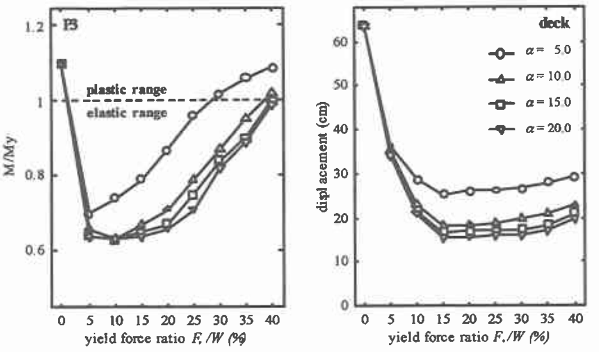

Fig. 10 Response variations with parameters of LRB bearings

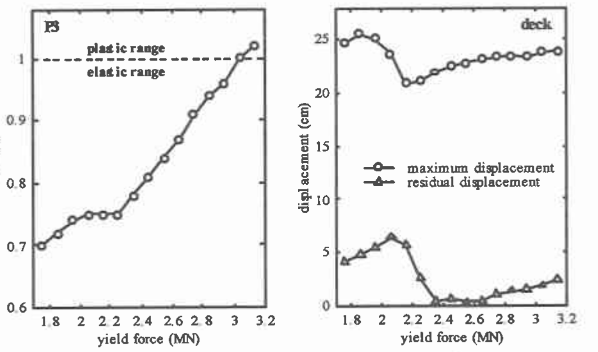

Fig. 12 Response variations with yield force of EDF system

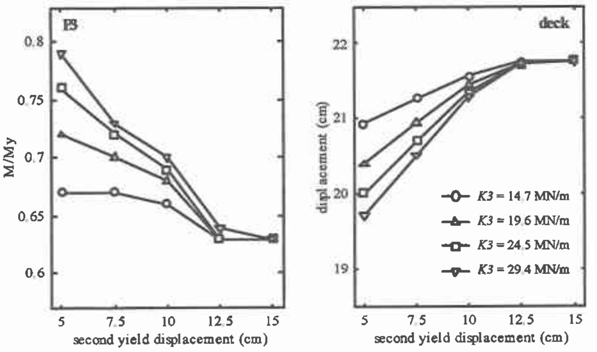

Fig. 11 Response variations with hardening of LRB bearings

(d) **Hardening effect of LRB bearing supports**: Lead-rubber bearings subjected to large deformation experience significant hardening behaviour due to geometrical effect. Trilinear analytical model is introduced to represent this hardening phenomenon and to evaluate its influence on the behaviour of seismically isolated viaducts.

Results presented in **Fig. 11** are given as a function of the second yield displacement and the third stiffness slope, and show that the hardening of LRB bearings at high strain has the favourable effect of reducing the maximum isolator displacement whereas shear forces acting on piers are sensibly increased. However, it should be noted that for the isolation devices of this study, with well-designed damping characteristics, maximum bearing deformation is maintained within a moderate range and consequently, hardening effect of LRB bearings is not excessively large.

(e) **Friction coefficient of EDF System**: In order to obtain maximum energy dissipation by hysteretic action of the EDF system avoiding excessive peak deck displacements, a yield force of 2.2 MN, corresponding to 25 per cent of the weight of the deck and implying a friction coefficient of the sliding plates of 0.25, is considered as design parameter.

Results from the analysis of the bridge with EDF systems are shown in **Fig. 12**. The peak deck displacement is reduced significantly as the yield force is increased from 1.7 to 2.2 MN, but from this value of yield force the response slightly increases. The ratio of maximum bending moment at base of pier to the yield moment monotonically increases as the isolator yield force is increased, being noted that the pier yielding limit is exceeded for high yield force values. If the friction coefficient is small, the sliding will occur for small values of forces. Piers are protected from seismic damage, but large deçk displacements are observed. Isolators with such characteristics are not recommended because the sliding can be caused even by service loads or small earthquakes. If the friction coefficient is excessively large the bearings do not slide, and large reaction forces at top of piers cause inelastic behaviour at base of piers. It is also observed that residual displacements are small, and it is not expected to interfere the post-earthquake serviceability of the viaduct.

5. CONCLUSIONS

Results from dynamic analysis of a highway viaduct model show that the replacement of steel bearings with base isolation bearings causes a significant improvement of seismic response. LRB bearings and EDF system demonstrate a good efficiency to protect the bridge from seismic loads. Reaction forces acting on bearings are decreased and therefore, a considerable damage reduction in structural elements can be achieved. In addition, the large displacement response of the isolated bridge deck can be effectively reduced by selecting appropriate levels of additional damping, introduced by the yielding hysteresis behaviour of LRB and the friction energy dissipation capacity of EDF system. Moreover, serviceability of the viaduct is not affected because such systems are capable of controlling the peak deck displacements thus reducing the required length of expansion joints. LRB bearings are simple and free maintenance devices with a slight advantage on EDF system which is composed by movable parts implying the necessity of maintenance and frequent inspections.

It is also concluded that variations in structural details, like stoppers of steel and RB bearings, significantly modify the seismic response of a highway viaduct. The use of such type of unseating prevention system is benefitial in limiting large bridge deck displacements, however, considerable damage to piers is caused.

Hardening effect of lead-rubber bearings tends to reduce maximum bearing displacements with a slight increment of reaction forces acting on the bearing. This variation is relatively small in case of moderate deformation level of the bearing, but it is recommended to take into account to achieve accurate seismic evaluation of highway viaducts.

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