第７回地震時保有耐力法に基づく橋梁等構造の
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NONLINEAR SEISMIC RESPONSE OF HIGHWAY VIADUCTS WITH DIFFERENT BEARING SUPPORTS

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1. INTRODUCTION

Base isolation is considered an effective technique for improving the seismic performance of bridge structures[1]. The basic principle of seismic base isolation consists in decoupling the structure from the destructive effects of earthquake ground motions. This is achieved by increasing the fundamental vibration period of the bridge beyond the energy-containing periods of earthquake ground motions, and also by the additional damping provided to dissipate the seismic energy[2].

Highway viaducts are ideal candidates for the application of base isolation technology, in either new design or for retrofitting of existing structures, due to the facility of installation, inspection and maintenance of isolation devices. For this reason, a large number of base isolation systems have been developed and implemented in bridges during the last decades[3].

The advantage of base isolation of substantially reducing the damage of bridges during earthquakes is sensibly complicated by the difficulty in election of most suitable devices within the great existing variety of products available, and by the fact that a number of parameters related to characteristics of these bearing supports can have a great influence on the bridge response. In spite of this, most of studies aim to evaluate the bridge seismic behaviour limited to a specific device type. Finding out that few research has been focused on comparative selection of the isolation bearings.

In this paper, in order to improve the seismic performance of highway viaducts, comparative analyses of the nonlinear response of a bridge model supported on various types of isolation systems are presented. Three different types of conventional base isolation devices such as laminated rubber, lead rubber and sliding rubber bearings are used for the passive control design. The nonlinear model of highway viaduct has been subjeted to the action of three different input ground motions with different peak accelerations and predominant periods. The nonlinear response comparison is accomplished by extensive parametric studies conducted by varying those bearing design parameters which have major influence on the overall bridge response. Moreover, the hardening effect of lead rubber bearings at high strain levels has been introduced, as an additional design parameter, to evaluate its influence on the behaviour of seismically isolated viaducts subjected to great earthquake ground motions.

2. ANALYTICAL MODEL OF VIADUCT

(1) Deck superstructure and piers

The highway viaduct considered in the analysis is a three-span continuous bridge having an overall length of 120 m divided in three equal spans of 40 m, as it is shown schematically in **Fig. 1**.

The analytical model assumes the composite action between the concrete slab and the steel girders for the deck superstructure, which is modeled by using linear elastic elements. The superstructure is supported on four hollow box section steel piers of 20 m height. Cross section characteristics of structural elements **(Fig. 2)** have been selected in order to obtain a good approximation to the real behaviour of the isolated bridge structure, ensuring near equal distribution of seismic lateral forces to the various substructure units.

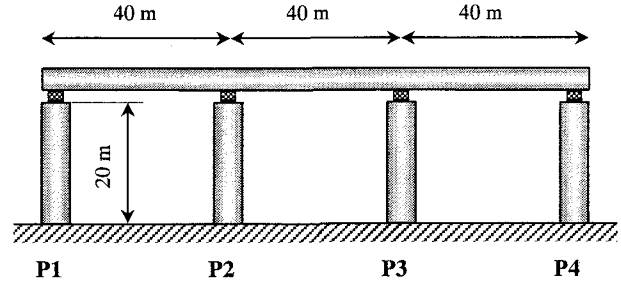

Fig. 1 Model of three-span continuous viaduct

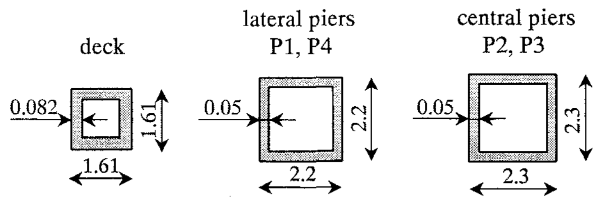

Fig. 2 Cross sections of deck and piers (m)

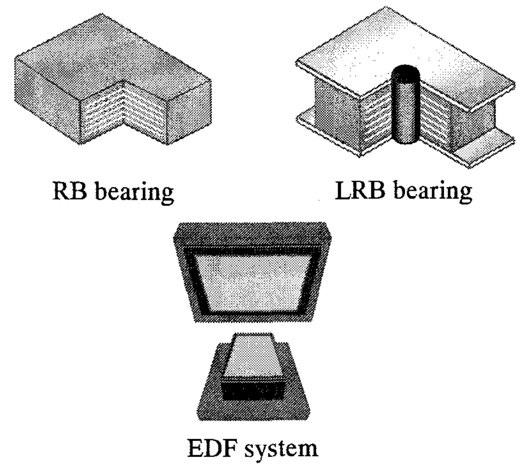

Fig. 3 Base isolation bearing supports

(2) Base isolation bearing supports

Three different types of isolation bearing systems (**Fig. 3**), installed between the top of bridge piers and beneath the deck superstructure, have been considered in the analysis.

a) Rubber bearings (RB)

A laminated rubber bearing consists of several layers of rubber alternated and bonded to rigid steel plates. The main characteristic of RB bearings is that they provide high vertical stiffness to sustain the structural weight while maintaining considerable flexibility in horizontal directions[4]. RB bearings of this study are restrained by two lateral steel stoppers in order to limit the maximum deck displacements in the longitudinal direction of the bridge. The RB system is modeled with the bilinear force-deformation element shown in **Fig. 4-a**. K_1 and K_2 represent the horizontal stiffness of rubber material and steel stoppers, respectively, whereas x_1 indicates the distance to stoppers of bearings.

b) Lead rubber bearings (LRB)

LRB bearings are modified RB bearings in which a lead plug is inserted to provide hysteretic energy dissipation and rigidity against minor earthquakes, wind and service loads[5]. LRB bearings are usually characterized with bilinear force-displacement hysteretic loop (**Fig. 4-b**), but trilinear analytical model is selected when hardening effect at high strain levels is considered (**Fig. 4-c**). The pre-yield stiffness K_1 corresponds to the stiffness of the lead plug, K_2 is the stiffness of the rubber, F_1 is the yield force of the lead plug, and K_3 and F_2 represent the hardening parameters effect.

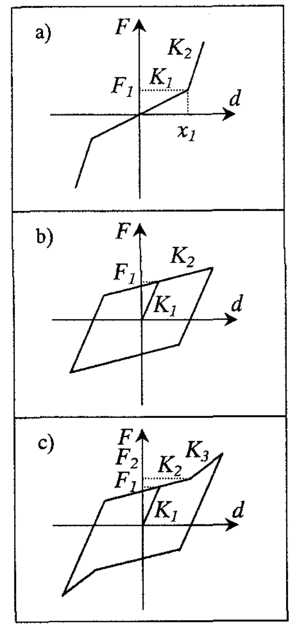

Fig. 4 Analytical models of bearing supports

c) Electricite de France (EDF) system

The Electricite de France system consists of a laminated rubber bearing with a top friction sliding plate[6]. For small loads it behaves like a RB bearing, but in case of large earthquakes 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 the bilinear analytical model presented in **Fig. 4-b**. K_1 is the stiffness of the RB bearing, while the sliding phase is represented by the friction force F_1 and the value of stiffness K_2.

3. METHOD OF ANALYSIS

The analysis on the bridge model is conducted using an analytical method based on the elasto-plastic finite displacement dynamic response analysis.

The governing nonlinear equation of motion[7] for the viaduct can be written in incremental form as:

$$[\mathbf{M}]\{\ddot{u}\}^{t+\Delta t} + [\mathbf{C}]\{\dot{u}\}^{t+\Delta t} + [\mathbf{K}]^{t+\Delta t}\{\Delta u\}^{t+\Delta t} = -[\mathbf{M}]\{\ddot{z}\}^{t+\Delta t} \tag{1}$$

where $[\mathbf{M}]$, $[\mathbf{C}]$ and $[\mathbf{K}]^{t+\Delta t}$ are the mass, damping and tangent stiffness matrices at time $t+\Delta t$, respectively. $\ddot{u}$, $\dot{u}$, Δu and $\ddot{z}$ are the accelerations, velocities, incremental displacements vectors and earthquake acceleration at time $t+\Delta t$, respectively.

The tangent stiffness matrix, considering both geometric and material nonlinearities, is adopted in this study, being the cross sectional properties of the nonlinear elements prescribed by 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 implicit time integration Newmark scheme is formulated and used to directly calculate the nonlinear responses, while the Newton-Raphson iteration method is used to achieve the acceptable accuracy in the response calculations. The damping of the structure is supposed a Rayleigh's type, with a damping coefficient of the first two natural modes of the structure of 2%[8].

The nonlinear seismic responses of the bridge are also calculated on the basis of the equilibrium of energy. To quantify the seismic structural response, Housner[9] formulated the fundamental concept that at any instant the sum of the kinetic energy, energy dissipated through normal damping, strain energy and plastic energy dissipated through permanent deformation, must be equal to the total input seismic energy.

The equation of energy balance[10] for the isolated structure subjected to the earthquake ground motion is obtained by multiplying both sides of Equation (1) by $\{\dot{u}\}^T$ and by integrating the product over the entire duration of the earthquake. The energy balance equation becomes

$$\int_0^t \{\dot{u}\}^T [\mathbf{M}]\{\ddot{u}\}dt + \int_0^t \{\dot{u}\}^T [\mathbf{C}]\{\dot{u}\}dt + \int_0^t \{\dot{u}\}^T [\mathbf{K}]\{u\}dt \quad (2)$$
$$= -\int_0^t \{\dot{u}\}^T [\mathbf{M}]\{\ddot{z}\}dt$$

where the right side of the equation is the absolute input energy (E_T) in terms of the total acceleration $\ddot{z}$ relative to a fixed reference axis. The first term of the left side of the equation represents the absolute kinetic energy (E_K) that includes the effects of the rigid body translation of the structure. The second term is the consumed energy due to damping mechanism of the system (E_D), and the third term corresponds to the absorbed strain energy (E_S), which is composed of recoverable elastic strain energy and irrecoverable hysteretic energy.

4. INPUT EARTHQUAKE GROUND MOTION

To assess the seismic performance of the multi-span continuous bridge, the nonlinear model is subjected to the action of three different input ground motions.

The Standard Earthquake Wave - Ground Type II (SEW-II) acceleration, given in **Fig. 5-a**, is characterized by peak ground acceleration of 686.8 gal and a dominant period of 1.02 seconds. This accelerogram, provided by the Japan Road Association[8], is modified from direct-inland-strike type earthquake records from the 1995 Hyogoken-Nanbu earthquake, and it has been selected to evaluate the performance of the highway viaduct according to the destructive energy content of this ground motion and the suitability of ground Type II for base isolation design. Rinaldi input wave, from the Northridge earthquake and represented in **Fig. 5-b**, has maximum acceleration of 826 gal with predominant period of 1.37 sec. And the Lomaprieta input ground motion, shown in **Fig. 5-c**, developes its peak acceleration of 559 gal at a dominant period of 0.64 sec.

5. NUMERICAL RESULTS

(1) Natural vibration analysis

Valuable information about structural behaviour of highway viaducts during earthquakes is provided by calculation of their natural vibration characteristics. For this reason, natural vibration analysis of the viaduct model supported on the three different types of base isolation bearings considered in this study is carried out.

The fundamental natural period corresponds to the modal vibration in the longitudinal direction of the bridge, and it is observed to be significantly influenced by parameters of the isolation bearings.

In case of viaducts with LRB and EDF systems, according to recommendations of Specifications of Highway Bridges[8], the fundamental natural period is pre-selected to obtain moderate period shift. Characteristics of both isolation bearing devices are selected to obtain periods slightly larger than twice the natural period of the bridge when no isolation bearing is applied (0.59 seconds). Depending on design parameters of the isolators considered in this study, the fundamental natural period of the viaduct provided with LRB and EDF base

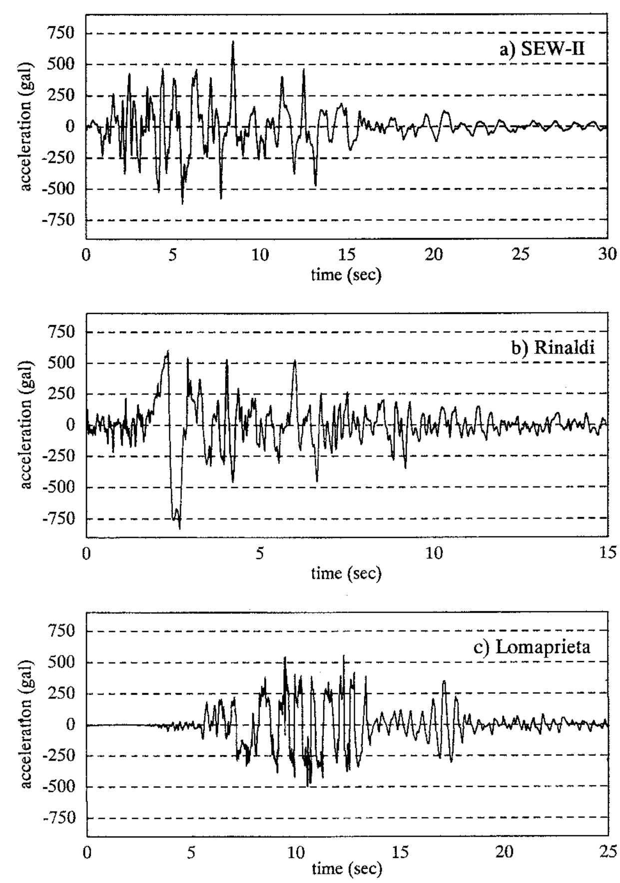

Fig. 5 Earthquake acceleration-time histories

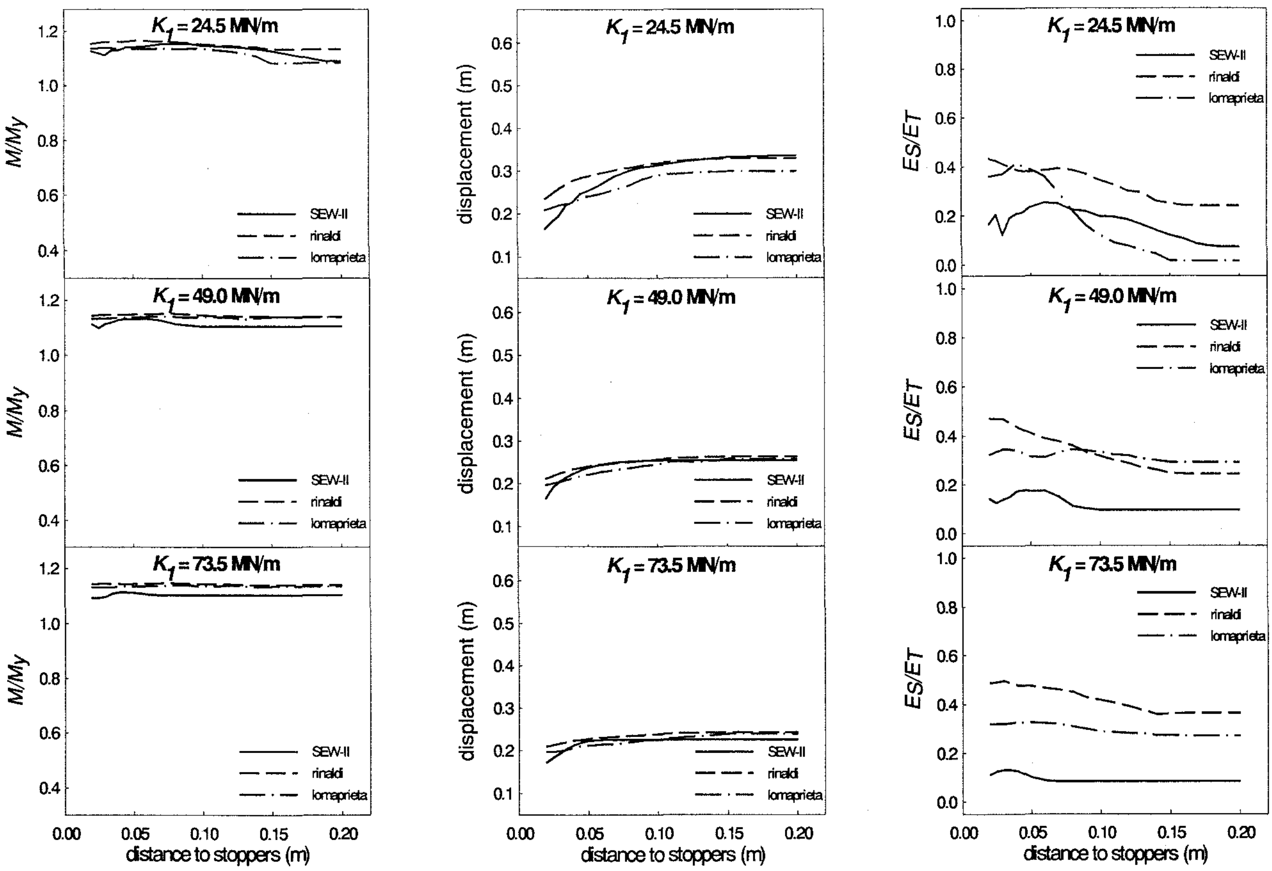

Fig. 6 Seismic response of RB isolated viaduct

isolation systems varies in the intervals 1.25~1.68 and 1.18~1.49 seconds, respectively. These values allow the viaduct to shift its fundamental natural period into ranges that exceed those of the input ground motion, with the objective of reflecting a major portion of the earthquake energy. On the other hand, the obtained moderate period shift is expected to limit the increased displacements experienced by the bridge deck during strong earthquake ground motions.

In contrast, lower period shift is obtained for the viaduct supported on RB bearings. Its fundamental period varies from 0.82 to 1.14 seconds for the stiff rubber and the soft rubber materials. This is due to the effect of the relatively high bearing stiffness. The absence of an additional mechanism to offer rigidity under service and low lateral loads makes necessary to limit the flexibility of this type of bearing supports.

(2) Nonlinear dynamic response

For a more comprehensive comparison of nonlinear responses, calculated results for the highway viaduct supported on the different bearing systems considered in this study are graphically presented under the same range of scales in three different types of plots unified in the same figure.

In the first plot type, at the left side of the figure, the ratio of absolute maximum bending moment to the yield moment at the pier bottoms (M/M_y) is presented. It is well-known that maximum bending moment at the base of bridge piers is considered to be an appropriate measure of seismic structural damage, and for this reason it has been adopted as an important response factor in this study.

Absolute maximum deck displacements are given in the second plot type at the center of the figure. Peak deck displacements provide additional information about the possibility of collision between deck and abutments in continuous bridges, and also they are an important factor in design of expansion joints.

In the third plot type, the ratio of strain energy to the total input earthquake energy (E_S/E_T) is represented at the right side of the figure. The strain energy is a good index of the seismic energy dissipated at bearing level as well as a good measure of the possibility of bending damage at bridge piers.

a) RB isolated viaduct

Seismic response of the viaduct isolated with RB bearings is shown in **Fig. 6**. Distance to stoppers and stiffness of rubber material have been selected as design parameters for the bearing supports.

By comparing the structural response factors, it is evident that sensitivity of calculated maximum moment ratio to variations with design parameters is much less than that related to maximum deck displacement response. An important point that can be seen in this figure is that the RB system is incapable of protecting the piers, which are above the elastic limit (M/M_y >1) for all study cases.

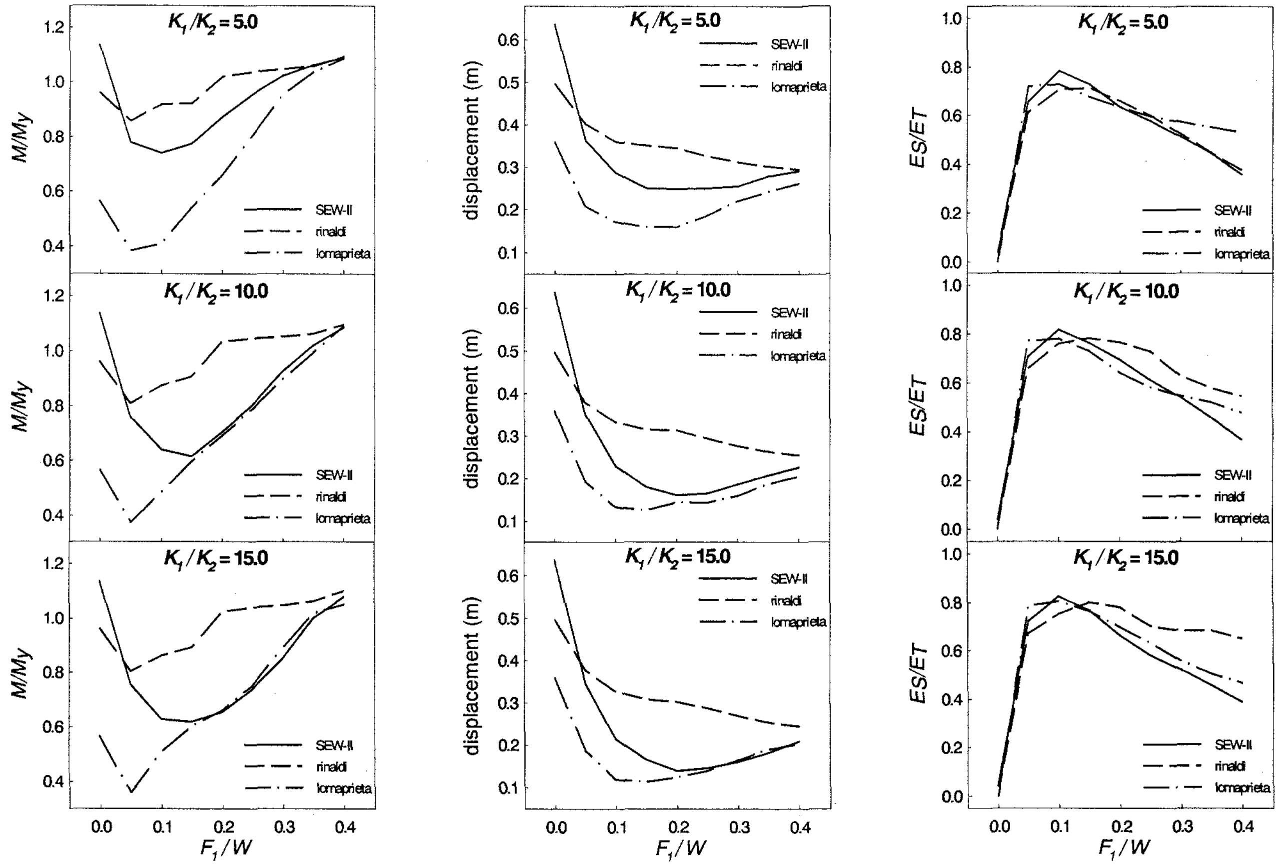

Fig. 7 Structural response of LRB isolated viaduct

However, it is observed that the absolute maximum deck displacements are positively reduced with the diminution of distance to stoppers. It should be noted that, depending on the input earthquake wave, from values of distance to stoppers of 0.16~0.19, 0.10~0.16, and 0.07~0.16 m in case of soft (K_1=24.5 MN/m), medium (K_1=49.0 MN/m) and stiff (K_1=73.5 MN/m) types of rubber material respectively, calculated response factors are observed to converge to certain constant responses, indicating that the effect of stoppers disappears. For those obtained values, when stoppers are not installed in the bearing system, a remarkable increase of deck displacement, especially for soft or medium type rubber materials, is observed. This means that an improve in the performance of viaducts isolated with RB bearings under the action of large earthquakes should consider the use of lateral stoppers.

From the seismic response, presented in terms of the energy transmitted to the viaduct by the earthquake ground motion, it is clearly seen that most of the total seismic energy input to the bridge structure is dissipated by damping mechanism. Calculated strain energy is exclusively attributable to plastic energy dissipated in the piers because the energy dissipation capacity of RB bearings is very small. These values of strain energy vary significantly with the flexibility of the rubber material, generally indicating that bearing supports with soft rubber may make the highway viaduct specially vulnerable to seismic loads.

b) LRB isolated viaduct

The effectiveness of the LRB isolation system has been evaluated varying two different design parameters: the lead plug yield force, expressed as a fraction of the deck superstructure weight (F_1/W), and the pre-yield to post-yield stiffness ratio (K_1/K_2).

The calculated results, presented in **Fig. 7**, indicate that the structural seismic performance of the viaduct is significantly improved for a number of combinations of LRB design parameter values. Elastic behaviour of piers (M/M_y<1) is observed for most of the cases. However, it is seen that isolators without lead plug (F_1/W=0.0) and isolators with high yield force level may induce inelastic pier behaviour for the three input earthquakes considered in this study. This is mainly due to the fact that the small energy dissipation capacity of isolators without lead plug makes the isolation system to be incapable of protecting the bridge against large earthquakes. On the other hand, the adoption of big size lead plugs for increasing the yield force level of the bearing, with the objective to obtain larger energy dissipation at the LRB bearings, may cause a negative effect in the seismic response. The hysteretic damping is sensibly reduced, the structure behaves like a non-isolated bridge and the large forces transmitted at the top of piers amplify significantly the bending moments at the bases. This important remarkable point indicates that an excessive yield force level could have a considerable effect on the increase of seismic structural responses.

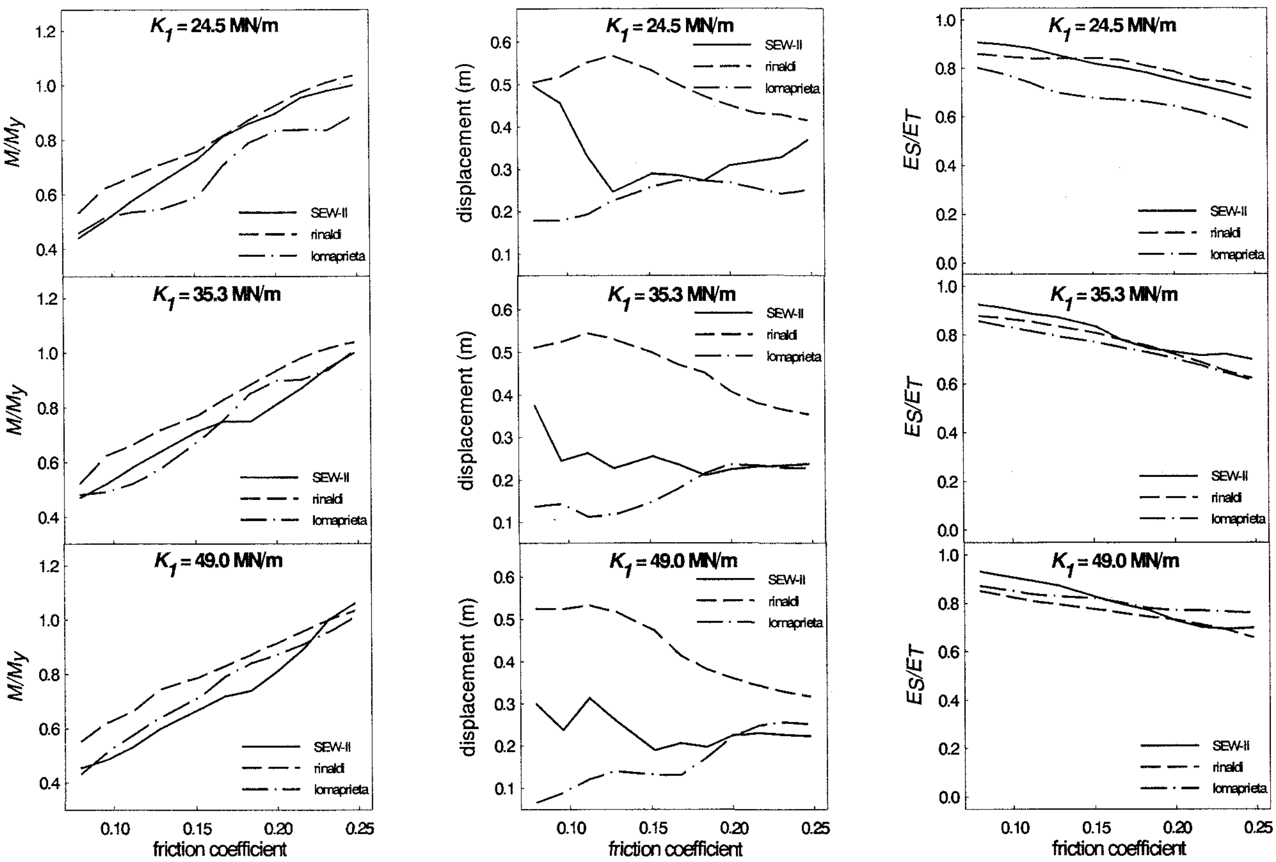

Fig. 8 Structural response of EDF isolated viaduct

Regarding to the peak deck displacement response, it is easily observed from the figure that high maximum displacements are obtained for values of F_1/W less or equal than 0.05. This means that for these cases the lead plug yields at relatively low force levels, resulting in considerable deformations of the LRB bearing supports, which are transmitted as high peak displacement response to the deck. In addition, large peak displacements are also generally found for LRB bearings with low stiffness ratio (K_1/K_2 =5.0) mainly due to the high level of deformation of these bearings provided with relatively flexible lead plugs that induce large deck displacement response.

Selection of the optimal characteristics for the LRB isolation bearings can be specially clarified by comparing the calculated results in terms of energetic quantities. The E_S/E_T ratio indicates that maximum values are obtained for F_1/W = 0.05, 0.10, and 0.15 in case of Lomaprieta, SEW-II and Rinaldi input ground motions, respectively. Due to the elastic behaviour of the piers in this range of parameters, this strain energy corresponds exclusively to the hysteretic energy dissipated at LRB bearing supports. Consequently, the high strain energy ratios (0.80~0.85) indicate that most of the transmitted seismic energy to the highway viaduct is dissipated at bearing level. The peaks indicate maximums of energy dissipation capacity of the LRB bearing supports, and a greater effectiveness of the isolators could be obtained for these values depending on the input earthquake wave.

c) EDF isolated viaduct

Seismic responses from the analysis of the highway viaduct provided with EDF system are shown in **Fig. 8.** In order to obtain optimal energy dissipation by hysteretic action of the EDF isolation system, a parametric study is conducted by varying two design parameters: the friction coefficient of the top sliding plate and the rubber stiffness of the bearing support.

From the calculated results, a first important point to note is that the ratios of maximum bending moment at base of the piers monotonically increases with the friction coefficient. Moreover, it is seen that the yielding limit of the piers is exceeded for large values of the friction force for all input earthquake ground motions considered in this study. When the friction coefficient is excessively large, the EDF system can not slide and the large reaction forces transmitted to the top of bridge piers may cause inelastic behaviour at the bottom. This phenomenon is also clearly appreciated by observing the variations of strain energy ratio. The strain energy, corresponding to the energy dissipated by friction at the EDF system, substantially decreases with the friction coefficient, perfectly indicating the lost in energy dissipation capacity for the bearings. Inadequate performance is also observed for small values of friction coefficient. In this case, the sliding may occur even for service loads or small earthquakes. Consequently, piers can be protected, but the peak deck displacement response is sensibly increased

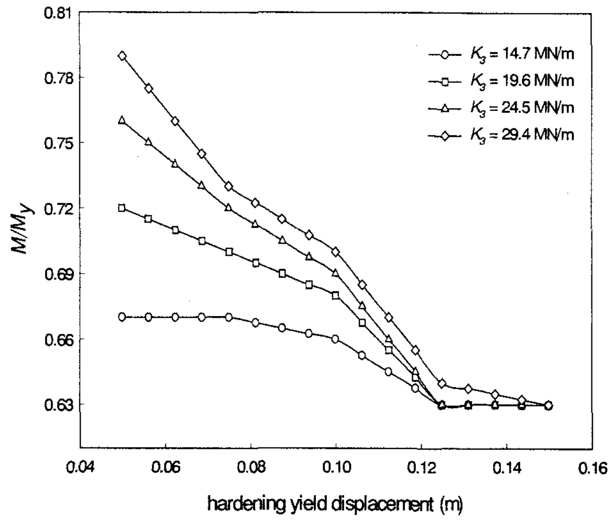

Fig. 9 M/M_y response variation with hardening of LRB bearing supports

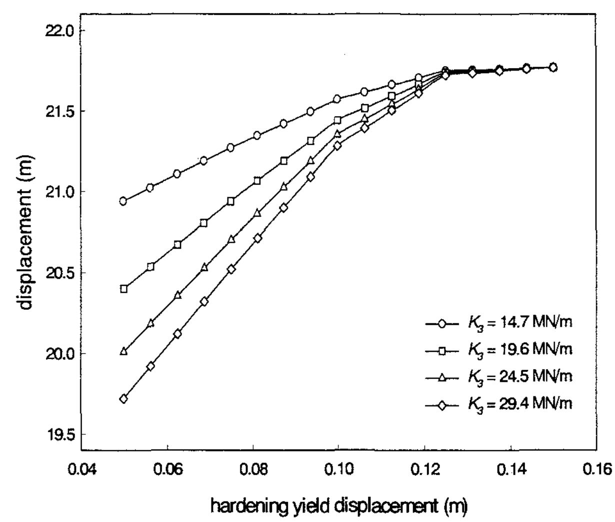

Fig. 10 Deck displacement response variation with hardening of LRB bearing supports

The influence of the rubber bearing stiffness is appreciated in the deck displacement response. It should be noted that flexible bearings (K_1=24.5 MN/m) increases the deck displacements to hardly assumable levels for designing of the expansion joints, causing an additional increase in the possibility of collision between deck and abutments during earthquakes.

Additional results, not presented in this study, indicate that residual displacements of the deck, related to the final position of the sliding plate of the EDF system, are generally small, and they are not expected to interfere the post-earthquake bridge serviceability.

d) Hardening effect of LRB bearings

Experimental dynamic tests for identifying the mechanical characteristics of LRB bearings have shown that this bearing supports exhibit significant hardening behaviour beyond certain strain levels[11].

This hardening phenomenon, attributed to material properties of the rubber and originated mainly due to geometric causes, sensibly modifies the response of the bearings at large shear strains. Subsequently, it could be expected that the overall seismic bridge response could be affected in case of large earthquakes.

LRB bearings are generally represented with bilinear force-displacement hysteretic loop but, in this study, trilinear analytical model is adopted when hardening effect at high strain levels is considered. Two different design parameters, the hardening yield displacement and the hardening stiffness, have been used as a design tool to investigate how their variations affect the global seismic performance of the bridge structure.

The effect of hardening has been evaluated under the action of SEW-II. The effect on the maximum bearing responses indicates that hardening generally tends to simultaneously increase the maximum forces acting on the bearings reducing the peak bearing deformation. The effects of hardening on the bending moment ratio, shown in **Fig. 9**, result in noticiable trend to amplify the ductility

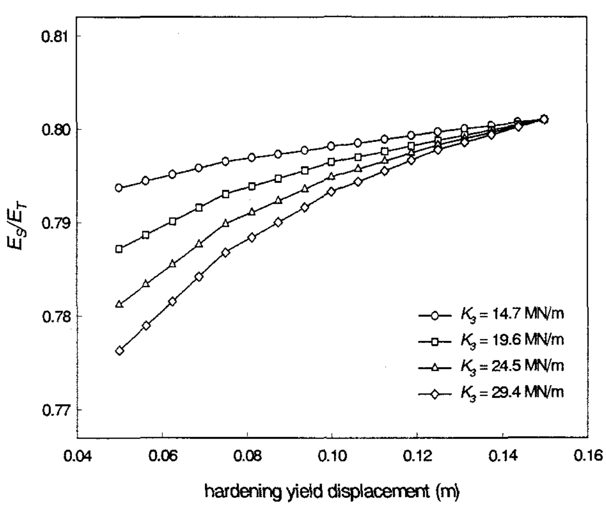

Fig. 11 E_S/E_T ratio response variation with hardening of LRB bearing supports

demands of the piers. This is because hardening increases the reaction forces acting on the LRB bearing which are directly transmitted to the piers. It is noted that bending moment is increased up to 25% in case of extremely flexible LRB bearings in which the hardening effect is observed at low levels of deformation. It is clear that hardening effect is pronounced for flexible LRB bearings with small yield force ratio. This is due to the high deformation experienced for these bearings in which the lead plug yields at relatively low levels of force, and consequently, the geometric effect leads to significative hardening behaviour.

From **Fig. 10**, it is observed that maximum deck displacement response is slightly reduced with hardening, as a consequence of reduction of bearing deformation. The maximum deck displacement response is expected to follow a similar trend of reduction as the experienced by maximum bearing deformations when hardening is considered in the bearing analytical model. Therefore, suggesting that in case of neglecting the hardening effect, a significant underestimation of deck displacement could be obtained.

The clear reduction in the E_S/E_T ratio, presented in **Fig. 11**, indicates that, considering the hardening effect, the energy dissipation capacity of the LRB bearings is smaller, and consequently bridge structural elements are exposed to larger seismic vulnerability. However, it should be noted that isolation devices with adequate damping characteristics are capable of controlling their maximum bearing deformation within moderate ranges and consequently, the hardening effects of these LRB bearings on the bridge seismic response are expected to be not excessively significant.

6. CONCLUSIONS

Comparative nonlinear dynamic response analyses have been carried out to investigate the influence of several bearing design parameters on seismic response of a highway viaduct model supported on three different types of base isolation bearings. Based on the calculated results the following conclusions can be drawn.

(1) The seismic response of isolated highway viaducts is significantly influenced by variations in design parameters of isolation bearings. Therefore, the advantage of base isolation of substantially reducing the damage of bridges during earthquakes needs to be accomplishing with a complete understanding of the isolation device parameters.

(2) RB bearings are found to be incapable of reducing the inelastic behaviour of piers in case of large earthquakes. However, an improved seismic protection of viaducts isolated with RB bearings should consider the use of relatively stiff bearings provided with stoppers positioned at small distance values.

(3) LRB and EDF systems demonstrate a good efficiency to protect the bridge from the destructive effects of strong earthquakes. Considerable damage reduction in structural elements can be achieved by the hysteretic behaviour of these types of bearings. In addition, the large displacement response of the isolated bridge deck can be effectively reduced by selecting appropriate levels of additional damping provided by the yielding of the lead plug and the friction of the sliding plate in case of LRB and EDF systems, respectively. However, on the other hand, calculated results indicate that selection of unsuitable bearing characteristics, such as lead plug size, flexibility of rubber material and friction coefficient values may increase all bridge responses. The base isolation feature of reducing the forces acting on the substructure could be inverted when subjected to strong earthquakes, eliminating the advantages provided by the base isolation design.

(4) Hardening effect of LRB bearings tends to simultaneously increase the maximum bending moment at the base of bridge piers, reducing the maximum deck displacements. These variations are expected to be relatively small in case of moderate seismic loads. However, special attention should be paid to hardening of LRB bearings, since and excessive period shift could have a considerable effect on the increase of seismic structural response due to hardening, and their effects could significantly modify the overall seismic response of highway viaducts under large earthquake ground motions.

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