13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3332

EFFECT OF HARDENING OF LEAD-RUBBER BEARINGS ON NONLINEAR BEHAVIOUR OF HIGHWAY VIADUCTS UNDER GREAT EARTHQUAKES

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SUMMARY

Lead-rubber bearings of isolated highway viaducts, due to their inherent flexibility, can be subjected to large shear deformations in the event of great earthquake ground motions. According to experimental test results, lead-rubber bearings experience significant hardening behaviour beyond certain high shear strain levels due to geometric effect. The aim of this study is to analyze the effect of hardening of lead-rubber bearings, induced by strong near-field earthquakes, on the overall nonlinear seismic response of highway viaducts. For this purpose, the bilinear force-deformation model of the bearing supports is substituted by a trilinear analytical model introduced to accurately represent the influence of hardening at high strain regions. The calculated results of nonlinear dynamic analysis indicate that, neglecting the effects of hardening, the underestimation of seismic forces transmitted to the substructure may hide plastic ductility of piers for cases in which the demands are expected to be under elastic range. It is also observed that the influence of hardening on peak deck displacements depends on the input earthquake characteristics as well as on the damping provided by the isolator devices. Therefore, careful attention should be paid to hardening of lead-rubber bearings, especially in case of bridges of unusual size or geometry, since its effects can substantially modify the overall structural response of highway viaducts in case of extreme earthquake ground motions.

INTRODUCTION

Lead-rubber bearing (LRB) is one of the most commonly used base isolation system which has found wide application in design of new highway bridges as well as for retrofitting of existing structures. This type of isolation bearing protects the bridge from earthquake ground motions increasing the structure fundamental period beyond the energy-containing periods of earthquakes and by dissipation of seismic energy through additional hysteretic damping by yielding of the lead plug. In addition, this lead plug(s) inserted in the bearing provides rigidity against minor earthquakes, wind and service loads. Bridges are ideal candidates for the adoption of base isolation technology due to the facility of installation, inspection and maintenance of isolation devices, which are proven to perform effectively reducing bridge seismic responses during earthquake shaking, as reported by Bessason and Haflidason [1]. However, the adoption of LRB isolation

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bearings may create certain disadvantages due to the increased flexibility introduced at bearing level. Excessively large deck displacement response in the event of strong earthquakes can result in collision between adjacent decks or decks and abutments (Malhotra [2]). On the other hand, the necessary adoption of non-standard expansion joints to accommodate large seismic deck superstructure movements at the abutment level in continuous bridges may lead to vibration, noise and maintenance problems to the bridge.

Several experimental dynamic tests for identification of the mechanical characteristics of LRB bearings have shown that these bearings exhibit significant hardening behaviour beyond certain shear strain levels (Sato et al. [3], Morishita et al. [4], HITEC [5]). This hardening phenomenon, attributed to rubber material properties and originated mainly due to geometric causes, sensibly modifies the response of the isolators in the large shear strain region. Subsequently, it is expected that the global seismic bridge response could be affected in case of large earthquakes. Especially, the action of near-field ground motions, characterized by strong long period velocity and displacement pulses, could cause large deformations in LRB bearings. Therefore, maximum displacements of the deck superstructure would be expected to be positively reduced due to the natural restraint in the isolator deformation from stiffening of rubber at large shear strains.

In this study, in order to improve the seismic performance of highway viaducts under great earthquakes, the effects of LRB bearing hardening have been considered to evaluate its influence on the overall behaviour of seismically isolated viaducts. For this purpose, the bilinear analytical force-deformation hysteretic model of the bearing supports is substituted by a trilinear nonlinear element, introduced to accurately represent the influence of hardening at high bearing deformation regions.

ANALYTICAL MODEL OF HIGHWAY VIADUCT

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 equal spans of 40 m, as shown schematically in Figure 1. The deck superstructure is modeled using linear elastic elements with properties based on the composite action between the concrete slab and the steel girders. The deck weight is supported on four hollow box section steel piers of 20 m height designed according to the seismic design code in Japan (JRA [6]) and modeled using fiber elements. Cross section characteristics of structural elements have been selected to obtain good approximation to the real behaviour of the isolated structure, ensuring near equal distribution of seismic lateral forces to the various substructure units.

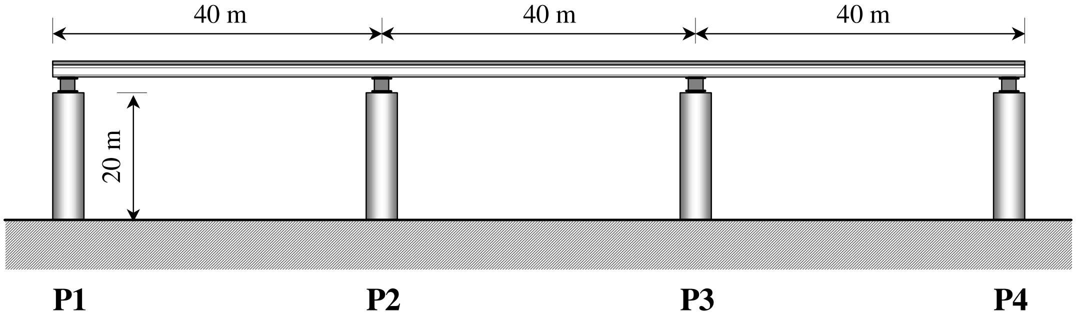


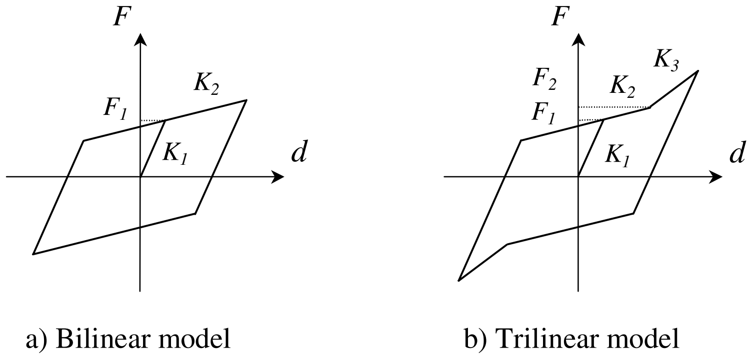
Figure 1. Model of three-span continuous highway viaduct

Lead-rubber bearing supports

The viaduct is isolated with LRB bearings installed at top of the steel piers. The isolation bearing behaviour is characterized by a high initial stiffness provided by the lead plug to avoid undesirable displacements under service requirements, wind action and low seismic loads. The shear stiffness decreases for moderate levels of deformation, allowing the isolator to uncouple the bridge from the damaging action of earthquake ground motions. For high shear strains, like those induced by near-field earthquakes, experimental tests carried out by Morishita [4] in order to characterize the mechanical properties of LRB bearings have shown a significant hardening behaviour due to geometrical effects.

LRB bearings have been represented using a number of analytical models, from the simplicity of the equivalent linear model composed of the effective stiffness and equivalent damping ratio formulated by Hwang et al. [7] to the sophisticated finite element formulation developed by Salomon et al. [8]. However, the most extensively adopted model for dynamic analysis of base isolated structures is the bilinear idealization for the force-displacement hysteretic loop (Ali et al. [9]). This model has demonstrated to provide an accurate prediction of the isolator behaviour under service conditions and low-to-moderate earthquake ground motions. Nevertheless, for the large shear strain range induced by near-field earthquakes the bilinear model becomes less reliable and unable to efficiently capture the stiffening behaviour exhibited by the isolators.

Two different analytical models for the bearings, presented in Figure 2, are used for nonlinear dynamic analysis in this study. In addition to the traditional bilinear model, a trilinear hysteretic analytical model has been introduced. This trilinear model is capable of accurately capture the large strain hardening behaviour and, due to its simplicity, enables an easy implementation with efficient use of computational effort. The pre-yield to post-yield stiffness ratio is kept constant at 10.0. The pre-yield stiffness (K_1) of the lead plug is fixed to 58.8 MN/m while the post-yield stiffness (K_2), corresponding to the shear stiffness of the rubber, is 5.9 MN/m. The lead plug yield force (F_1) has been considered a parameter of study related to the size of the lead plug. By varying the size of the lead plug or equivalently modifying the ratio of bearing yield force to the superstructure weight (F_1/W), from 0% (the case without plug) to 24% by intervals of 2%, a total of 13 different LRB bearings have been considered. K_3 and F_2 represent the hardening parameters, which are fitted to the test data carried out using shaking tables in the typical range that is reported for elastomeric bearing characteristics in literature (Sato et al. [3], HITEC [5]). Characteristics of LRB bearings for central and lateral piers have been calculated to enhance the force-distribution advantages of seismic isolation, overcoming the differences in dead load applied from the superstructure to the piers.



a) Bilinear model b) Trilinear model

Figure 2. Nonlinear analytical models of LRB bearings

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 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 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%.

The nonlinear highway viaduct model is subjected to the action of eight different near-field earthquake ground motions summarized in Table 1. These input waves are characterized by the presence of high peak accelerations and strong velocity pulses with a long period component as well as large ground displacements (Erdik and Durukal. [10]). They have been selected due to the destructive potential of long duration pulses on flexible structures equipped with isolation systems that can lead to a large isolator displacement, as investigated by Jangid and Kelly [11].

Table 1. Input earthquake ground motions

	PGA* [gal]	PGV* [kine]	PGD* [cm]	Fund. Period [sec]
25 April 1992 Cape Mendocino (Cape Mendocino)	1466.1	129.11	59.07	0.282
13 March 1992 Erzincan (Erzincan Station)	433.0	92.48	24.95	2.048
17 January 1995 Kobe (JMA)	816.5	92.02	234.51	0.688
18 October 1989 Lomaprieta (Los Gatos)	558.6	98.82	37.89	0.640
25 April 1992 Cape Mendocino (Petrolia)	648.4	90.89	26.75	0.811
17 January 1994 Northridge (Rinaldi Station)	824.2	172.58	48.74	1.365
17 January 1994 Northridge (Sylmar Station)	825.5	128.78	30.63	1.575
17 January 1995 Kobe (JR Takatori)	706.6	139.59	37.65	1.201

(* PGA: Peak Ground Acceleration; PGV: Peak Ground Velocity; PGD: Peak Ground Displacement)

CALCULATED RESULTS AND DISCUSSION

Natural vibration analysis

The accuracy of the fundamental natural period of a base isolator plays an important role in predicting the maximum seismic responses of a base isolated bridge. The fundamental natural period of the viaduct is calculated by using the effective stiffness (K_{eff}) of the LRB bearings based on Equation (1) and the iteration procedure shown in Figure 3,

$$K_{eff} = \frac{F_{\max} - F_{\min}}{d_{\max} - d_{\min}} \qquad (1)$$

where F_{max} and F_{min} are the maximum and minimum shear forces corresponding to the positive and negative design displacements d_{max} and d_{min}, respectively.

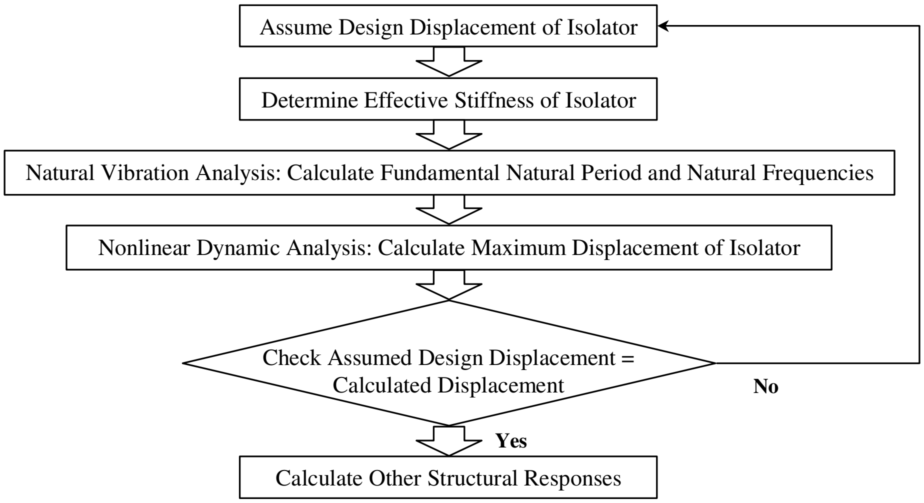


Figure 3. Iteration procedure for calculation of fundamental natural period

According to recommendations of Specifications for Highway Bridges in Japan (JRA [6]), the pre-yield to post-yield stiffness ratio (K_1/K_2) of the LRB bearings is preselected to obtain moderate period shift. Characteristics of isolation bearing devices are selected to obtain periods slightly larger than twice the natural period of the bridge when no isolation is applied (0.59 seconds). 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 the size of the lead plug inserted in the isolation bearings. Depending on the yield force level of the lead plug of the isolators, the fundamental natural period varies in the interval 0.84-1.37 seconds. Low values of period indicate that the size of the lead plug is excessively large and the viaduct is not able to shift its fundamental natural period into ranges that exceed those of the input ground motions. On the other hand, the moderate period shift obtained for the other values allows for reflecting a major portion of the earthquake energy, limiting the increased displacements experienced by the bridge deck during strong earthquake ground motions. It may be also noticed that the fundamental period is calculated using the bilinear analytical model, being supposed that its variation with hardening effect is relatively small.

Nonlinear dynamic response

Nonlinear analyses for the viaduct model, designed either accounting for hardening or neglecting it, have been carried out under the same input earthquake ground motions. For a comprehensive comparison of the nonlinear response of the isolated bridge, calculated results are presented firstly at bearing support level where the hardening phenomenon takes place, and secondly at deck superstructure and piers to evaluate the effect of hardening on important structural elements of the highway viaduct.

Maximum response of bearing supports

The effect of hardening on peak bearing responses is shown in Figure 4. Envelopes of absolute maximum shear forces and displacements for the LRB bearings indicate that generally hardening tends to simultaneously increase the maximum forces acting on the isolation bearings reducing the peak bearing deformation. Quantification for these variations depends on the size of the lead plug inserted in the bearings, as well as on the input earthquake ground motion. It is clear that hardening effect is pronounced for 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 low force levels and, consequently, the geometric effect leads to significant hardening behaviour. The maximum bearing responses show great differences for the different seismic records. For example, the effect of hardening is small in case of Lomaprieta input because peak accelerations of the earthquake ground motion corresponds to low periods (0.64 sec) which are out of the range of the natural periods of the viaduct. However, it is noted that in case of Takatori input wave (1.20 sec), bearing supports with small lead plugs are subjected to extreme levels of deformations because the natural period of the base isolated bridge coincides with major dominant periods of the ground motion.

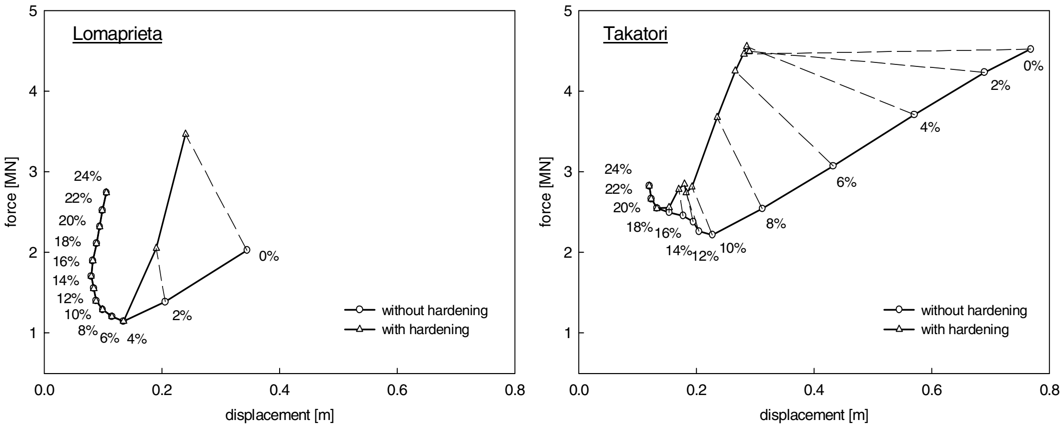


Figure 4. Envelopes of absolute maximum bearing responses

Maximum response of piers and deck superstructure

It is well-known that bending moment at the base of bridge piers is considered to be a good estimation of seismic structural damage, while maximum deck displacement is an important response factor related to the possibility of damage due to collision between deck and abutments and crucial from the design point of view of expansion joints at the abutments in continuous bridges. In Figure 5, the calculated results are presented as a function of the viaduct fundamental natural period, which is modified by the different effective stiffness values of isolation bearings obtained by variation of the lead plug sizes. The vertical axis at left gives the values of the ratio of absolute maximum bending moment to the yield moment at pier bottoms (M/M_y), while absolute maximum deck displacements are also given in the figure with the values to be read in the right vertical scale.

The bridge responses indicate, as expected, that pier ductility demands are increased with hardening as a consequence of increase in reaction forces acting on the bearings. It is also observed a noticeable trend to amplify the maximum bending moment at the piers with the natural period of the viaduct because the effect of hardening is larger in case of flexible bearings. An important remarkable point is that the base isolation feature of reducing forces acting on the substructure with the increase of the isolation period could be inverted when hardening effect is considered. Moreover, for Rinaldi and Takatori cases, plastic ductility of piers is found when the demands without considering the hardening are expected to be under elastic range. It indicates that an excessive period shift could have a considerable effect on the increase of seismic structural responses due to hardening effect.

The maximum deck displacement response is expected to follow a similar trend of reduction as the experienced by maximum bearing deformations. However, considerable differences in seismic response, depending on the input ground motions, are observed. A contradictory phenomenon is particularly observed in some cases (Kobe and Lomaprieta) and minimum reduction or even higher maximum displacements with hardening are appreciated. The reason is that, even the bearing shear deformation is considerably reduced by hardening effect, pier top displacements become larger and consequently, deck displacements may increase or decrease depending on the counterbalance between both contributions, top

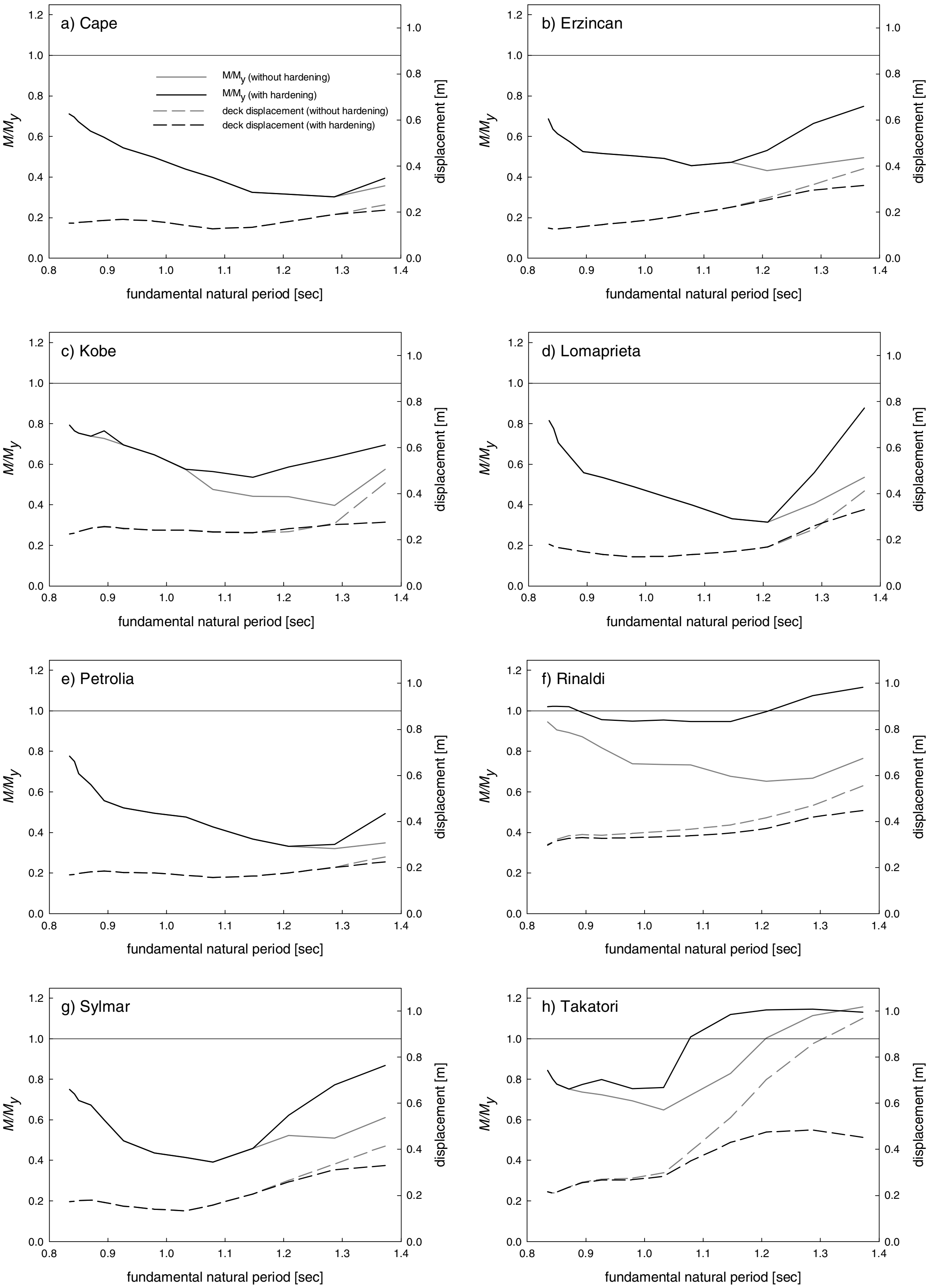


Figure 5. Piers and deck absolute maximum responses

pier displacements and bearing deformations, to the total deck displacement. Thus suggesting that in case of neglecting hardening, the maximum deck displacement is greatly affected by deformation of bearings, while in cases considering hardening the contribution to deck displacements from the pier top response is significant. For Takatori record, the LRB bearings are subjected to larger deformations as a result of the particular nature of this motion. Therefore, ignoring the effect of hardening, the peak deck displacements are sensibly overestimated because, even hardening increases the displacements at piers substantial reduction in terms of peak bearing deformation results in smaller maximum total deck displacement.

Energy dissipation of LRB bearing supports

The nonlinear seismic response of the viaduct is also calculated on the basis of the equilibrium of energy. In Figure 6, the ratio of strain energy to the total input earthquake energy (E_S/E_T) is represented. Selection of the optimal characteristics for the LRB isolation bearings can be clarified by comparing the calculated results in terms of energetic quantities. The peak of strain energy ratio indicates a maximum of energy dissipation capacity of the LRB bearing supports, and a greater effectiveness of the isolator could be obtained for these values depending on the input earthquake wave. The appropriate value for the yield force of the bearing is dependent upon the characteristics of the earthquake ground motions, varying in the interval F_1/W=6.0-10.0% for all cases. These values agree with the previous results that indicate similar yield force levels to achieve a good balance between of maximum bending moment transmitted to the piers and maximum displacements at deck superstructure. It can be also observed in the figure that the energy dissipation capacity of LRB bearings is only slightly modified by hardening effects. The seismic energy dissipated at bearing level decreases due to reductions in the area of the hysteretic loops when hardening is taken into account.

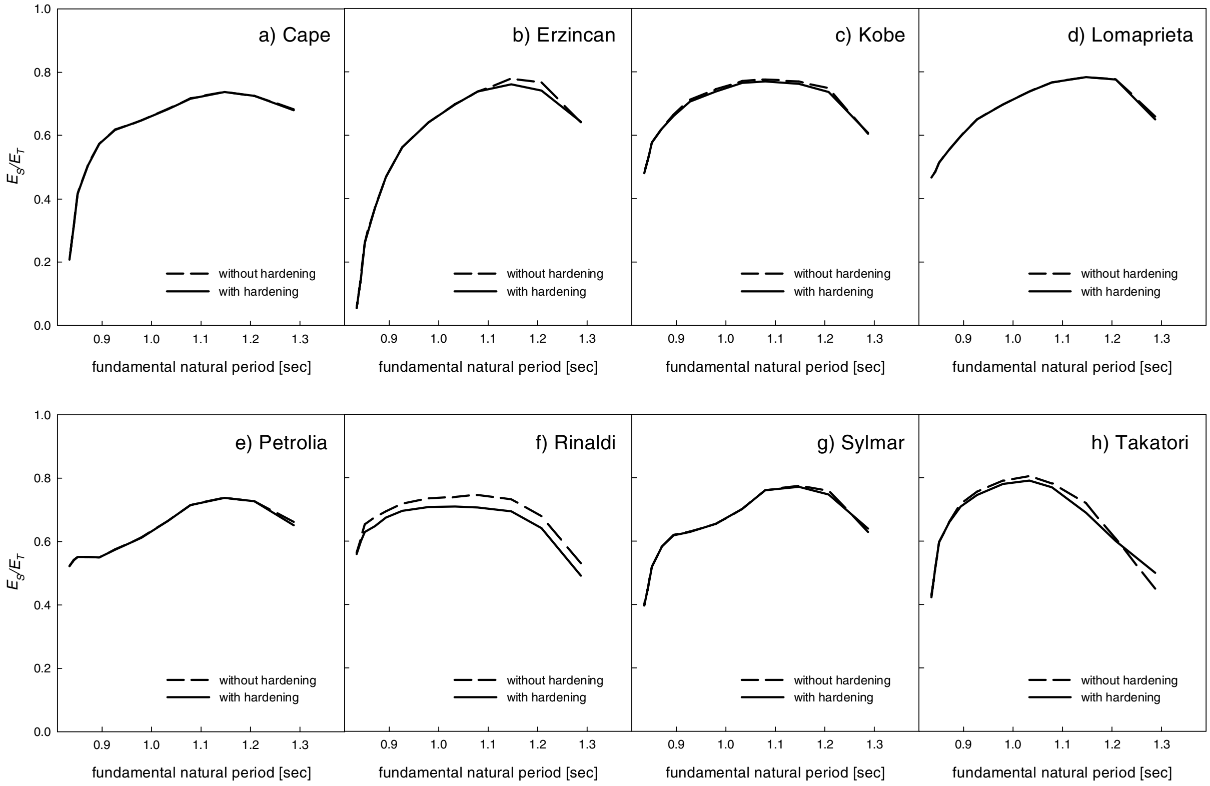
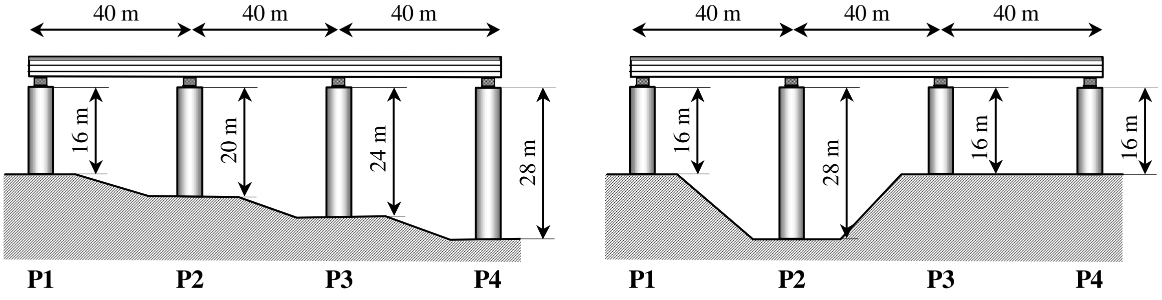


Figure 6. Energy dissipation ratio at bearing supports

HIGHWAY VIADUCTS WITH PIERS OF UNEQUAL HEIGHTS

The effects of nonuniform distribution of masses and stiffnesses along highway viaducts supported on piers of unequal heights may result in complicated seismic behaviour. The installation of LRB bearing supports is generally positive since the inherent isolator flexibility can be used to distribute the seismic loads to all substructures, achieving an uniform force distribution. Moreover, it becomes possible to direct loads to specified piers by changing the characteristics of the base isolation bearings, indicating the substructure units to have minimal seismic forces. The advantage of base isolation of distributing the seismic lateral forces to the substructure in a way that benefits the global design is sensibly complicated in case of irregular bridges because one or more piers will attract significantly larger lateral inertia force from the superstructure. Especially, in the event of strong earthquakes, elastomeric bearings can work in the high strain zone where hardening effect takes place. Therefore, it would be expected that bearing stiffening could have more important effect on highway viaducts with different pier heights than in regular structures.

Due to limitations of numerical simulations it is not possible to consider a large number of bridge models including a wide range of variation in pier heights. Therefore, the influence of unbalanced distribution of seismic loads due to hardening effect on the seismic response of isolated bridges is investigated using two representative models selected having common geometry with the exception of the substructure, as shown in Figure 7. In Model 1 the irregularity of the bridge is introduced by gradually increasing the pier heights, while Model 2 represents a typical case of bridge with great contrast of height between adjacent piers.



(a) Model 1 (b) Model 2

Figure 7. Models of highway viaducts with piers of unequal heights

In order to quantify the effects of hardening of LRB bearings, the calculated peak responses of models with hardening are compared with those of corresponding bridges ignoring these effects. Eight LRB bearings with different size of lead plugs, from F_l/W=2.5% (case a) to F_l/W=20.0% (case h), modeled with bilinear and trilinear analytical models, are used parametrically. A careful adjustment of bearing stiffness to select properties of the LRB bearings according to the pier height and the differences in dead load supported from the superstructure. The aim is to attract the appropriate proportion of seismic loads according to the resistance capacity of each substructure, ensuring fully elastic behaviour and a near equal distribution of ductility demands over all piers.

To evaluate the effects of LRB bearing hardening on the seismic performance of the multi-span continuous bridges, the nonlinear models are subjected to the action of two seismic ground motions. Standard Earthquake Wave (SEW)-Ground Type I and SEW-Ground Type II horizontal component accelerations, represented in Figure 8, are modified from direct-inland-strike type earthquake records from the 1995 Hyogoken-Nanbu (Kobe) earthquake, and they have been selected according to their destructive energy content and the suitability of ground types I and II for base isolation design. These input earthquakes have been scaled in accelerations, multiplying by a factor *a*, to clearly appreciate the effects of hardening in the high strain levels.

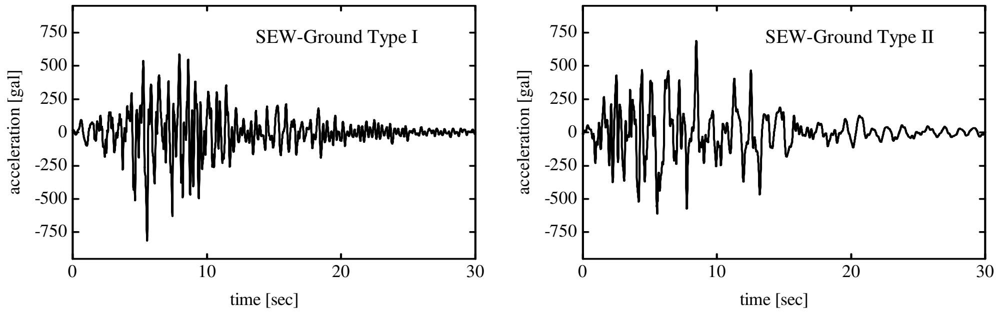
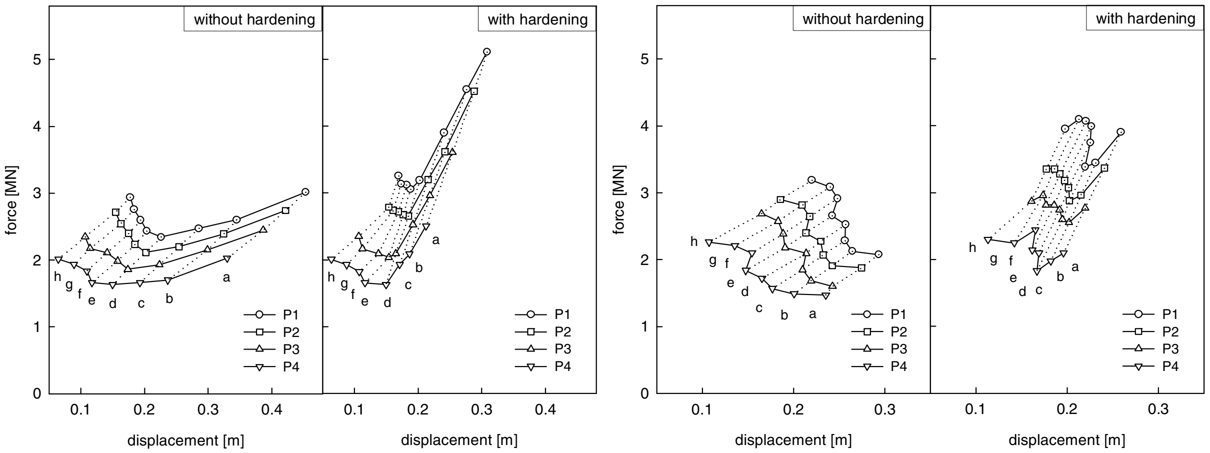


Figure 8. Input earthquake ground motions

The peak bearing responses, presented in Figure 9, indicate great differences for the two seismic input waves. The effect of hardening is small in case of SEW-Ground Type I, and it has been necessary to amplify the original input accelerations by a factor *a*=3.0 to clearly appreciate the hardening behaviour of the LRB bearings. This is because peak accelerations of the earthquake ground motion correspond to low periods (0.73 sec), which are out of the range of the natural periods of the viaducts (0.94-1.40 sec in case of Model 1, and 0.78-1.31 sec for Model 2). It is also observed in this figure the difference in seismic force distribution for the isolation bearing supports depending on the pier height. Seismic forces are gradually reduced as the pier height is increased. This fact results firstly from the natural tendency of superstructure inertia forces to be attracted by the stiffer substructure elements, like short piers. Secondly, it has been enhanced by selection of different properties of the LRB bearings with the aim of protecting the tall piers, especially vulnerable to seismic loading due to the significant amplification of bending moment response at the pier bottoms with the increase of pier height.

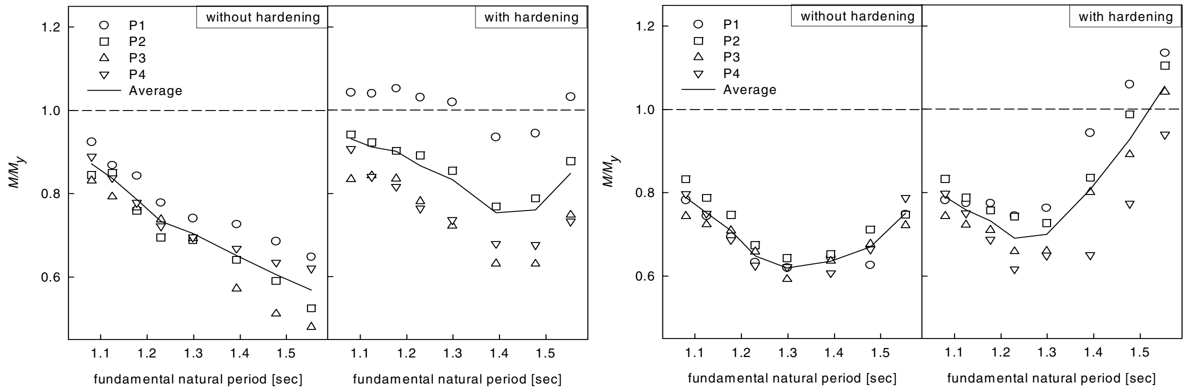


a) Model 1 under SEW-Ground Type I (*a*=3.0)

b) Model 1 under SEW-Ground Type II (*a*=1.0)

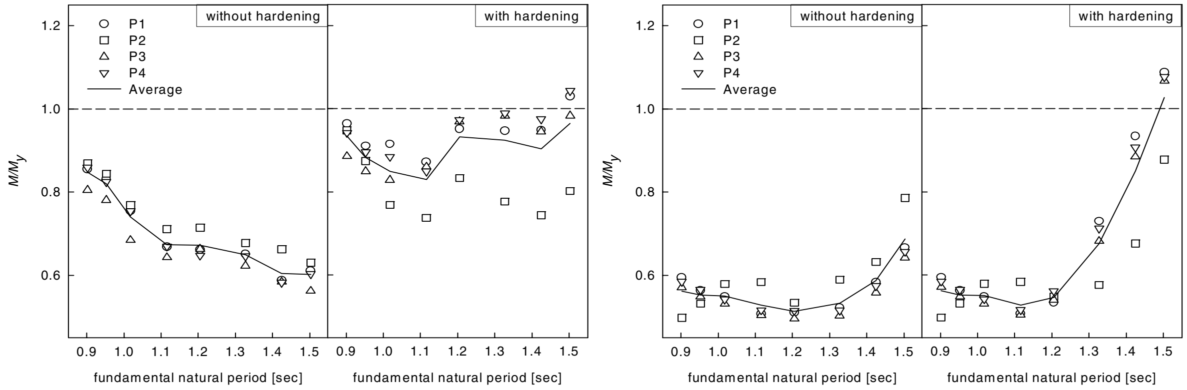
Figure 9. Envelopes of maximum bearing responses

One of the differences between conventional and base isolation design is that in isolated bridges the lateral load distribution is a function of the force-deformation characteristics of the isolators. Therefore, in the original design strategy, when hardening is ignored, the loads are distributed in a reasonably uniform way to all substructures. As it is observed in Figure 10, the ductility demands for all piers remain fully elastic and approach a constant, since the bearings are sized such that the force transmitted into the piers at maximum displacement would not exceed the moment capacity of the piers. This balance of pier ductility, relatively complicated to obtain in case of these types of irregular bridges, is broken when hardening is considered. It is clearly observed that the hardening effect results in a new redistribution of forces, and higher transmitted forces are concentrated on short piers while lower are resisted at tall piers. Maximum differences of bending moment ratio for the piers are over 50% in several cases, while for models designed neglecting the hardening effect the maximum differences are less than 10 % for all cases. In case of Model 1, it is observed that moment ratio is higher than average values for P2 and especially for P1, the shortest pier. For Model 2, the most remarkable fact is the lower than the average maximum bending moment acting on P2, the tallest pier, because LRB bearings of tall piers do not attract as much force as the other bearings since most of the deck displacement is absorbed by the pier. Consequently, bearings of short piers are subjected to large deformations resulting in important large reaction forces due to hardening. Ignoring the hardening effect, maximum response of tall piers is overestimated, and more important, it is noted that short piers are in a critical situation for what concerns the ductility demands. The short piers do in fact take up more shear forces than expected, being possible that the ductility of the short piers increases beyond their capacity.



a) Model 1 under SEW-Ground Type I (a=3.0)

b) Model 1 under SEW-Ground Type II (*a*=1.0)

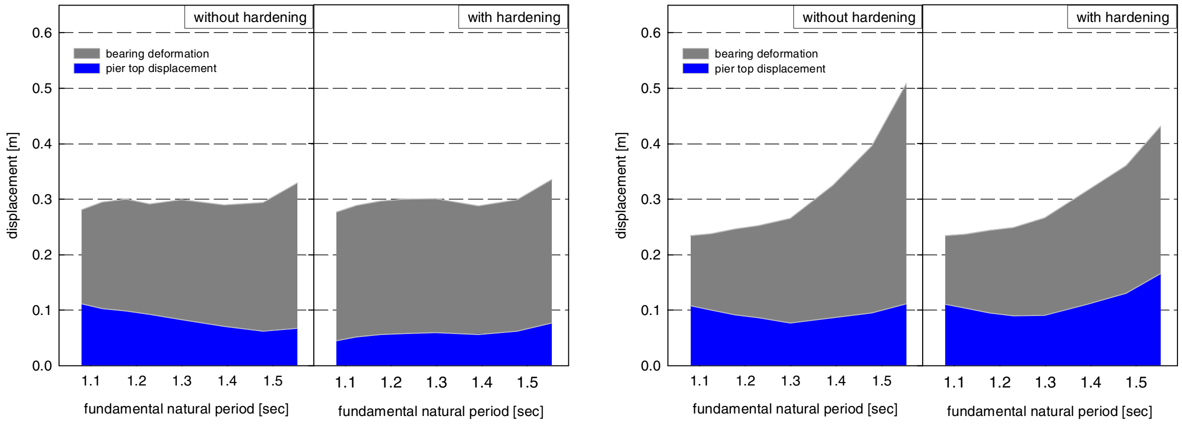


c) Model 2 under SEW-Ground Type I (*a*=3.0)

d) Model 2 under SEW-Ground Type II (*a*=1.0)

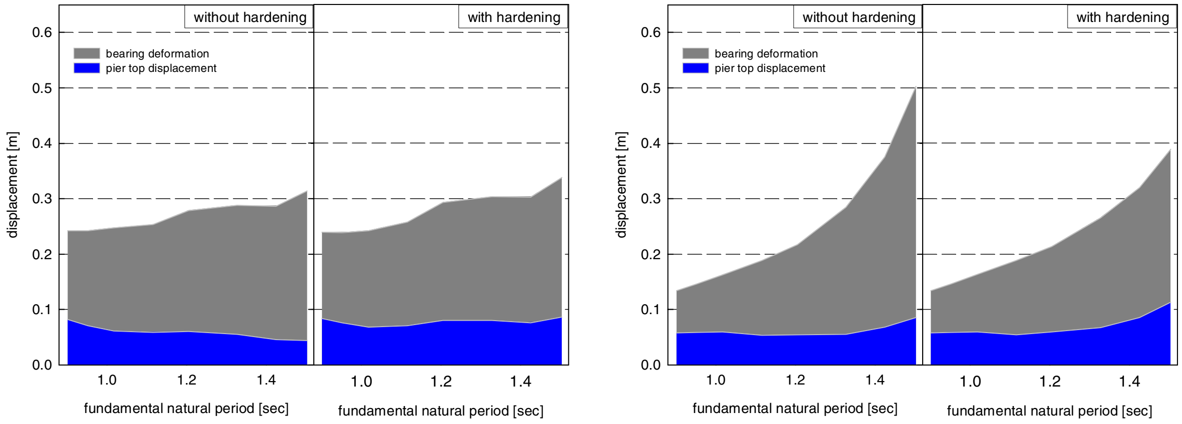
Figure 10. Ratio of absolute maximum bending moment response at base of piers

Figure 11 compares the hardening effect of LRB bearings on the absolute maximum deck displacements. In this figure, deck displacements are presented as the contribution of movement of the pier tops plus the shear deformation of the isolation bearing supports. It can be noticed that hardening effect on deck displacements is small for SEW-Ground Type I (*a*=3.0). Maximum deck displacements with hardening are slightly higher than those without hardening because, even the bearing deformation is considerably reduced, the contribution to total deck displacements by pier top displacements is larger. For SEW-Ground Type II, the LRB bearings are subjected to larger deformations as a result of the larger energy content of this motion. Therefore, the reduction in maximum bearing deformation is more important than in case of SEW-Ground Type I. Ignoring the effect of hardening, the absolute maximum deck displacement is overestimated because, significant reduction in terms of peak bearing deformation results in smaller maximum total deck displacement, as it is explained in the previous section. It should be noted that both viaduct models analyzed in this study are bridges with tall piers. Although these bridges may attract smaller spectral accelerations due to their long fundamental periods, displacements at the piers location and deck superstructure are very large. Therefore, the difficult decision on the adoption of base isolation techniques for this type of irregular structures should be carefully analyzed. Application of partial base isolation with limited period shift, a design procedure known as Menshin Design in Japan, could be considered a satisfactory and adequate alternative in order to obtain reduced deck displacement response.



a) Model 1 under SEW-Ground Type I (*a*=3.0)

b) Model 1 under SEW-Ground Type II (*a*=1.0)



c) Model 2 under SEW-Ground Type I (*a*=3.0)

d) Model 2 under SEW-Ground Type II (*a*=1.0)

Figure 11. Absolute maximum displacement response of deck superstructure

CONCLUSIONS

The effects of hardening of lead-rubber bearings at high shear deformation levels on the overall seismic response of highway viaducts are examined in this study through nonlinear finite element dynamic response analysis.

The calculated results indicate that, neglecting the hardening effect, the underestimation of seismic forces transmitted to the substructure may hide plastic ductility of piers for cases in which the demands are expected to be under elastic range. In addition, the results also demonstrate that, under the excitation of large earthquakes, the effect of hardening would modify substantially the distribution of seismic forces to each substructure. The equilibrium of piers ductility, significantly unstable especially for highway viaducts with piers of unequal heights, is broken. Hardening produces a new redistribution of forces and larger forces tend to concentrate on short piers while lower forces are resisted at tall piers. Therefore, ignoring the hardening effect, maximum bending moment response of tall piers is overestimated and, on the other hand, the short piers do in fact take up more shear forces than expected, being possible that the ductility of the short piers increases beyond their capacity.

It is also concluded that, even peak bearing deformations tend to decrease with the effect of hardening, reductions in maximum displacements of the deck are relatively small. Moreover, for several earthquake ground motions, deck displacement response does not follow the expected trend of reduction and values are slightly larger because of the contribution of increased displacements of pier tops due to higher transmitted reaction forces. Consequently, deck displacements may have both possibilities of increasing or decreasing with hardening depending on the counterbalance between the contributions of top pier displacements and bearing deformations to the total deck displacement response.

The hardening effect is obviously of special relevance from the point of view of analytical modeling. The most important implication is that the bilinear model assumption is not acceptable in case of large earthquake excitations. The adoption of more accurate force-deformation analytical models for lead-rubber bearings is required, being the trilinear analytical idealization very efficient to represent the bearing behaviour without excessive computational cost.

The above considerations indicate that, under strong earthquakes, special attention should be paid to hardening of lead-rubber bearings, since their effects can significantly modify the overall structural seismic response of highway viaducts.

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