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DUCTILITY DEMANDS OF BASE ISOLATED BRIDGES IN MEXICO

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SUMMARY

Several highways have been built recently from the central part of the country to the cities located on the coast and long span bridges of various materials and structural shapes have been projected. Seismic isolation could have applicability in Mexico, especially on bridges located close to the Pacific Coast of Mexico. This paper describes the analytical study of the seismic response of typical structural systems of bridges used in Mexico, incorporating isolation devices. Dead and live loads are chosen according to the current bridge regulation code in Mexico. Initially, several two and three dimensional elastic bridge models were analyzed using a wide range of mechanical and geometrical parameters of isolators. The models were subjected to strong seismic motions recorded near to the subduction zone. Aditionally, two dimensional non-linear models were analyzed using DRAIN2DX program to determine ductility demands on the bridge models. Strength and stiffness characteristics of the structure and the isolation systems were of primary interest in the study. Special attention is devoted to limit states of behavior, considering mainly the strength and ductility demands of the substructure and isolation system Results show the beneficial effect of using isolation systems to reduce the seismic response on certain type of bridges located in areas near to the subduction faults in Mexico. Seismic response is clearly dependent on the type of substructure, superstructure and specially to the isolator parameters. The strength of the isolators was found close related to the maximum displacement of the system. Finally the paper gives some issues of further studies towards the proposal of design guides for bridges with isolators in Mexico.

INTRODUCTION

Mexico is located in a very high seismically area. Frequently strong earthquakes have origin on the subduction fault zone located at the boundary of the Pacific and North-American Plates. Dynamic characteristics of the seismic records near to the Pacific Coast of Mexico show high-energy contents of high frequencies, making attractive the use of isolation systems to reduce the seismic response of bridges in this region.

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Regardless of the large number of structures isolated in the world, in Mexico there is only one bridge recently built with base isolators. Two of the main impediments for the general use of these systems in Mexico are: the small number of analytical and experimental studies to create confidence in the engineering community and the lack of regulation codes with specific recommendation rules for the design of base isolated structures.

This paper describes an analytical study of the seismic response of bridges with base isolators subjected to earthquakes recorded on the Pacific Coast in Mexico. The study deals with two existent bridges located close to the coast and with a parametric study of bridge models with isolators.

DESCRIPTION OF THE BRIDGES

Base Isolation devices
Lead-rubber hysteretic bearings were used for the analytical studies. This isolator is manufactured of an elastomeric bearing with a lead plug core. It presents a very stable hyteretic rules and they can be represented by a bilinear model behavior (Robinson, 1982 [1] and Skinner et al, 1996 [2]). According to experimental results, the post-yielding stiffness is about 10% of the elastic stiffness and vertical stiffness is more than 300 times the shear stiffness. Several studies have recommended shear stiffness of the isolators about 1 or 2 times the total weight of the super-structure (W) and yield force of 0.05 to 0.10W (Blakeley et al, 1980 [3] and Einserberger and Rutenberg, 1986 [4]).

Motin del Oro bridge (MOB)
The bridge is located in the state of Michoacan, close to the Pacific Coast in México. It is 110 meter long and it was recently retrofitted with external presstressed cables. The superstructure of the bridge is a four-span continuous highway concrete bridge with single-cell box girder (fig 1). Piers and abutments are built of cast-in-place reinforced concrete. To fulfill the safety factors of the current code requirements related to the live loads and seismic activity of the region, the bridge was retrofitted and the original bearings were replaced by elastomeric bearings. This bridge was selected for its location, near to the earthquake epicenters of the strongest earthquakes of the country, and because there are several bridges in this region with similar structural configurations.

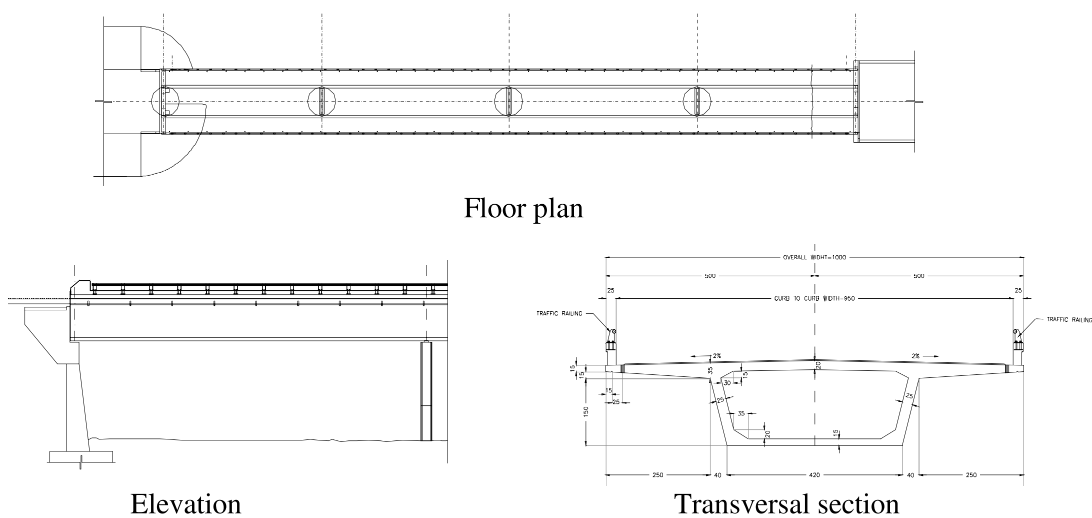
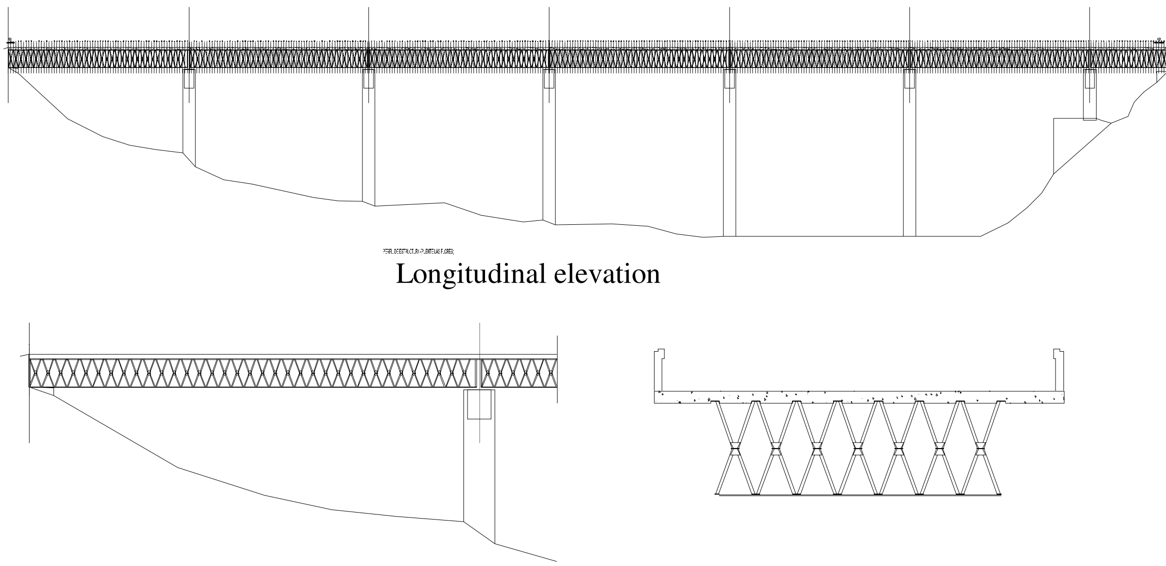


Fig 1. Motin de Oro II bridge

Las Flores bridge (LFB)
The second bridge selected is 231 meter long and it is located in a highway of the state of Chiapas. It is a seven-span 3D-steel truss bridge on tall concrete reinforced piers and abutments (fig 2). Recently, its safety was evaluated for gravitational and seismic loads specified on the current regulation codes. After this evaluation, the superestructure was replaced by two longitudinal steel beams and anchored to one of the abutments which was longitudinally restrained to the ground.



Longitudinal elevation

Elevation

Transversal section

Fig 2. Las Flores bridge

ANALYTICAL STUDIES

Structural models
The seismic response of the bridges was determined based on a 3-D time history analyses using the SAP2000 program (CSI, 2000 [5]). Elastic behavior is assumed for the elements of the bridge and non-linear behavior for isolators. The structural elements of the substructure and superstructure were modeled using frame elements and the deck using a mesh of finite elements. Biaxial-plasticity models were used for isolators. The bridges were subjected to three seismic signals recorded close to the Pacific Coast in Mexico. Two of them (UNION and CALES stations) correspond to the september, 1985 Michoacan Earthquake (Ms=8.1) and the last one (Manzanillo station) was recorded during the October, 1995 Manzanillo Earthquake (Ms=7.5). Figs. 3, 4 and 5 show the seismic records and their corresponding response spectra for 5% of critical damping.

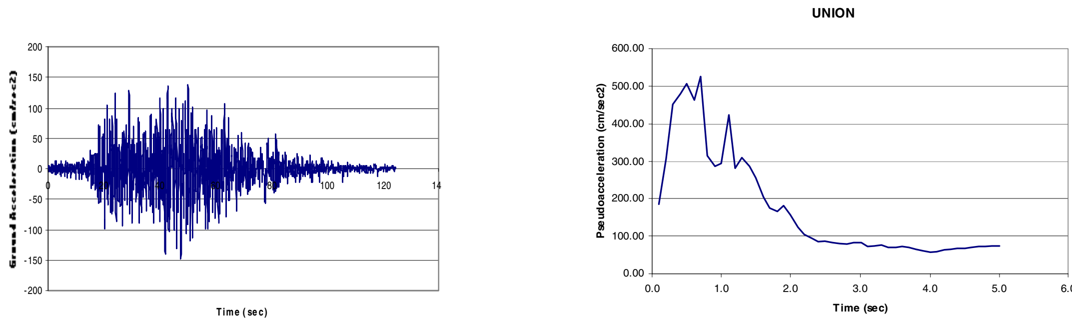


Fig 3. Seismic record and pseudoacceleration response spectra of the September, 1985 Michoacan Earthquake. UNION station

The strongest earthquake was recorded on the Manzanillo station, with a maximum ground acceleration of 400 cm/seg^2. Pseudo-acceleration response spectra shows a high response amplification for the period of 0.2 sec. and there is an important reduction of the energy content of the record for periods greater than 0.5 sec. UNION and CALES records have smaller maximum ground acceleration (close to 150 cm/seg2). As compare with the Manzanillo record, UNION and CALES records have a wider amplification range period of response, showing the highest values for periods smaller than 1.2 sec.

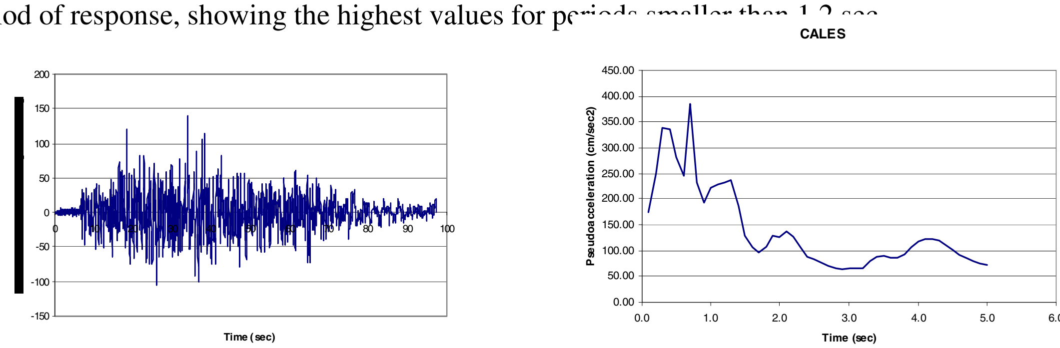


Fig 4. Seismic record and pseudoacceleration response spectra of the September, 1985 Michoacan Earthquake. CALES station

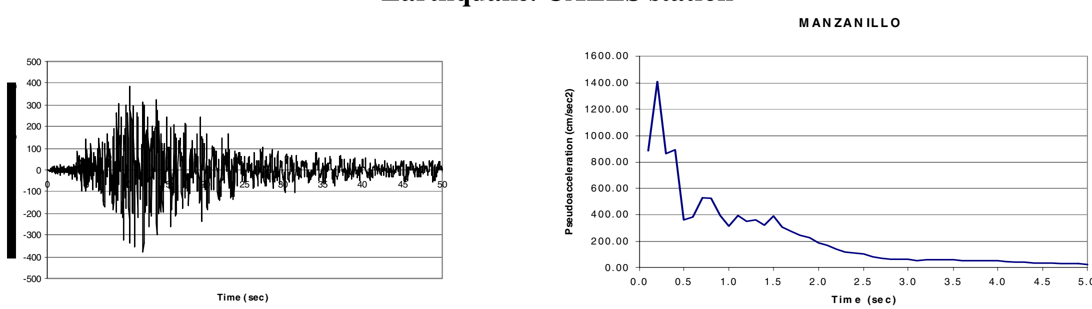


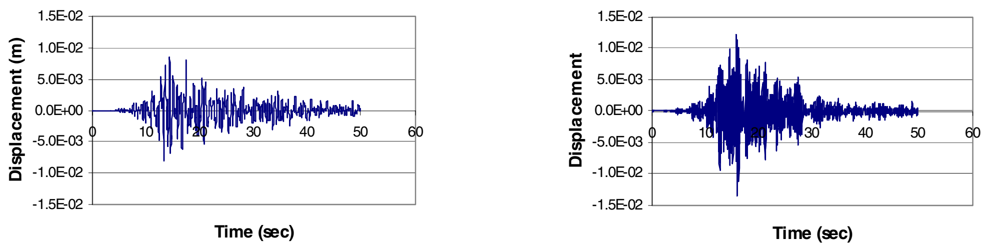
Fig 5. Seismic record and pseudoacceleration response spectra of the October, 1995 Manzanillo Earthquake. Manzanillo station

Seismic response of the bridges

Motin de Oro II bridge

The seismic performance of the bridge was determined for the original bridge structure and for several bridge models with isolation. Each model corresponds to different stiffness and strength characteristic values of the isolators. The bridge without isolators has the first transversal vibration period of 0.29 sec and the first longitudinal vibration period of 0.19 sec. Fig. 6 shows the displacement time history of the pier 2 with and without isolators, for the case when the isolators increase the fundamental period of the bridge three times and is subjected to the Manzanillo Record. Fig. 7 presents the corresponding time history of the shear forces. Maximum displacements of the bridge with or without isolators are not quite different but it is evident from the graphs the lengthening of the bridge period when isolators are incorporated. Shear forces in piers are strongly reduced (almost four times) in the isolated bridge showing the efficiency of the system.

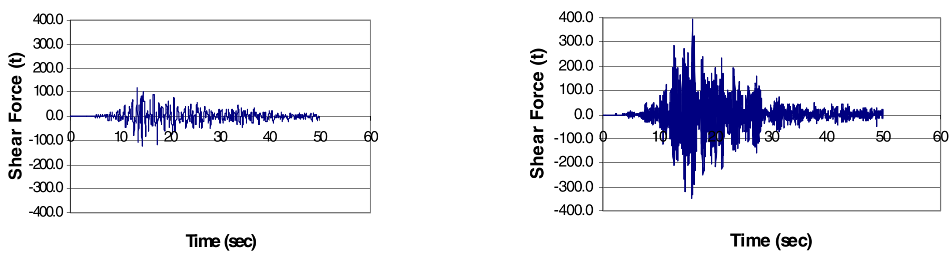
The hysteretic behavior of the isolator located on pier 2 is showed in fig. 8. Isolator remains most of the time history in the non-linear branch of behavior, having an important contribution on the energy dissipation of the bridge.



With isolators

Without isolators

Fig 6. Displacement time history in pier 2 subjected to the Manzanillo record



With isolators

Without isolators

Fig 7. Time history of base shear forces in pier 2 subjected to the Manzanillo record

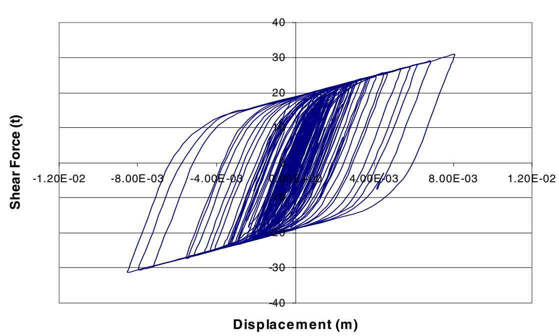
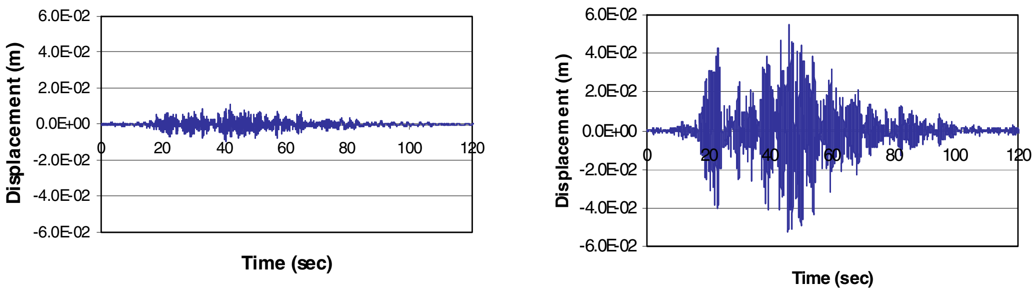


Fig 8. Hysteretic behavior of isolator on pier 2 subjected to the Manzanillo record

Las Flores bridge

The first period in transversal direction of this bridge is 0.66 sec, which locates it in zones of high amplification for the UNION and CALES response spectra and in the descendant curve of the Manzanillo response spectra. Nevertheless, because of the severity of the Manzanillo signal, its spectral pseudo-acceleration of this record, for this period, is similar to the Union record and greater than the CALES record.

A shown in fig 9, displacements of pier 4 are strongly reduced when we utilized isolators which increases three times the fundamental period of the bridge, allowing the pier to move with almost not amplification from the ground. The strength of the isolators were chosen to maximize the hysteretic energy dissipated and to guarantee the stability of the device, as well. This behavior can be explained based on the response spectrum of the UNION record and observing the isolator performance. The increase of the period moves the bridge to zones of minor responses and the wide hysteretic curves of the isolators produce additional damping in the structural system.

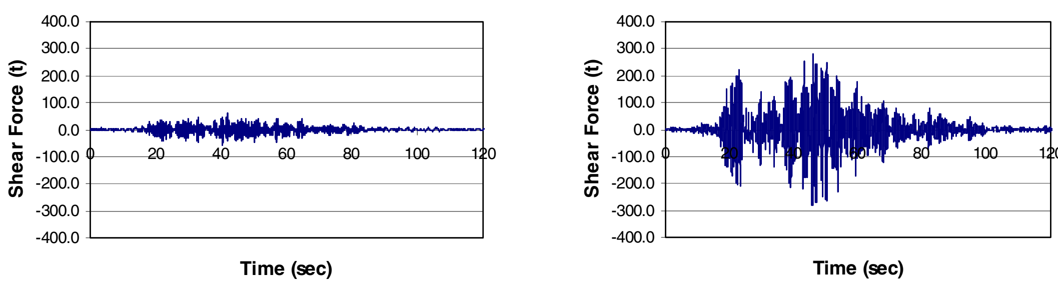


With isolators

Without isolators

Fig 9. Displacement time history of Pier 4. Las Flores Bridge, UNION record

Demands on base shear forces are far more reduced when the isolators are incorporated. As seen in fig 10, time history of shear forces in pier 4 show the uncoupled movement of the pier, related to the ground, for the isolated model, showing the favorable contribution of the isolators on the seismic response of the bridge.



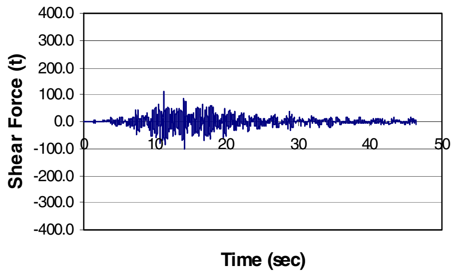
With isolators

Without isolators

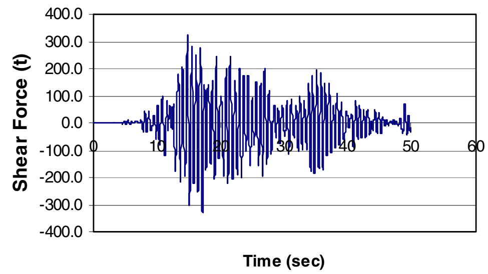
Fig 10. Time history of shear forces in pier 4. Las Flores Bridge, UNION record

Reflecting the shape of the response spectra of the earthquakes, the bridge displacement demands for the Manzanillo record show smaller reduction of displacements as compare with the one obtained with the UNION record.

Despite the different duration and energy content of the UNION and Manzanillo earthquakes, the maximum shear forces generated in pier 4 are similar (fig. 11). Again, for the isolated bridge model, Manzanillo record produces smaller response reductions than UNION record. Nevertheless, the forces in the pier of the isolated model are reduced as much as three times of the corresponding model without isolation.



With isolators



Without isolators

Fig 11. Time history of shear forces in pier 4. Las Flores Bridge, Manzanillo record

Parametric study

A parametric study was carried out to determine the possible inelastic behavior of the substructure of isolated bridge models subjected to the seismic records previously commented. There were selected 64 bridge models, varying some parameters related to the most common structural types of bridges in Mexico.

The total superstructure width of the bridges is 10 meters and they are between 25 and 40 meters long. Depending on the length, the superstructure was formed by steel girders or prestressed concrete beams and the material of the deck, in both cases, is reinforced concrete. Piers and abutments were also considered of reinforced concrete. One of the main parameters studied was the fundamental period of the models. We chose four periods for each bridge model, changing the height of the columns form 4 to 15 meters. Isolators were included between the substructure and the superstructure with the geometrical properties needed to increase from three to six times the fundamental period of the models. In the following paragraphs it will be commented some of the results obtained.

Seismic response of the models

The seismic response of the 40 meters long model is forthcoming presented. Table 1 shows the original fundamental periods of the non-isolated bridges for four different heights and the corresponding periods of the isolated models for three different lateral stiffness of isolators yielding to increase in 3, 4.5 and 6 times its fundamental period.

Table 1. Fundamental periods of the 40 meter long bridge models

Height (m)	$T_{\text{non-isolated bridge}}$ (seg)	$T_{\text{isolated bridge}}$ **(seg)**		
4	0.159	0.476	0.715	0.988
7	0.337	1.099	1.520	2.038
10	0.428	1.303	1.928	2.567
15	0.783	2.409	3.518	4.685

The following figures present the seismic response of the bridges as function of the fundamental period of each model. Graphs show displacements and shear forces in piers and isolators and the hysteretic behavior of isolators. Several yield strengths of the isolators were selected to determine the best behavior of the models, controlling the stability of the devices.

Figure 12 show base shear forces divided by gravitational weight (shear base coefficient) of one of the piers for the 4 and 7 meters high bridge models. In both cases, the maximum response obtained corresponds to the Manzanillo record, followed by the UNION record and finally the CALES record had the minimum demands.

Strongly response reductions are presented for isolated models subjected to the Manzanillo record. The less flexible model of isolator (which increase three times the period) reduce shear forces appreciably, but most important response decreases are attained increasing to 4.5 and 6 times the period of the non-isolated model. It is not found quite different behavior of the bridge, regarding to maximum responses, when one of the two more flexible isolator models is used.

CALES and UNION records increase shear forces demands for the first isolator used. It can be realized considering the response spectra of the records (figures 3 and 4) and the fundamental period of the bridge. Both response spectra have amplifications for periods close to one second. This is not the case of the 7 meters high model which does not present major shear forces due mainly to its isolated period.

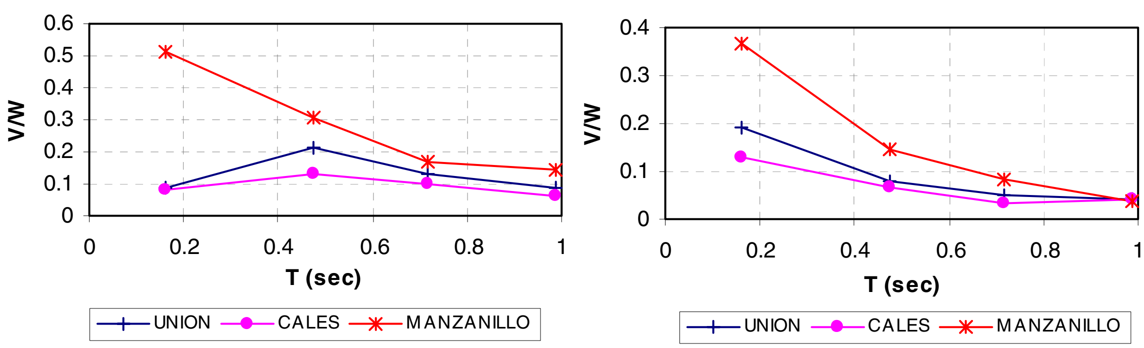


Fig 12. Shear base coefficient for bridge models of four meters high (left) and seven meters high (right)

Figure 13 presents shear responses of the two more flexible models (10 and 15 meter high piles). Demand reductions for the isolated model with period of 0.43 sec show the same trend of 7 meter high models. Again, the response drops for the three times period increment of the non-isolated model. The Manzanillo record generates maximum base shear coefficients slightly greater than 0.4W for the original model and is reduced to values close to 0.1W incorporating isolators. Nevertheless UNION and CALES records have smaller reductions for the isolated models, base shear forces are reduced to half of the maximum values of the non-isolated model when the stiffest isolator is incorporated.

For the most flexible models analyzed, the best behavior is achieved using isolators which increase three times the period of the bridge. More flexible isolators do not have important contribution to the response reductions of the bridge, showing the uselessness of the further increment of the bridge period.

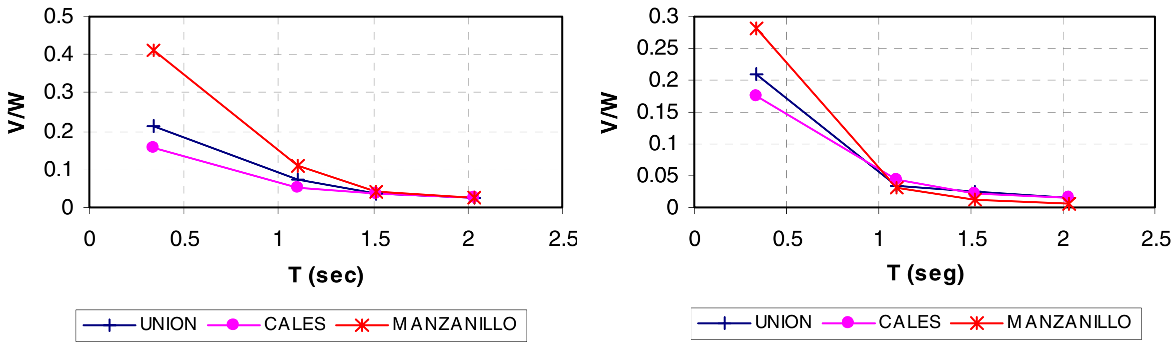


Fig 13. Shear base coefficient for bridge models of ten meters high (left) and fifteen meters high (right).

As seen in figures 14 and 15 and according to the foregoing behavior commented, the displacements of the less flexible models have increments when isolators are incorporated, mostly due to the frequency content of the UNION and CALES records. Using the second type of isolators (increasing 4.5 times the period of the system), the bridge displacements are reduced to values smaller than the corresponding to the non-isolated model when the structure is subjected to the Manzanillo record. This is not the case of the bridge behavior for the UNION and CALES records where displacements increase even with the incorporation of the more flexible isolator model.

However the similar curve trends, the bridge model with seven meter high piers, reduces displacements for all the cases studied when the period of the bridge is 4.5 times the original bridge period. Displacement demands for these models are far more greater than the demands of the more rigid model. It is also remarkable to observe the important response reduction of displacements in the range of period increment from 3 to 4.5.

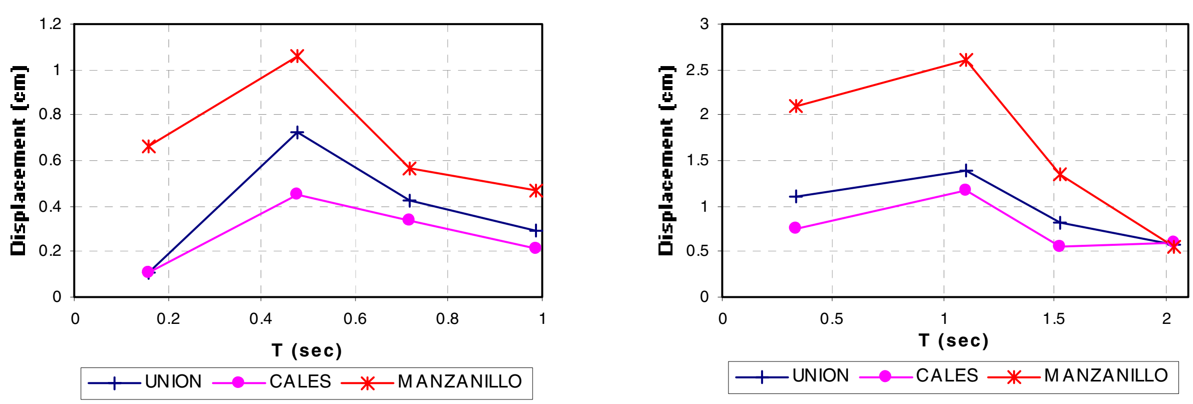


Fig 14. Displacements demands for bridge models of four meters high (left) and seven meters high (right).

Results for the ten and fifteen meters high models (fig 15) are quite different than the previous mentioned. The first model presents the most considerable response reductions when the period increment lies between 3 a 4.5 times the original period of the bridge. When the models are subjected to the Manzanillo record, the inclusion of isolators reduces the displacements, even in the case of the less flexible isolator model. There is not, however, a significant change on displacement demands when this isolator is incorporated on the bridges subjected to the UNION and CALES records. Closer results are found, with the three seismic excitations, in the response of the most flexible bridge model. There is a considerable change of behavior, as compared with the ten meters high model, particularly for the first period increment of the bridge.

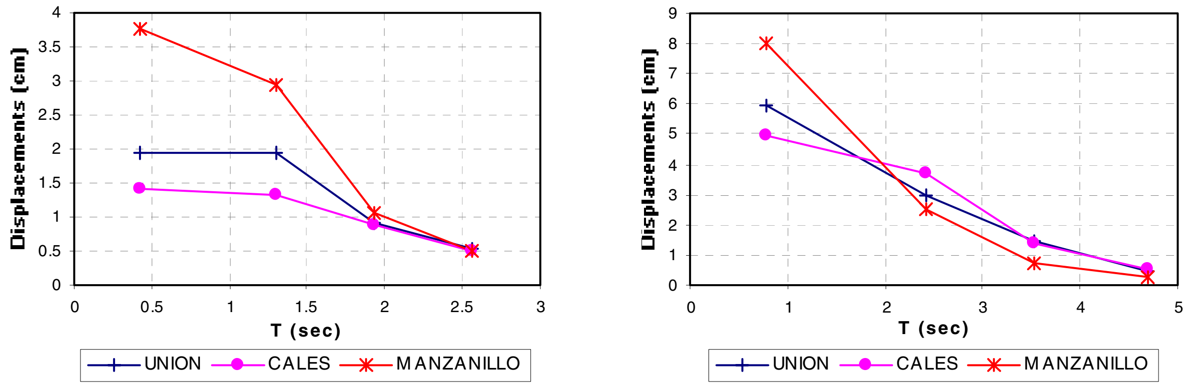


Fig 15. Displacements demands for bridge models of ten meters high (left) and fifteen meters high (right).

Typical hysteretic behavior of isolators is showed in figure 16. The figure in the left is the seismic response of the second isolator model incorporated on the short period bridge model and the figure in the right corresponds to the response of the first isolator model included on the more flexible bridge model. As expected, larger displacements are obtained in the latter model and both graphs illustrate substantial energy dissipation of the devices.

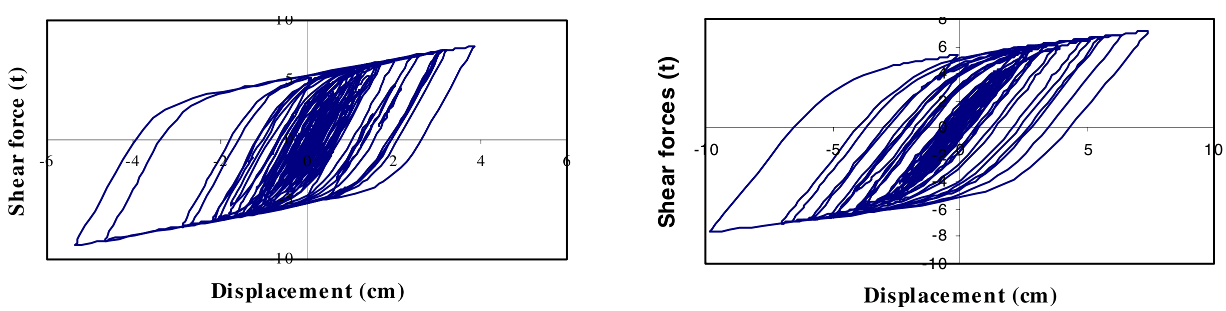


Fig 16. Typical hysteretic behavior of isolators.

Ductility demands

One of the most common hypothesis used to model isolated structures is to suppose elastic behavior of the structural elements and inelastic behavior of isolators. There are however, many factors related to the seismic performance of bridges that can not guarantee in advance the fulfillment of this hypothesis. In this part of the study it is used the parametric study to conduce an estimation of the ductility demands of the models when isolators are incorporated. The inelastic analyses were carried out using the program DRAIN2DX [6]. First of all, frame models were created for each of the four non-isolated models. The structural design of the bridge elements was accomplished using the design routines of the sap2000 program [5]. It was necessary to design the frame elements to obtain their yield surfaces for the inelastic analysis with the DRAIN2DX program [6].

Frame models preserve the dynamic properties of the tri-dimensional models in the direction of analysis, for the non-isolated and isolated models. Initially, all of them were subjected to the aforementioned three seismic excitations. DRAIN2DX program results give plastic rotation demands in the structural elements of the frame. There were processed all the parameter combinations and determined the elastic and inelastic substructure demands. In all cases studied, piers remain in the elastic branch of behavior.

In order to evaluate the possible subestructure inelastic behavior of the isolated bridges for strongest earthquakes, the seismic records were scaled to obtain, on the non-isolated bridges, ductility demands close to four. Then, isolated models were subjected to the scaled accelerograms and the seismic response determined. Several inelastic analyses were carried out and in neither case did we find inelastic behavior of the substructure of the isolated models of the bridges.

CONCLUSIONS

This paper shows the isolation systems as an attractive structural technique for improving the seismic performance of bridges located close to the Pacific Coast in Mexico. Three seismic signals originated in the subduction fault were used and two existent bridges with typical structural configuration were analyzed. Additionally, it was conducted a tri-dimensional parametric study varying in a wide range the main parameter values of strength and stiffness characteristics of isolators and bridge models. Finally, an inelastic frame analysis was achieved to determine the possible inelastic behavior of the substructure of isolated bridges.

The most significant response improvement was obtained when isolators increase the period of the bridge between three and four times. For the seismic records used, there was not found any advantage of increasing further the original period of the bridges.

Even for the strongest record utilized, the substructure of the models remains in the elastic range of behavior, showing that the hypothesis commonly employed for the analysis of isolated bridges is in general suitable. It must be considered that usually piers and abutments are traditionally structural elements well reinforced.

Some of the impediments to apply these systems on the structural conception of bridges in Mexico are related to the lack of design codes and the lack of cost-benefit studies. Analytical and experimental studies to fulfill this goal must be increased in the near future. The results we obtained were promising, encouraging us to pursue the studies directed to propose and implement regulations for isolated bridges in Mexico.

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