COMPARATIVE ANALYSIS OF SEISMIC ISOLATED SYSTEMS IN BRIDGES

APPLICATION TO A STUDY CASE

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Abstract

This paper represents the resume of a study where is evaluated the structural response of bridges with the application of different seismic isolation. The anti-seismic devices used are Viscous Dampers, High Damping Rubber Bearings (HDRB) and Lead Rubber Bearings (LRB).
A viaduct already built was chosen to be used as a prototype for analytical purposes. Linear analysis and non-linear analysis were used depending on the considered devices.
The results obtained in the structure without seismic isolation are compared with the results obtained in the structure with anti-seismic devices.

Keywords: Bridges, Seismic Action, Viscous Dampers, High Damping Rubber Bearings, Lead Rubber Bearings

1 Introduction

Nowadays the bridges design is totally developed to explore the ductile structure's properties. This purpose allows the energy dissipation under strong seismic action, obtained through the formation of plastic hinges or by other mechanisms. With this kind of conception the structural integrity is guaranteed, although several damages may occur.

The consideration of Seismic Isolation Systems guarantees that structural elastic behaviour is ensured, because it strengthens superstructure flexibility.

Analysis and comparison of structural efficiency of the anti-seismic systems, composed by Viscous Dampers, HDRBs and LRBs, are the objective of this paper. For this purpose the finite elements program *SAP 2000* was used. [1]

2 Seismic Isolation Systems

2.1 Viscous Dampers

A Viscous Damper dissipates energy by pushing fluid through an orifice, producing a damping pressure, which creates a force. That force is given by:

$$F = C|v|^{\alpha} sign(v) \tag{1}$$

where C is the damping coefficient of the damper, v is the velocity across the damper and α is the velocity exponent. A non-linear dynamic analysis was used on the models with Viscous Dampers, where the properties values used were: C = 2000kN(m/s)$^{\alpha}$ and α = 0,25.

2.2 High Damper Rubber Bearings

High damping elastomeric bearings are laminated rubber bearings consisting of rubber layers reinforced by bonded steel plates. Such bearings have a cyclic behaviour, similar to hysteretic behaviour with very slender hysteresis loops. Their stiffness behaviour should be considered as linear elastic in the horizontal direction [2]. Due to this factor a linear dynamic analysis was applied on models with HDRBs devices.

The horizontal stiffness (k) of each HDRB was designed with a structural frequency target (f) of 0,4Hz, resulting in k = 7669kN/m, while vertical stiffness was admitted 500 times superior to horizontal stiffness. The damping of this bearing adopted on models was 10%.

2.3 Lead Rubber Bearings

LRBs are the most commonly used isolators on bridges, as they provide an economical, reliable and simple solution for protecting medium and short span bridges. [3]

Lead Rubber Bearings are similar to the HDRB, but a cylindrical lead core is inserted at the centre to increase the initial stiffness and damping capacity. This procedure presents LRB with bilinear stiffness behaviour, in which elastic stiffness (k_2) is 10 times superior to post-yield stiffness (k_1) [4]. Due to the bilinear behaviour a non-linear dynamic analysis must be adopted.

The yield strength of the lead core (Fy) was defined as a function of the vertical reaction in each bearing due to static loads (Pi). This means there are a great variability of solutions in LRBs depending on stiffness and yield strength. To calibrate these solutions three LRB models were designed, considering, for simplification, that all bearings will get the same yield force, since the vertical reaction is similar on each pier.

Table 1 – Horizontal stiffness and yield strength of each device used in the LRBs models

	Fy (kN)	*k1* (kN/m)
Model with *Fy=5%*Pi and *k1* obtained for *f=0,4Hz*	470	7669
Model with *Fy=2,5%*Pi and *k1* obtained for *f=0,4Hz*	235	7669
Model with *Fy=5%*Pi and *k1* obtained for *f=0,2Hz*	470	1917

The model with better results on structure response was compared with the other anti-seismic devices.

3 Bridge Model

The bridge model used in this study was built in concrete and it has an overall deck length of 464m, split in ten interior spans with 40m and two end spans with 32m. The deck has a straight development from one abutment to the other and it is supported by eleven piers alignments, composed by two piers each. Superstructure oscillate mass is 19.426,81ton.

Deck cross section is defined by a slab composed by two beams. The modelling of the deck consists in attributing a *frame* element to each beam and connecting these elements with transverse rigid bars.

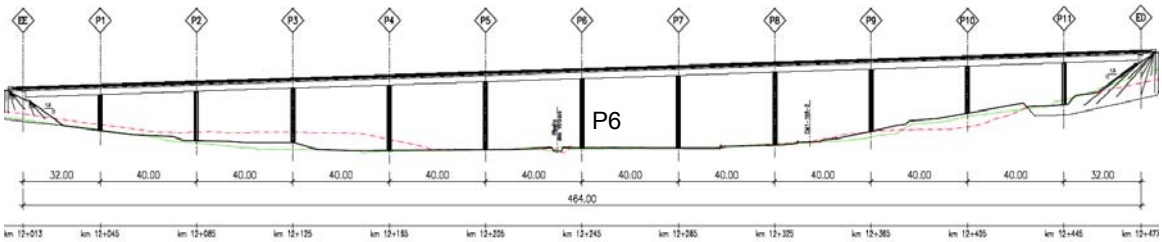

Figure 1 – Elevation view of viaduct

Bearings above the abutments are free under longitudinal direction, so it was possible to assume that abutments mass did not participate in structural seismic response.

The piers have a circular section of 2,20m diameter and the heights are presented in Table 2. The foundations were assumed as fixed in the model.

Table 2 – Alignments piers heights

Alignments	Height [m]
P1	14,00
P2	19,20
P3	23,00
P4	25,00
P5	26,00
P6	25,40
P7	26,60
P8	26,80
P9	25,20
P10	20,90
P11	18,60

The concrete considered in the viaduct is of type C35/45, that means a strength of E=33,5GPa. This value had to be multiplied by 1,25 because seismic action was assumed as “fast shares”, resulting in a strength of E = 41,875GPa.

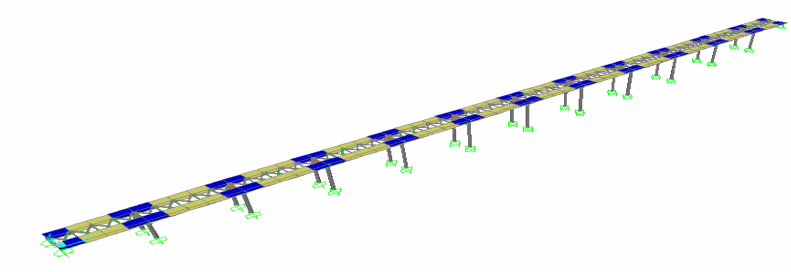

Figure 2 – 3D view of the model representing the analyzed viaduct

4 Seismic Action

The seismic action considered in this study is represented by a strong earthquake with a long distance to the epicentre. The structure was admitted in the seismic Zone 1 of the Portuguese territory, and the soil type assumed was of type C, that represents deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres. The design spectrum of the Eurocode 8, that characterizes these circumstances, is presented in Figure 3. An equivalent damping coefficient of 5% has been adopted proper of a concrete structure.

In this study, linear and non-linear dynamic analyses were performed depending on the considered devices. Non linear analysis obliged that artificial accelerograms had to be modelled, because modal spectrum analysis did not measure the non-linear behaviour of the devices.

Ten artificial accelerograms were generated in order to be compatible the prescribed spectrum. The average artificial spectrum was very close to the Eurocode 8 spectrum, validating the seismic action used, as it's possible to verify in the Figure 3.

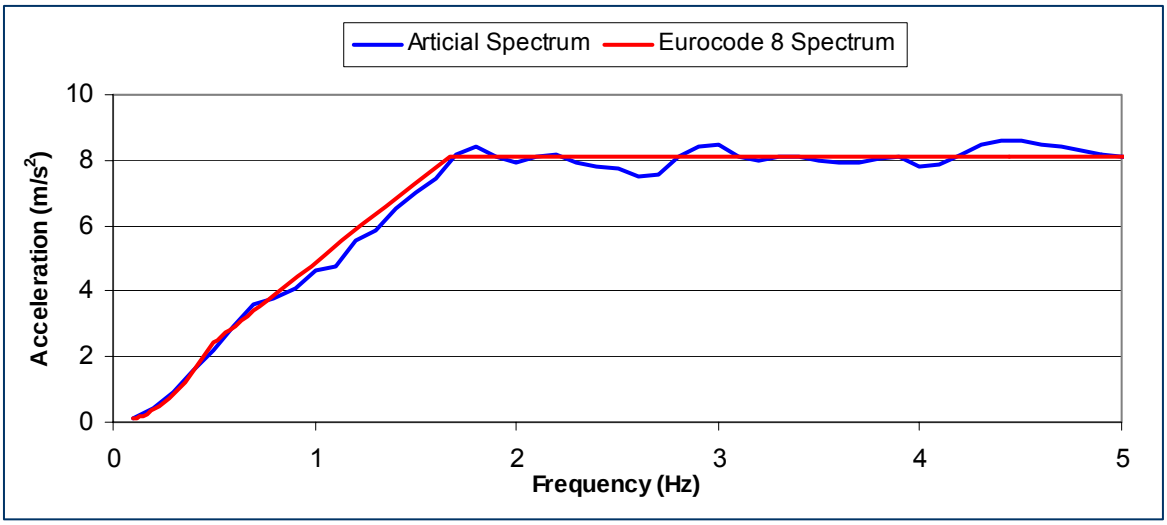

Figure 3 – Comparison between Eurocode 8 Spectrum and Artificial Spectrum

5 Comparison between Seismic Isolated Models and Non Isolated Model

5.1 General

The models considered were: *Non-Isolated Model*; *Model with Viscous Dampers*; *Model with HDRBs*; *Model with HDRBs and Viscous Dampers*; *Model with LRBs*; and *Model with LRBs and Viscous Dampers*. In these models shear forces in the structure and deck displacements were evaluated. The shear forces are obtained only for seismic action, and were measured in the Base Reactions and in an isolated pier, to get a value that didn't get abutments participation. The deck displacement was registered in longitudinal direction.
In the study the seismic action was admitted in longitudinal and transversal directions, however it was possible to conclude that seismic isolated systems didn't participate in structural response in transversal direction. The fact of the bridge model has a straight behaviour explains this situation.

As mentioned in Point 2.3, three variants of the *Model with LRBs* were analysed and the solution with better results was the one with k_1 = 1917kN/m and Fy = 470kN. In the *Model with LRBs and Viscous Dampers* same process was applied, being the solution with better results the one with k_1 = 7669kN/m and Fy = 235kN.

5.2 Reactions

5.2.1 Reactions on Base and in the Pier P6

The analysis of Figure 5 indicates that models with better reactions control were the models with HDRBs or LRBs associated to Viscous Dampers.

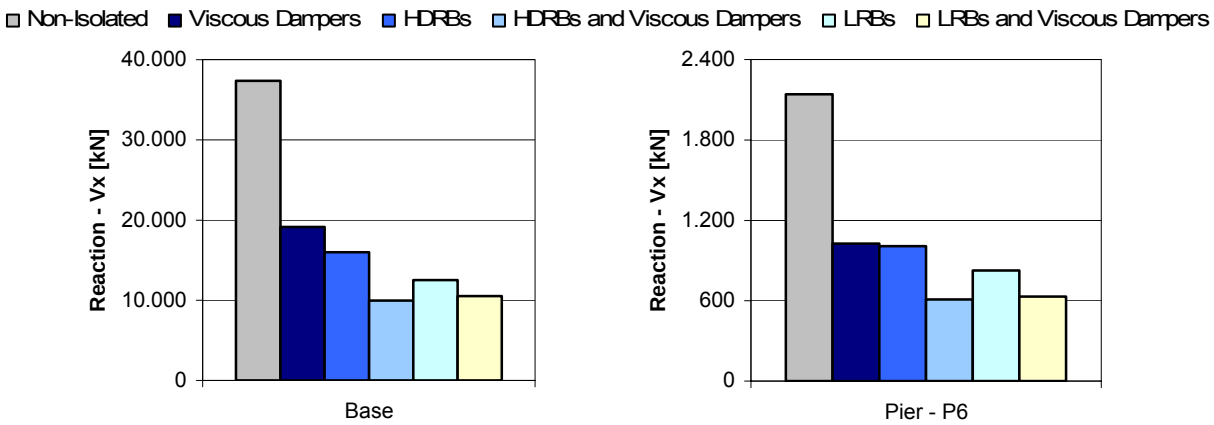

Figure 5 – Comparison of reactions between seismic isolated models and non isolated model

Reactions of the *Non-Isolated Model* reduce almost 50% in the *Model with Viscous Dampers*. In the other seismic isolated models the reduction was superior to 50%, reaching 70% in the Models with HDRBs or LRBs and Viscous Dampers.

From the *Model with Viscous Dampers* to the *Model with HDRBs and Viscous Dampers* the reactions reduction was 47,85% in the Base, and 40,59% in the Pier P6. While from the *Model with Viscous Dampers* to the *Model with LRBs and Viscous Dampers* the reactions reduction was 45,01% in the Base and 38,51% in the Pier P6. This leads to the conclusion that adding devices with high initial stiffness, like LRB or HDRB, to Viscous Dampers, guarantees the better forces control transmitted to structure.

Between the *Model with HDRBs* and *Model with HDRBs and Viscous Dampers* the reactions difference was 37,55% in the Base and 39,74% in the Pier P6. Between the *Model with LRBs* and the *Model with LRBs and Viscous Dampers* the reactions difference was not so significant, since only reached the 16,04% in the Base and 23,58% in the Pier P6. However it was possible to verify that the participation of Viscous Dampers contributes to considerable force reductions transmitted to structure, justified by the elevated damper that is present in this kind of devices.

Comparing the *Model with HDRBs* and the *Model with LRBs* the reactions difference was 21,58% in the base and 18,03% in the Pier P6. This difference was expectable since HDBR equivalent stiffness was 7.669,40kN/m, superior to LRB equivalent stiffness that was 4.592,05kN/m, that means LRBs devices allow lower forces transmitted to structure due to greater displacement permission.

The reaction difference between the *Model with HDRBs and Viscous Dampers* and the *Model with LRBs and Viscous Dampers*, was 5,44% in the Base and 3,50% in the Pier P6. This minimum difference is related with the similar equivalent stiffness in both models.

5.2.2 Viscous Dampers Force

The Viscous Dampers force was similar in each analysed model. This means that adding HDRBs or LRBs to a seismic isolated system composed by Viscous Dampers did not guarantee the reduction of the force on the device.

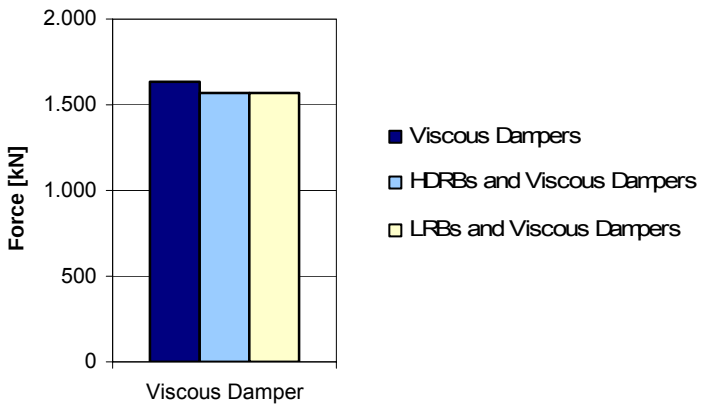

Figure 6 – Comparison of Viscous Damper force between the models with this device

5.2.3 *Force-Displacement relationship of HDRBs*

In Figure 7 the comparison of the HDRBs behaviour in the models with and without Viscous Dampers is represented, in which it is possible to observe the force and displacement reduction due to the addition of Viscous Dampers.

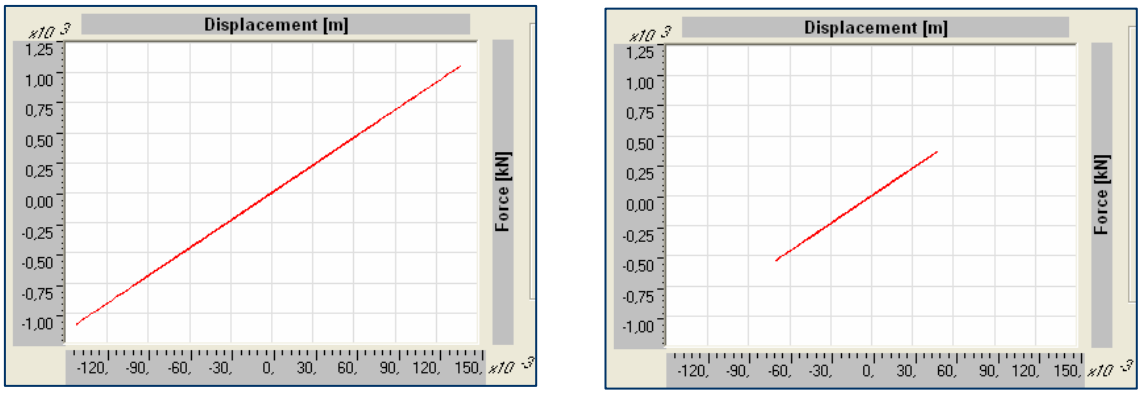

Figure 7 – Comparison of force-displacement relationship of HDRBs between the *Model with HDRBs* (left) and the *Model with HDRBs and Viscous Dampers* (right)

5.3 Displacements

The models with lower longitudinal deck displacements were the models where admitted Viscous Dampers.

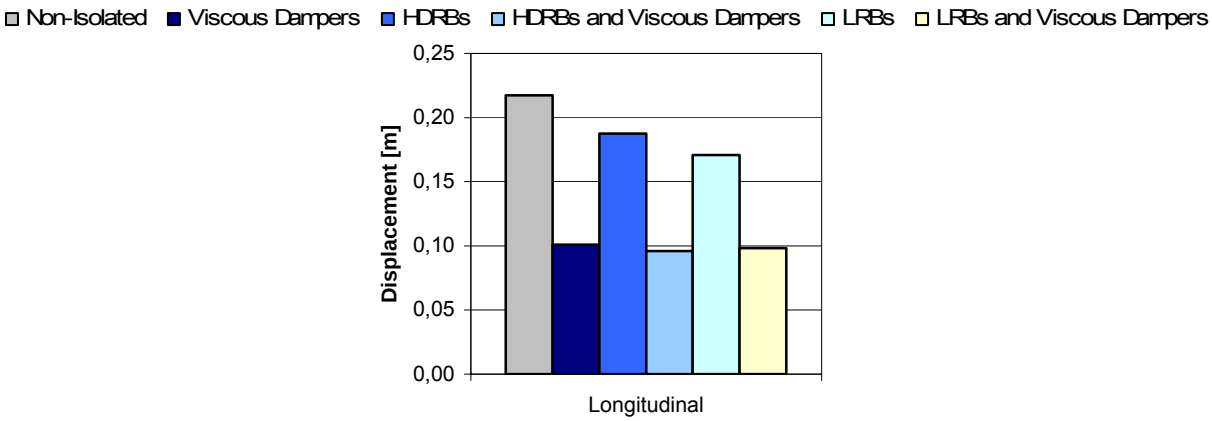

Figure 8 – Comparison of deck displacements between seismic isolated models and non isolated model

As it is possible to observe the models with Viscous Dampers presents a reduction higher than 50% when compared with *Non-Isolated Model*. The addition of HDRBs and LRBs to a seismic isolation system composed by Viscous Dampers did not grant a better displacements control since the reduction verified was only 4,97% and 2,17% respectively.

The displacements reduction between the *Model with HDRBs* and the *Model with LRBs* was justified by the different damping of each device, because the LRB device presents an

equivalent damping of 31%, and the HDRB device presents a damping of 10%, as indicated on Point 2.2. This result shows that LRBs devices assure a better deformations control than HDRBs devices.

Other parameter used on the displacements analysis was the dispersion of results of each model, due to the seismic action represented for the artificial accelerograms. The results dispersion was measured by the ratio between the Standard Deviation and the Average. This analysis allows evaluate the models' reliable results.

It was conclusive that *Model with LRBs* was the model with greater dispersion of results, as illustrated in Figure 9. This fact is justified by the abrupt stiffness decrease that LRB presents after the yielding of the lead core. This behaviour causes the displacements increase.

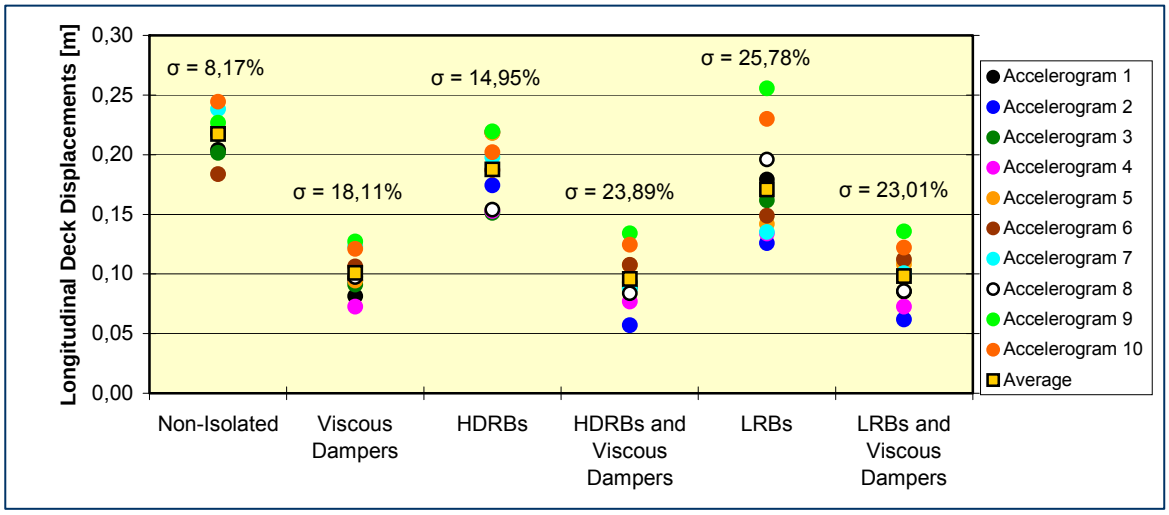

Figure 9– Comparison of the deck displacement of each artificial accelerogram between the models with seismic isolation systems and non isolated model

6 Conclusions

The structure considered in this study presents a frequency of 0,51Hz, meaning that it is a flexible structure. In this type of structures was proven that the use of Viscous Dampers guarantees an efficient control of deformations, while the HDRBs or LRBs devices guarantee an efficient control of reactions.

The association of Viscous Dampers to HDRBs and LRBs allows improve the seismic isolation systems behaviour, since this consideration ensure a high control of displacements and reactions.

The solution with Viscous Dampers and LRBs will be the most indicated because it presents equivalent results to the solution with Viscous Dampers and HDRBs for seismic action, but for

services loads presents a better behaviour, given by the high initial stiffness that LRBs devices present.

References

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