1st Latin-American Workshop on Structural Health Monitoring
LATAM-SHM 2023
December, 5-8 2023

Implementation of Seismic Eco-Isolators in a vehicular bridge

Juan Sebastian Martinez*[a], Andres Alvarez G.[†], Felipe Guerrero M.[†], Albert R. Ortiz[†], Peter Thomson R.[†], Johannio Marulanda A.[†]

[*] Research Group in Seismic, Wind, Geotechnical, and Structural Engineering (G7)
Universidad del Valle
Campus Meléndez, Calle 13 # 100-00, Cali, Colombia
e-mail: juan.martinez.sandoval@correounivalle.edu.co, web page: https://eicg.univalle.edu.co/G-7/

Key Words: Structural Control, Seismic Isolators, Computational Simulation, Finite Element Models, Calibration of FE Models.

Abstract. *Seismic Eco-Isolators are passive structural control elements currently in development. Their primary objective is not only to mitigate the risk of collapse or severe structural damage caused by seismic events but also to represent a low-cost alternative with greater ease of production compared to conventional isolators typically found in Colombia. This study presents an evaluation of the implementation of Eco-Isolators in a specific case study: a vehicular bridge located in the city of Cali, using computational simulations in finite element models.*

1 INTRODUCTION

One of the most widely used methodologies for structural control to mitigate the risk of severe damage during seismic events in civil structures is seismic isolation. In Colombia, a country with high seismic hazard zones such as the city of Cali, there are several instances of seismic isolator applications in various types of structures, including vehicular bridges. These isolators are typically produced and validated in other countries, necessitating their importation and transportation to construction sites, which increases the cost of implementation and hinders widespread adoption in the country, unless it involves high-budget projects. Eco-Isolators utilize crumb rubber from discarded tires and domestically produced polyester reinforcement fibers as essential raw materials. This approach aims to reduce production costs and promote domestic manufacturing of these elements. Within the scope of research on the development and validation of these elements, an assessment of their suitability for application in different types of structures is conducted. This study analyzes their performance in the case of a representative vehicular bridge in the city of Cali using finite element modeling.

2 ECO-ISOLATORS

Eco-Isolators are un-bonded fiber-reinforced elastomeric seismic isolators (U-FREIs). Their name is due to the fact that their primary component is a recycled rubber matrix derived from discarded tires. These bearings have layers of recycled rubber and polyester fiber. These polyester fibers are manufactured in Colombia. Between these layers, sheets of polyester fiber are placed, which are produced in the country. This composition aligns with one of the objectives of developing these elements: the production of seismic isolators at a lower cost compared to conventional ones, by using a raw material that is more affordable to obtain and, in large-scale production, contributes to the reduction of the environmental impact generated by the waste of non-functional tires. Their un-bonded condition means they are not fixed to the structure through connections, which also reduces installation costs. [1,2]

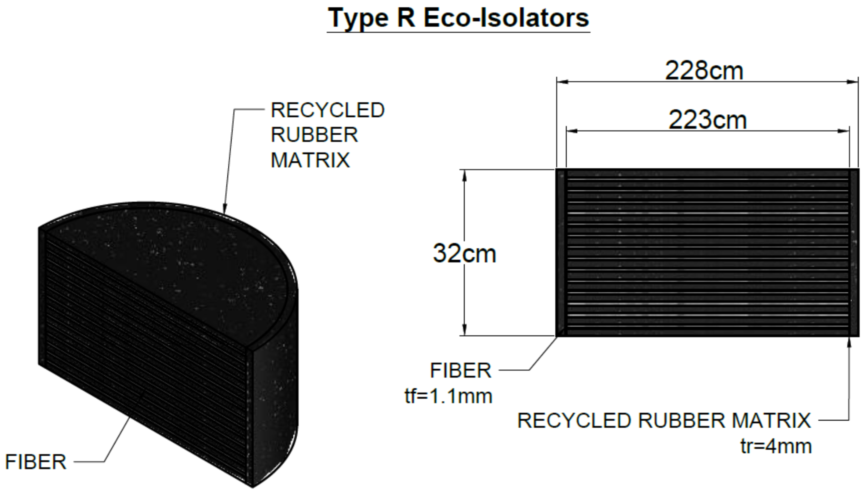

Figure 1: scheme of the Eco-Isolators designed for the straight section of the bridge (called "type R").

3 FINITE ELEMENT MODEL

For the performance evaluation of the seismic isolation system implemented in the bridge, a finite element model was developed using the commercial software SAP2000. Three different models were used: a model of the bridge without seismic isolators, a model with the currently installed seismic isolators (LCRB), and a model with the newly designed seismic isolators (Eco-Isolators). The two primary functionalities of the model are:

1. *Static structural analysis*: Through this process, the load demands are determined, which serve as input parameters in the design process of Seismic Eco-Isolators. To achieve this, the load assembly required to effectively represent the demands to which the bridge is subjected is modeled.
2. *Performance evaluation*: Computational simulations are conducted, including response spectrum analysis and time-history analysis. The variations of fundamental periods, accelerations in decks, maximum basal shears, maximum shears in piles and displacements of decks were analyzed.

The model was created with reference to the structural drawings and data of the bridge, provided by the company that designed it. [3].

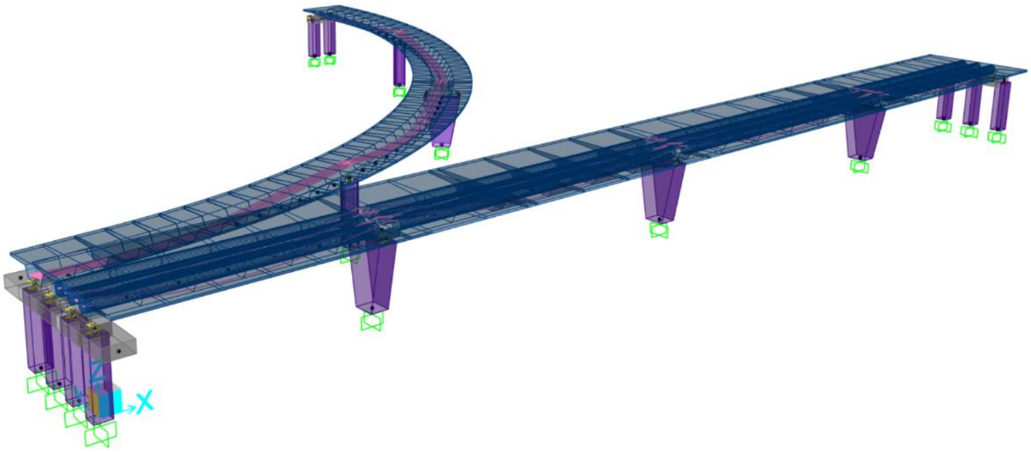

Figure 2: Finite-element model of the bridge made in SAP2000.

3.1 Finite element model calibration

The model was calibrated with the aim of adjusting its dynamic properties to closely match those of the actual structure. This process was carried out using the results of a dynamic characterization report of the bridge conducted in 2016 by the G-7 Research Group [4] as a reference. In this report, a modal identification protocol was performed through ambient vibration tests. The input data obtained from the report for the model calibration process included the natural frequencies and corresponding modal shapes for the first ten identified modes.

It was evident that the natural periods of the first vibration modes identified in the study had very low values, which did not correspond to the dynamics of an isolated vehicular bridge. This can be explained by the minimal excitation the isolators experienced during ambient vibration tests. Thus, accelerometers were not able to capture the modal properties dependent on the dynamics of these elements. Due to this, it was decided to adjust the modes of the finite element model independently of the isolators (from the sixth mode onwards), which coincided with the primary modes identified in the study, as will be seen below.

Two criteria were employed to assess the similarity of frequencies and modal shapes between the experimental data (e) and those obtained in the model (a): Percentage difference in Modal Assurance Criterion (MAC) and difference of frequencies.

$$MAC_{ae} = \frac{|\varphi_a^T \ \varphi_e \ |^2}{\varphi_a^T \ \varphi_a \ \varphi_e^T \ \varphi_e} \tag{1}$$

$$\left|\frac{f_{e_i} - f_{a_i}}{f_{e_i}}\right| \cdot 100 \tag{2}$$

The MAC criterion (1) allows for a comparison between the modal vectors obtained from the two mentioned sources, where φ_a corresponds to the vector obtained analytically in the finite element model, and φ_e corresponds to the vector obtained experimentally in the modal identification study. The MAC is quantified on a scale from 0 to 1, where it equals 0 when there is no absolute correspondence between both vectors and equals 1 when the correspondence is consistent and total [5].

The modal vectors consist of modal deformations obtained at specific points located along the straight and curved sections of the bridge. These points are positioned every 10% of the total length of each section. Thus, on the straight section (120m), points are located every 12m, and on the curved section (130m), they are situated every 13m along the span.

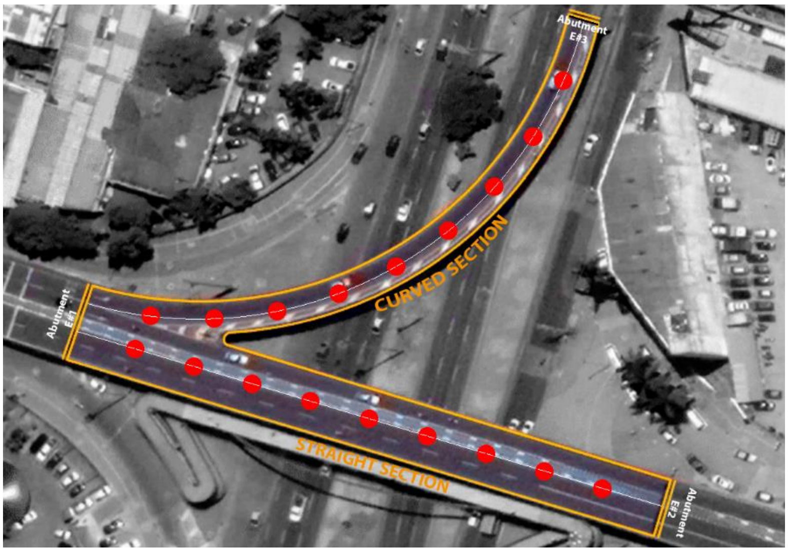

Figure 3: Points of evaluation in the bridge's decks. Each red circle represents one of them.

As shown in Figure 3, both the straight and curved sections of the bridge feature nine points. Each red point represents a location that coincides with the positions of the accelerometers in the different setups established during the ambient vibration tests conducted in the study [3]. These points also correspond to the nodes of the finite element model where modal displacements were obtained. The calibration of the model involved refining the geometric configuration of the model and varying its stiffness, specifically the piers and decks. This refinement specifically included:

1. Increased discretization of the frame-type elements corresponding to the decks, by adding more nodes along the spans.
2. Variation of the elastic modulus (E) of the concrete in the decks, piers, and abutments.
3. Variation of the moment of inertia (I) in both directions of the structural element sections. A modifying factor for reducing this property due to section cracking was incorporated.
4. Variation of the horizontal stiffness (Kh) of the modeled LCRB-type isolators.

The mentioned parameters were varied in an iterative process until a sufficient level of correspondence was achieved between the compared modes. The results are presented below:

Table 1: MAC matrix.

MAC MATRIX							
	Exp. Mode 1	**Exp. Mode 2**	**Exp. Mode 3**	**Exp. Mode 4**	**Exp. Mode 5**	**Exp. Mode 6**	**Exp. Mode 7**
Analytical Mode 6	0.779	0.001	0.025	0.023	0.013	0.234	0.174
Analytical Mode 7	0.789	0.001	0.020	0.022	0.012	0.231	0.165
Analytical Mode 8	0.000	0.392	0.608	0.052	0.122	0.073	0.417
Analytical Mode 9	0.048	0.751	0.456	0.018	0.059	0.041	0.214
Analytical Mode 10	0.088	0.088	0.785	0.026	0.039	0.001	0.429
Analytical Mode 11	0.004	0.001	0.148	0.505	0.295	0.108	0.773

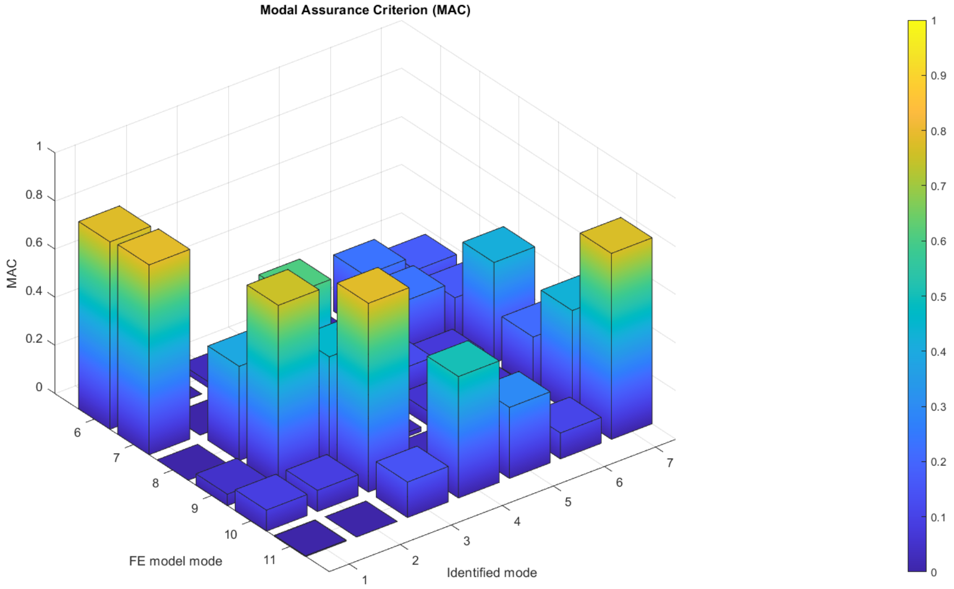

Figure 4: MAC of the comparison between modal shapes.

A significant correspondence is evident in the highlighted cases in Table 1. The modes exhibit a correspondence that is not only evident in the MAC criterion but also in the frequency difference criterion:

Table 2: Modal frequencies and periods.

Modal frequencies and periods					
FE Model			Experimental results		
Analytical mode	Frec (Hz)	T (s)	Experimental mode	Frec (Hz)	T (s)
6	1.99	0.50	1	2.15	0.47
7	1.99	0.50	2	2.49	0.40
8	2.61	0.38	3	2.87	0.35
9	2.68	0.37	4	3.37	0.30
10	2.82	0.35	5	4.03	0.25
11	3.43	0.29	6	5.8	0.17
12	3.86	0.26	7	10.7	0.09

.

Table 3: Frequencies difference.

Frequencies difference (%)							
	1	**2**	**3**	**4**	**5**	**6**	**7**
6	7.4	20.1	30.7	40.9	50.6	65.7	81.4
7	7.2	19.9	30.5	40.8	50.5	65.6	81.4
8	21.5	4.9	9.0	22.5	35.2	55.0	75.6
9	24.5	7.5	6.7	20.5	33.6	53.8	75.0
10	31.1	13.2	1.8	16.4	30.1	51.4	73.7
11	59.4	37.7	19.4	1.7	14.9	40.9	68.0

There is a corresponding agreement between the two criteria for the highlighted modes in the tables. By calibrating the finite element model sufficiently to achieve this level of correspondence, it was assumed that the adjustment of the bridge's dynamics, which does not depend entirely on the excitation of the seismic isolators, has been achieved. Furthermore, with the isolators having the mentioned parameters, it was assumed that the horizontally dependent modes entirely influenced by the response of these elements also have a sufficient level of adjustment to proceed with the analyses. It was taken into account that when implementing the Eco-Isolators system, the modal response of the bridge is subject to variation, so adjusting the modes that depend entirely on the isolators was not the primary focus of this process.

4 ECO-ISOLATORS SYSTEM DESIGN

Three types of isolators were defined based on the bridge's geometric configuration and the loading conditions they support: Type R isolators (located at the supports of the straight section), Type C isolators (in the curved section), and Type E isolators (at the abutments of the bridge). The same quantity of isolators was designed as currently exists in the structure: 18 in total, with 6 of Type R, 4 of Type C, and 8 of Type E. These three types were designed separately because the load demands vary considerably between these three zones. This approach provides greater control over optimizing the isolators' geometry. As essential parameters in the process, it was established that:

- All isolators must have the same target period (T) or a value very close to it.
- All isolators must be designed considering the same percentage of design shear deformation (γ_s). In this case, it was set at 150%. This also ensures uniform shear modulus and horizontal damping percentage for the isolators.
- All isolators must be designed for an equal or very close design displacement.

For defining the target period, it was taken into account that the range of fundamental periods of the soil in the area where the bridge is located varies between 1.5s and 2s. Within the design process, choosing target periods exceeding 2s resulted in very high design displacements that could compromise the serviceability conditions of the structure, even exceeding values of over 1m. Due to this, the decision was made to start with target periods below the mentioned range, with 1.2s as the initial target period in all three design processes. This value had slight variations among the three cases, with a maximum difference fixed at 2.5%, ensuring uniformity in the overall system response. The design process was based in large part on the provisions of [6,7].

A target property was defined for optimizing the designs: the diameter of the isolators. Considering their locations (at the pier/abutment interfaces and the decks), there is limited space available for placement, which directly depends on the dimensions of these zones. Therefore, control over the required cross-sectional areas is necessary. This, along with the substantial dead load demands from the superstructure (decks) that they must support, also influences the required diameter.

The design displacement for the isolators was set within a range between 34.5cm and 36cm, which was considered acceptable to proceed with the design process. The ratio between the design displacement and the height of the rubber was defined as 1.5 (150%), aiming to reduce the shear modulus (G), which leads to a reduction in the nominal area required for the isolator.

Table 4: Design results for straight section Eco-Isolators (type R).

Final design for type R Eco-Isolators: T=1.227s		
Property	**Value**	**Unit**
Demands		
Weight of structure above the isolators	18699.6	kN
1,2D+L+E (highest)	9612	kN
0,8D-E (lowest)	5184.2	kN
Geometry		
External diameter	228	cm
Internal diameter	223	cm
Number of rubber layers	63	un
Rubber layer thickness	4	mm
Total isolator height	32.02	cm
Total rubber height	25.2	cm
Radial coating thickness	0.25	cm
Weight	1.0182	Ton
Vertical deformation	0.9608	cm
Mechanical Properties		
Vertical stiffness (Kv)	7774.8	kN/mm
Vertical damping	172894.7	kN*seg/m
Effective horizontal stiffness (Keff)	8.3	kN/mm
Shear modulus (G)	0.6	Mpa
Horizontal damping	553.8	kN*seg/m
Elastic stiffness (K1)	41.7	kN/mm
Yield stress	1050.4	kN
Stiffness ratio (Kv/Kh)	932.8	-

5 PERFORMANCE EVALUATIONS

The performance evaluation of the Eco-Isolators consists of two types of tests performed by means of computational simulation on the FE models. These consist of a multimodal response spectrum analysis and a time-history analysis.

The analyses are performed on three models: one without seismic isolation, one with the current seismic isolators (LCRB) and one with the designed Eco-Isolators. These are located on a series of supports consisting of piers and abutments. The supports of the straight section are named R1, R2, R3 (all have two isolators in each). The supports of the curved section C1 (one isolator), C2 (two isolators) and C3 (one isolator). Additionally, the supports of abutments

E1 (four isolators), E2 and E3 (both with two isolators).

The analyses were performed in two main directions: X global axis (coincides with the longitudinal direction of the majority of the model) and Y global axis (coincides with the transverse direction of the majority of the model). See figure 5.

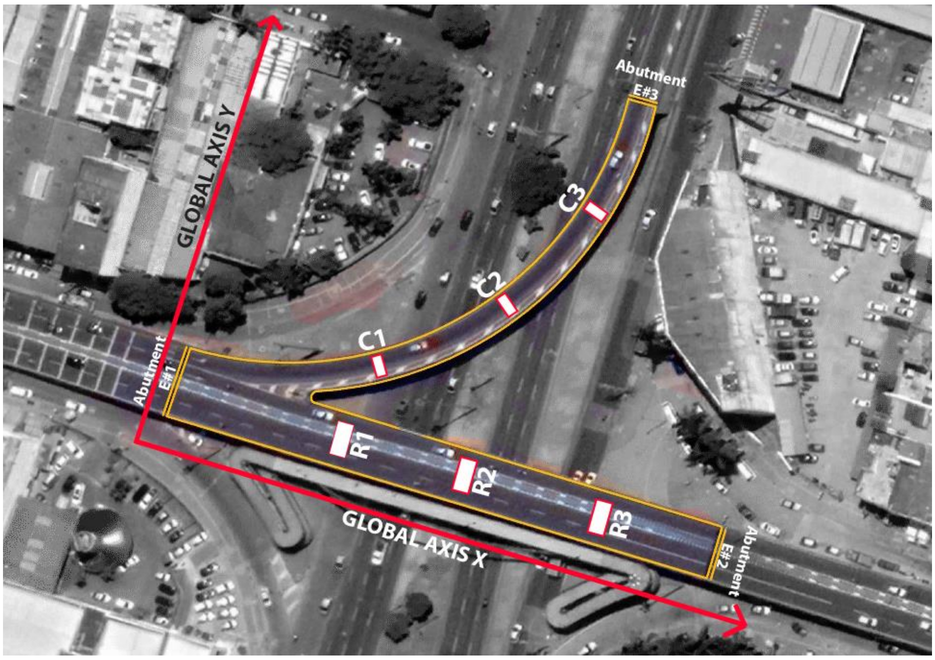

Figure 5: Location of the points where the isolators are located.

5.1 Response spectrum analysis

This analysis was carried out using the envelope design spectrum corresponding to seismic zone 4C, where the bridge is located, as defined in the Cali Seismic Microzonation Study [8]. This pseudo-acceleration spectrum was entered into the model in the global X and global Y directions.

The results show that seismic isolators, both conventional (LCRB) and Eco-Isolators, lead to an increase in the natural periods associated with the vibration modes of the structure.In Colombia there is no methodology regulated by the design standard (NSR-10) that allows reducing the design spectrum of the structure taking into account the increase of its damping. However, keeping the spectrum without reducing it, much lower pseudo-accelerations are obtained when using Eco-Isolators. Figure 6 shows that the latter have a lower performance than the LCRB isolators. However, the increase in natural period is still considerable, which translates into lower basal shears in both directions of analysis, as shown in Figure 7.

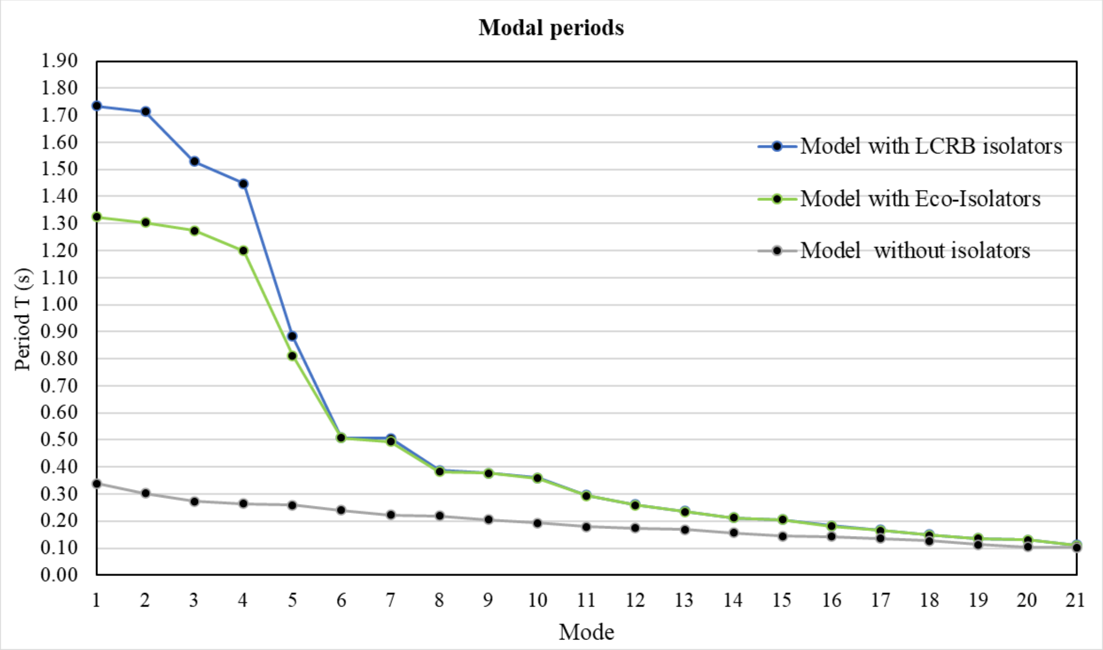

Figure 6: Period variation between the three analysis cases

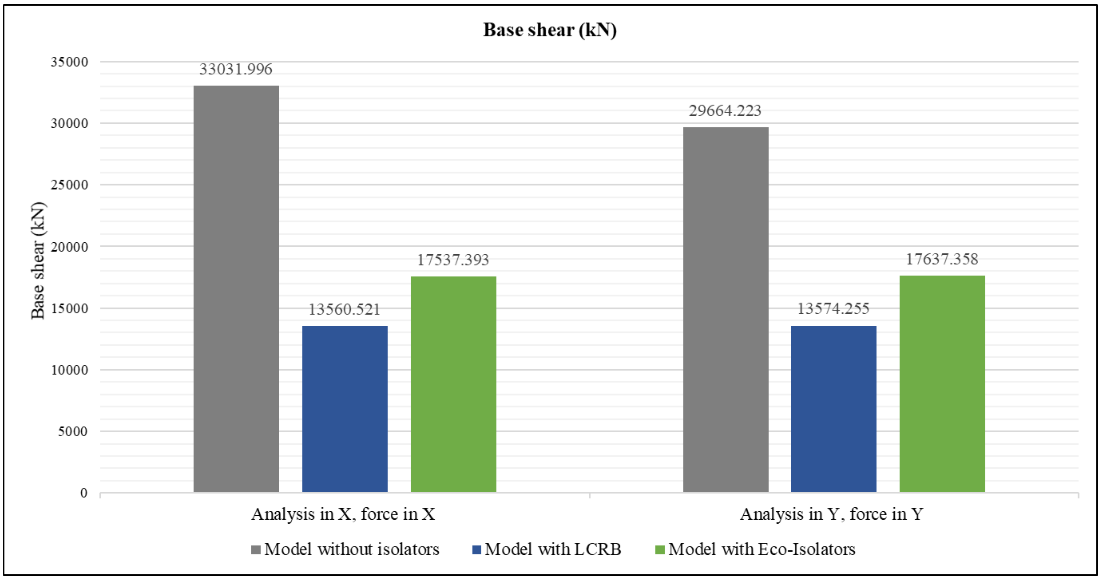

Figure 7: Base shear variation between the three analysis cases.

5.2 Time-history analysis

The time-history analysis was carried out using the accelerographic signals in the E-W (coincident with the global X-axis) and N-S (coincident with the global Y-axis) directions of five seismic events. These records were selected taking as a reference the recommendations of

Ingeominas [8], where a series of signals appropriate for the representation of the seismic conditions of the city is suggested. The accelerograms were adjusted using the Al Atik and Abrahamson [9] methodology, in which they are calibrated so that their pseudo-acceleration response spectra coincide with the design spectrum of the area where the bridge is located. In this way, site effects due to parameters such as the type of subsoil are taken into account. The selected signals are:

Table 4: Selected seismic signals for analysis.

Earthquake	Date	Station	Magnitude (Mw)	PGA (g)	Seismic source	Depth (km)	Epicentral distance (km)
Italy1997	26/Sept./1997	AS010	6	0.188	Cortical	6	21
Japan 2005	20/Mar./2005	FKO001	6.6	0.113	Cortical	12	33
Japan 2003	26/May./2003	MYG005	7	0.178	Deep	61	89
Chile 2005	13/Jun./2005	Iquique	7.9	0.281	Deep	117	119
Mexico 1985	19/Sept./1985	UNIO	8.1	0.122	Superficial	21	91

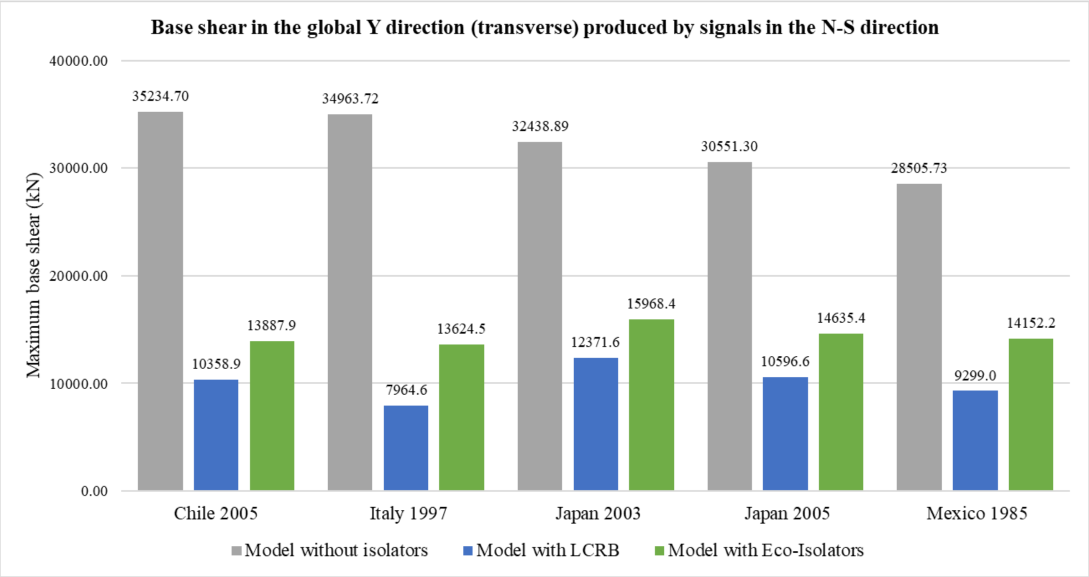

Figure 8: Base shear in the global Y direction (transverse) produced by signals in the N-S direction.

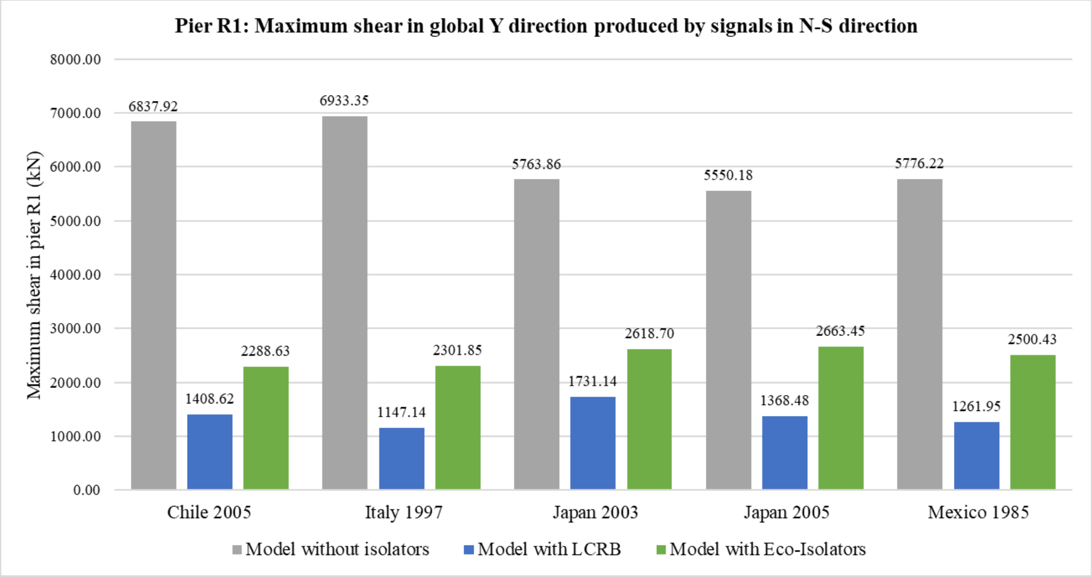

Figure 9: Pier R1: Maximum shear in global Y direction produced by signals in N-S direction

Similar to the results obtained in the response spectrum analysis, a considerable reduction of the base shear and maximum shear in the piles is evidenced. Figure 9 shows the results corresponding to pile R1, which shows reductions of up to 66%, which represents a considerable reduction compared to values of up to 80% corresponding to conventional isolators (LCRB). Once again, it can be observed that, although the Eco-Isolators do not reach the performance of the latter, they still fully meet their structural control objectives.

12 CONCLUSIONS

- The dynamic-dependent vibration modes of seismic isolators can be difficult to detect in environmental vibration tests in the framework of the identification of the dynamic properties of an isolated structure. This is because these elements do not present sufficient excitation during these procedures. The implementation of tests in which the structure is subjected to stimuli of greater magnitude, especially in the horizontal axes, is recommended.
- The implementation of Eco-Isolators increased the natural period of the bridge, which led to a reduction of the pseudo-acceleration readings in the response spectrum. Likewise, a considerable reduction of basal shear and shear forces in the infrastructure elements (piers and abutments) was evidenced. This translates into the mitigation of vulnerability to seismic excitations.
- The Eco-Isolators present a lower performance, but not far from conventional isolators (as could be evidenced in their comparison with the performance evaluations of the model with LCRB isolators). However, it was evidenced that they fulfill their purpose. Additionally, their production cost is lower due to the acquisition of raw materials (recycled rubber and fibers produced in Colombia), in addition to the installation costs that are reduced because they are un-bonded. If large-scale production is established in Colombia, import and transportation costs would also be reduced.

ACKNOWLEDGMENTS

Special thanks to the research group G-7 of the Universidad del Valle for the technical and intellectual support in each phase of the research. Additionally, special thanks to the project "Evaluation of the Durability of Sisimic Insulators made with Elastomeric Matrix of Recycled Rubber", code CI 21187, financed within the framework of the internal call of the Universidad del Valle. Finally, we would like to thank engineers Andrés Álvarez, Albert Ortíz and Felipe Guerrero for their guidance and support during the development of the work.

REFERENCES

[1] Ortega, L., Herazo, M., Alvarez, A., Ortiz, A., & Madera, I. (2021). Caracterización mecánica de prototipos de aisladores sísmicos con matriz de caucho reciclado mediante compresión monotónica y residual. Jornandas geotécnicas y estructurales.

[2] Toopchi-Nezhad, H., Tait, M. J., & Drysdale, R. G. (2011). Bonded versus unbonded strip fiber reinforced elastomeric isolators: Finite element analysis. Composite Structures, 93(2), 850-859.

[3] Pedelta. (2012). Planos estructurales del puente de la intersección de la carrera 44 por calle 10, cali, colombia. *Pedelta Colombia S.A.S.*

[4] G-7 Reseach Group. *Caracterización Dinámica Del Puente Vehicular De La Calle 10 Con Carrera 44, Santiago De Cali*. (2016).

[5] Pastor, M., Binda, M., & Harčarik, T. (2012). Modal assurance criterion. *Procedia Engineering*, *48*, 543-548.

[6] Kelly, J. M., & Konstantinidis, D. (2011). Mechanics of rubber bearings for seismic and vibration isolation. John Wiley & Sons.

[7] Safety, I. S. (2003). Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (FEMA 450). FEMA: Washington, DC, USA.

[8] Ingeominas, D. (2005). *Estudio de microzonificación sísmica de Santiago de Cali*. Cali, Colombia.

[9] Al Atik, L., & Abrahamson, N. (2010). An improved method for nonstationary spectral matching. Earthquake spectra, 26(3), 601-617.