16th World Conference on Earthquake Engineering, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 4697
Registration Code: S-O1464748289

RECENT APPLICATIONS OF SEISMIC ISOLATION AND ENERGY DISSIPATION SOLUTIONS IN LATIN AMERICA

C. Mendez-Galindo(1), G. Moor(2), J. Nieto-Higuera(3), J.C. Rodriguez-Bahena(4), J.C. Delgado-Trejo(5),
B. Bailles(6), C. Sanchez-Pire(7), L.A. Duran-Perez(8)

(1) Manager - Seismic Devices, mageba International, cmendez@mageba.net
(2) CEO, mageba USA, gmoor@magebausa.com
(3) Seismic Engineer, mageba Mexico, jnieto@mageba.mx
(4) Seismic Engineer, mageba Mexico, jrodriguez@mageba.mx
(5) Technical Sales Manager, mageba Mexico, jdelgado@mageba.mx
(6) Area Manager, mageba International, bbailles@mageba.net
(7) Sr. Seismic Engineer, mageba Mexico, csanchez@mageba.mx
(8) Seismic Engineer, mageba Mexico, lduran@mageba.mx

Abstract

The design of critical structures to withstand the effects of earthquakes continues to gain importance all over the world. Most recently, several countries in Latin America have started to implement advanced seismic protection systems. The main objective of these systems is always the people's safety. However, the integrity of the structures and their serviceability immediately after an earthquake play an important role in the speed of the emergency response, particularly bridges, hospitals and schools. Additionally, the cost associated with repair or reconstruction of damaged structures is likely to be small compared to the economic impact caused by disruption of serviceability after an earthquake and during the long reconstruction phase.

Seismic isolation systems provide an alternative to conventional earthquake resistance design such as strengthening of structural elements (columns or beams), and have the potential for significantly reducing seismic risk without compromising safety, reliability, and economy of structures. As an alternative to seismic isolation, energy dissipation becomes essential in terms of seismic protection. The use of effective devices able to dissipate high amounts of energy ensures that other structural elements do not undergo excessive demands that could cause significant damage.

This paper presents some of the recent applications of seismic protection in Mexico, Venezuela, Ecuador and Peru. All these countries are located in active seismic areas that have experienced strong earthquakes. The development of the engineering expertise in the region, together with the availability of affordable and effective systems have encourage the use of advance seismic protection technologies, such as elastomeric and pendulum isolators, as well as viscous dampers. The study cases presented in this paper serve as evidence of the increasing interest of designers, contractors and owners for safer and efficient structures, which above all ensure the safety of the population, and mitigate structural damage.

Keywords: seismic isolation; energy dissipation; Latin America; applications

1. Introduction

The application of seismic protection strategies to protect structures from earthquakes is becoming increasingly popular and more widely demanded in regions that are prone to seismic activity, including, in particular, a number of countries in Latin America. The main objective of any seismic protection system must always be people's safety, but the ability of key structures, such as bridges and important buildings, to survive an earthquake and remain in service immediately afterwards is critical for an effective emergency response. The cost associated with making such critical elements of a region's infrastructure earthquake-proof is likely to be negligible compared to the economic impact of loss of serviceability after an earthquake and during the long reconstruction phase [1].

The most important methods of seismic protection of structures today include seismic isolation, whereby violent ground movements are isolated from the structure by suitably designed bearings, and energy dissipation, whereby the excess energy introduced to a structure during an earthquake is safely dissipated, e.g. by means of viscous dampers. A further method of limiting or preventing damage to a bridge during an earthquake is the use of "fused" expansion joints in its deck, which will fail in a controlled way when excessively large horizontal movements arise during an earthquake. Each of these methods is described below, and illustrated by case studies from recent applications in Latin America.

2. Seismic Isolation

Seismic isolation involves the provision of specially designed bearings, known as seismic isolators, which will support a structure's superstructure in normal circumstances but isolate them, primarily in the horizontal plane, from the violent,ground movements that might occur during an earthquake. The flexibility thus provided in the horizontal plane lowers the structure's natural frequency, increasing its natural period and thereby reducing the accelerations to which it is subjected as shown in Fig. 1. Seismic isolators generally also provide some degree of energy dissipation, which further reduces the destructive accelerations as shown in Fig. 2.

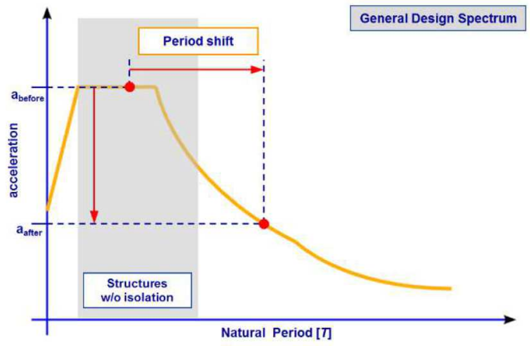

Fig. 1 – Reduction of accelerations by period shifting

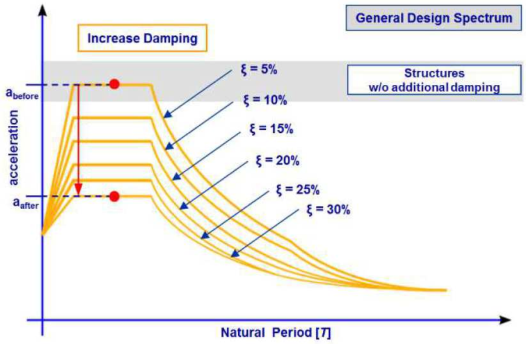

Fig. 2 – Reduction of accelerations by added damping / energy dissipation

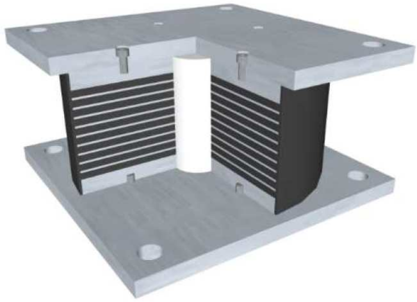

Fig.3 – 3D model of a Lead Rubber Bearing

Another important contribution of an effective seismic isolation system is the re-centering it can provide after an earthquake, avoiding residual displacements which would otherwise disrupt the structure's serviceability. It is very often possible to retrofit seismic isolation to an existing structure if required, by temporarily lifting the superstructure and replacing its conventional bearings with suitably designed isolators [2].

2.1 Lead Rubber Bearings (LRB)

A particularly effective, efficient and user-friendly type of seismic isolator is the LRB, a relatively simple solution which combines the key isolation, energy dissipation and re-centering functions in a single compact unit (Fig. 3). LRBs are similar to standard reinforced elastomeric bearings with steel connection plates at top and bottom for connection to the superstructure and substructure, with one key difference: they also include a lead plug at the core, joining one connection plate to the other, which deforms plastically when subjected to large horizontal forces during an earthquake and thus dissipates energy, reducing it locally by up to 30%, through hysteretic damping and heat generation [3]. Thanks also to its relatively small size and robustness, and corresponding advantages in relation to installation in a new structure, retrofitting in an existing structure and inspection and maintenance (generally limited to periodic visual inspections), LRBs are the most widely used seismic isolation solution in the world. Some recent examples of their use in Latin America follow [4].

2.2 Case Study: Seismic isolation of Hotel via Vallejo, Mexico City, Mexico

This building, housing two different Marriot hotels, the Courtyard and the Fairfield, is being constructed on top of a large new mall called Via Vallejo in the center of Mexico City. The 10-floor building, shown in Fig. 4, has been designed to not only withstand the effects of the severe earthquakes in Mexico City, but also to ensure the serviceability of the hotel during and after the seismic event. To improve the seismic response of the building, the responsible design engineers performed extensive, complex, three-dimensional dynamic analyses which confirmed that the best strategy was to seismically isolate the hotel from the mall underneath. This is being achieved by the provision of 18 LRBs to support the entire hotel structure (Fig. 5). The technical specifications and dynamic properties of the isolators are show in Table 1. The hysteresis loop is shown in Fig. 6.

Fig. 4 – Representation of the Hotel Via Vallejo, Mexico City

Fig. 5 – Isolators at the base of the Hotel Via Vallejo building during construction

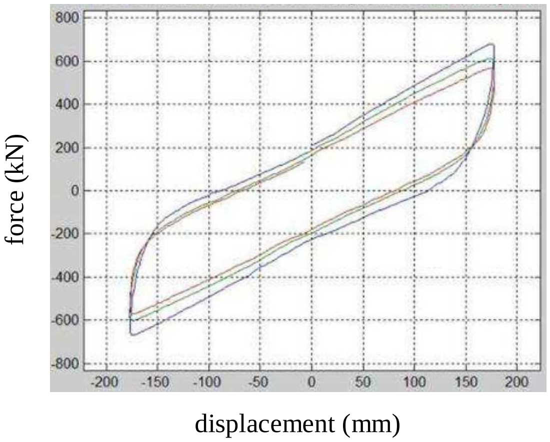

Fig.6 – Hysteresis Loop of Via Vallejo Building

Table 1 – Technical specifications of LRB designed for Hotel Via Vallejo.

Parameter	Symbol	Unit	Type A
Diameter	D	mm	750
Total height	H	mm	329
Maximum static load	N_{Sd}	kN	6,350
Maximum seismic load	N_{Ed}	kN	5,500
Design displacement	d_{bd}	mm	200
Horizontal force	V_{bd}	kN	597
Post-elastic stiffness	K_d	kN/mm	2.18
Effective stiffness	K_{eff}	kN/mm	2.99
Characteristic strength	Q_d	kN	161
Energy dissipated per cycle	EDC	kN-m	129.31
Damping ratio	ξ	%	17

2.3 Case Study: Seismic isolation of Sky Building, Guayaquil, Ecuador

The Sky Building (Fig. 7) in Guayaquil, Ecuador will be part of a commercial complex called Aerocity. This 15-floor building, which consists of four parking levels and eleven office floors, has been designed in accordance with the latest advances in terms of seismic protection, to ensure that it will be able to survive a severe earthquake without suffering damage that could jeopardize its serviceability at any time.

Fig. 7 – Representation of the Sky Building

Fig. 8 – Installation of an LRB during construction

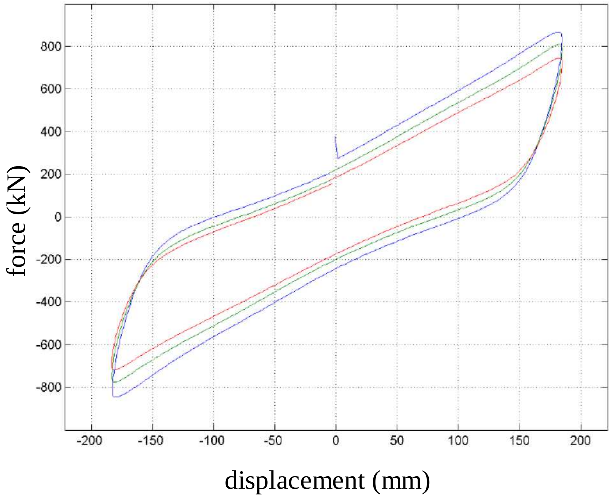

Fig. 9 – Hysteresis Loop of isolators for Sky building

Table 2 – Technical specifications of LRB designed for Sky Building

Parameter	**Symbol**	**Unit**	**Type A**	**Type B**	**Type C**
Diameter	D	mm	850	750	700
Total height	H	mm	340	340	347
Maximum static load	N_{Sd}	kN	10,000	6,000	6,000
Maximum seismic load	N_{Ed}	kN	8,500	7,000	5,000
Design displacement	d_{bd}	mm	200	200	200
Horizontal force	V_{bd}	kN	734	578	506
Post-elastic stiffness	K_d	kN/mm	2.68	2.09	1.84
Effective stiffness	K_{eff}	kN/mm	3.67	2.89	2.53
Characteristic strength	Q_d	kN	198	161	154
Energy dissipated per cycle	EDC	kN-m	158.5	129.31	111.5
Damping ratio	ξ	%	17	17	17

The seismic protection strategy chosen for this building is based on the seismic isolation principle, with 64 LRBs installed on top of the parking structure to support the hotel structure (Fig. 8), isolating the movements of one from the other. Three different types of LRB were designed for different loading scenarios, with 44 flat sliders also contributing to the isolation system.

Table 2 presents the technical specifications and dynamic properties of the LRBs designed for this project. The hysteresis loop is shown in Fig. 9.

2.4 Case Study: Seismic isolation of PDVSA Oil Refinery, Falcon, Venezuela

In the process of making an oil refinery in a seismically active part of Venezuela safe from the destructive effects of earthquakes, heat exchange tanks were seismically isolated from ground movements in 2012 (Fig. 10). The uninterrupted operation of such refineries is of great importance to the Venezuelan economy, with revenue from petroleum exports accounting for over 50 % of the country’s GDP and roughly 95 % of total exports.

This project required the use of six LRBs with a diameter of 220 mm and height of 165 mm including 20 mm steel connection plates. The lead core at the bearing’s vertical axis has a diameter of 44 mm. Each bearing is designed for a vertical service load of 780 kN and to allow seismic displacements of up to 100 mm, as shown in Table 3.

Fig. 10 – Oil refinery area equipped with elastomeric isolators

Table 3 – Technical specifications of LRB designed for PDVSA Oil Refinery

Parameter	Symbol	Unit	Type A
Diameter	D	mm	220
Total height	H	mm	165
Maximum static load	N_{Sd}	kN	780
Maximum seismic load	N_{Ed}	kN	450
Design displacement	d_{bd}	mm	100
Horizontal force	V_{bd}	kN	59
Post-elastic stiffness	K_d	kN/mm	0.42
Effective stiffness	K_{eff}	kN/mm	0.59
Characteristic strength	Q_d	kN	186
Energy dissipated per cycle	EDC	kN-m	87
Damping ratio	ξ	%	17

3. Energy Dissipation / Damping

Energy dissipation is another very important way of protecting structures from the effects of earthquakes. Since energy can neither be created nor destroyed, the potentially enormous amount of energy introduced to a structure during an earthquake must be safely transmitted to connecting structures or dissipated (Fig. 2) if it is not to cause severe damage. As described above, seismic isolators very often include an element of energy dissipation, but energy dissipation can also be provided by other means such as shock absorbers (viscous dampers).

Independent damping solutions such as shock absorbers can provide a much higher degree of damping than seismic isolators, and may be the only solution where seismic isolators cannot be retrofitted to an existing structure or in structures where seismic isolation cannot be recommended (e.g. in the case of soft soils). Quite frequently, optimal seismic isolation and energy dissipation performance can be ensured by combining seismic isolators with independent shock absorbers on the same structure.

3.1 Shock Absorbers (Viscous Dampers)

Shock absorbers are velocity-dependent devices that consist primarily of a piston, a piston rod and a cylinder pipe (Fig. 11 and Fig. 12). They allow free movements of a structure during service conditions, but control displacements and dissipate energy during sudden movements due to earthquakes or during exceptional loading from traffic, wind, etc. The resistance force provided by the unit depends on the flow of a viscous fluid from one chamber of the cylinder pipe into the other, through small holes whose size determine the damping characteristics of the shock absorber. By dissipating energy from sudden, exceptional loading, shock absorbers reduce the impact on the structure, protecting it from damage. This allows the design of the structure to be optimized, avoiding conventional strengthening which might be rarely or never needed during the lifetime of the structure.

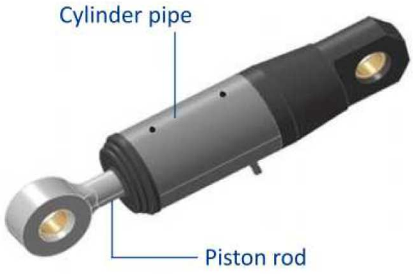

Fig. 11 – Model of a shock absorber (viscous damper)

Fig. 12 – Installed shock absorber

Shock absorbers dissipate over 30 % of the energy introduced, which can be additional to the energy dissipation effect of seismic isolators if also used to protect the same structure. The viscous fluid used is protected against aging by special additives, while the fluid itself protects the device from inner corrosion. Viscosity of the fluid remains nearly constant with respect to temperature variations, making the system thermally compensated. The sealing, which prevents the loss of the fluid and consequent diminishing performance, is the most critical element of the hydraulic system and must be designed and constructed to the highest quality standards. Only high-grade seals that demonstrate quasi-zero wear and absolute physical and chemical compatibility with the viscous fluid should be used.

3.2 Case Study: Seismic energy dissipation at Lerma 256 Building, Mexico City, Mexico

Telmex, the largest telephone company in Mexico, owns several buildings in Mexico City. One of these buildings is currently obsolete due to the new seismic specifications in the city. The Lerma Building is a 17-floor structure including four parking levels, twelve office floors and one penthouse, as shown in Fig. 13. The building's dimensions are 25 m x 15.3 m. The high risk of damage in a very likely earthquake motivated the development of a retrofitting plan. After a detailed evaluation of the options, it was decided to add dampers at different levels in order to improve the dynamic response (Tables 4 to 6).

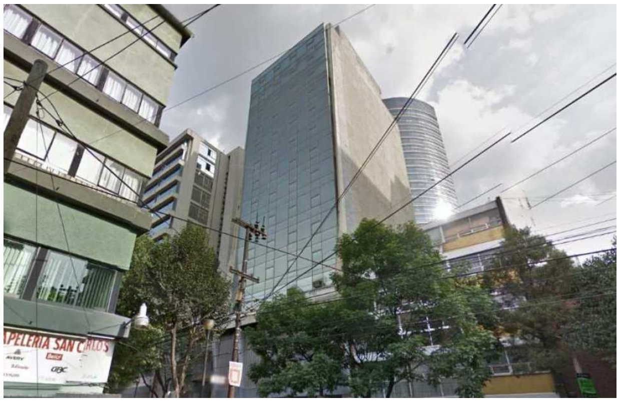

Fig. 13 – Exterior view of Lerma 256 building

Fig. 14 – SA installed in the Lerma 256 building

Table 4 – Technical specifications of Shock Absorbers designed for Lerma 256 building

Parameter	Symbol	Unit	Type A	Type B
Diameter	D	mm	220	180
Length (at central position)	L	mm	1,004	969
Maximum load	N_{Sd}	kN	800	600
Maximum stroke	d_{bd}	mm	± 50	± 50
Alpha	α	-	0.1	0.1
Constitutive law parameter	C	kN/(mm/s)	484	364
Energy dissipated per cycle	EDC	J	66,000	49,600

Table 5 – Test results of shock absorbers designed for Lerma 256 building, type SA 600 ± 50

Test Type	Test Stroke (± mm)	Velocity (mm/s)		Cycles	Freq. (Hz)	Ramp	Result Test	Min	Nominal Value	Max.
Pressure Test						Ramp	No Leakage			
Low Velocity	37.5	0.05		1		tr	5			± 60
Constitutive Law Test	25	1.5	(1%)	3	0.01	sin	411	322	379	436
	25	37.5	(25%)	3	0.3	sin	511	445	523	602
	25	75	(50%)	3	0.6	sin	555	476	560	645
	25	112.5	(75%)	3	0.9	sin	580	496	584	671
	25	150	(100%)	3	1.19	sin	606	511	600	691
Damping Test	23	75.4	50%	5	0.5	sin	45.6	Theoretical EDC	49.6	42.16

Table 6 – Test results of shock absorbers designed for Lerma 256 building, type SA 800 ± 50

Test Type	Test Stroke (± mm)	Velocity (mm/s)		Cycles	Freq. (Hz)	Ramp	Result Test	Min	Nominal Value	Max.
Pressure Test						Ramp	No Leakage			
Low Velocity	37.5	0.05		1		tr	15			± 80
Constitutive Law Test	25	1.5	(1%)	3	0.01	sin	527	428.42	504.03	579.63
	25	37.5	(25%)	3	0.3	sin	640	591.11	695.42	799.74
	25	75	(50%)	3	0.6	sin	725	633.53	745.33	857.14
	25	112.5	(75%)	3	0.9	sin	790	659.75	776.18	892.6
	25	150	(100%)	3	1.19	sin	850	679.01	798.83	918.65
Damping Test	23	75.4	50%	5	0.5	sin	60.36	Theoretical EDC	66.25	56.31

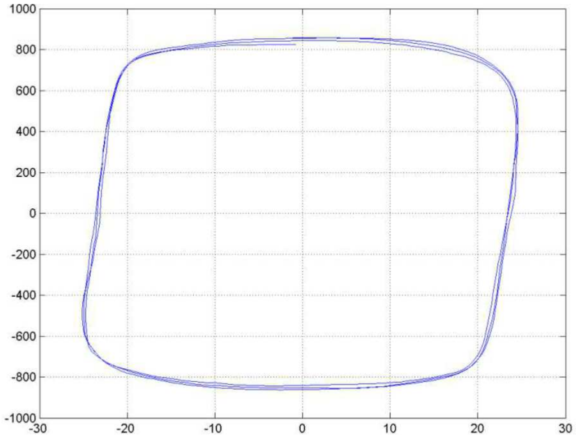

Fig.15 – Hysteresis loop of the SA 800 ± 50 installed at Lerma 256 building

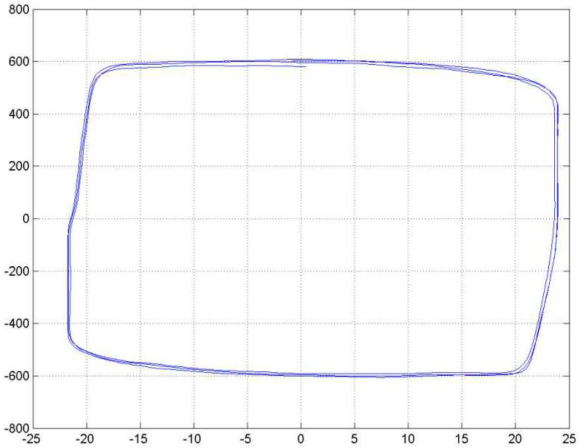

Fig.16 – Hysteresis loop of the SA 600 ± 50 installed at Lerma 256 building

Following evaluation of multiple configurations of dampers, considering variations of loads, displacements and number of devices, it was decided to install 76 shock absorbers (Fig. 14) at carefully selected locations on the building.

Two types of shock absorber were required, for maximum loads of 800 kN and 600 kN respectively, each with a displacement capacity of 50 mm. The details of the dynamic properties of the shock absorbers are presented in Table 4. The detailed test results of the prototype testing of the shock absorbers are presented in Table 5 and 6. The hysteresis loop are shown in Fig. 15 and Fig. 16.

3.3 Case Study: Damping of Merida Cable Car, Venezuela

The Merida Cable Car in Venezuela connects the city of Mérida, at an altitude of 1,640 m above sea level, to Espejo Peak in the adjacent mountains, which is at an altitude of 4,765 m. Climbing over three kilometers along its route of 12.5 km, it is one of the longest and highest cable car systems in the world. It was opened in 1960, and closed in 2008, having reached the end of its service life. The construction of a new cable car system to replace the old one was completed in 2016 (Fig. 17).

The project required two shock absorbers, complete with connection brackets, each designed for a maximum load of 480 kN and maximum stroke of +/- 50 mm, as shown in Table 7. For quality control purposes and to ensure that the dampers perform in service as designed, one shock absorber was subjected to a low velocity test, a constitutive law test and a damping efficiency test, while both units were subjected to pressure and stroke verification tests. The detailed test results of the prototype testing of the shock absorbers are presented in Table 8. The hysteresis loop is shown in Fig. 18.

Fig. 17 – View of the Merida cable car in Venezuela

Table 7 – Technical specifications of Shock Absorbers designed for Merida Cable Car

Parameter	**Symbol**	**Unit**	**Type A**
Diameter	D	mm	160
Length (at central position)	L	mm	980
Maximum load	N_{Sd}	kN	480
Maximum stroke	d_{bd}	mm	± 50
Alpha	α	-	0.3
Constitutive law parameter	C	kN/(mm/s)	70.16
Energy dissipated per cycle	EDC	J	21,300

Table 8 – Test results of shock absorbers designed for Merida Cable Car, type SA 480 ± 50

Test Type	Test Stroke (± mm)	Velocity (mm/s)	Cycles	Freq. (Hz)	Ramp	Result Test	Min	Nominal Value	Max.
Pressure Test					Ramp	No Leakage			
Low Velocity	20	0.1	1		tr	2			± 40
Constitutive Law Test	25	6 (1%)	3	0.04	sin	116	105	121	139
	25	150 (25%)	3	0.95	sin	304	275	317	364
	25	300 (50%)	3	1.91	sin	390	339	390	449
	30	450 (75%)	3	2.39	sin	461	382	440	506
	30	600 (100%)	3	3.18	sin	500	417	480	552
Damping Test	20	113	5	0.9	sin	20	Theoretical EDC	21.3	18.1

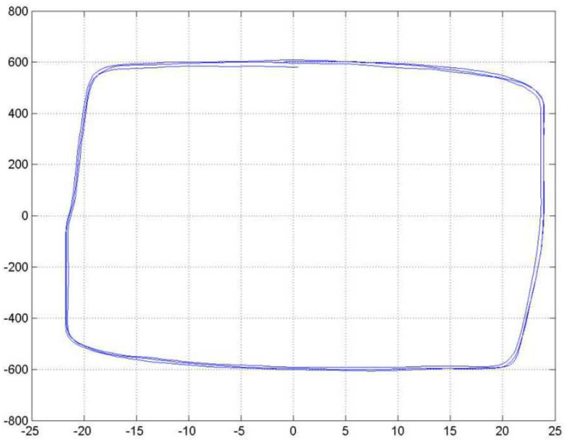

Fig.18 – Hysteresis loop of the SA 480 ± 50 installed at Merida Cable Car

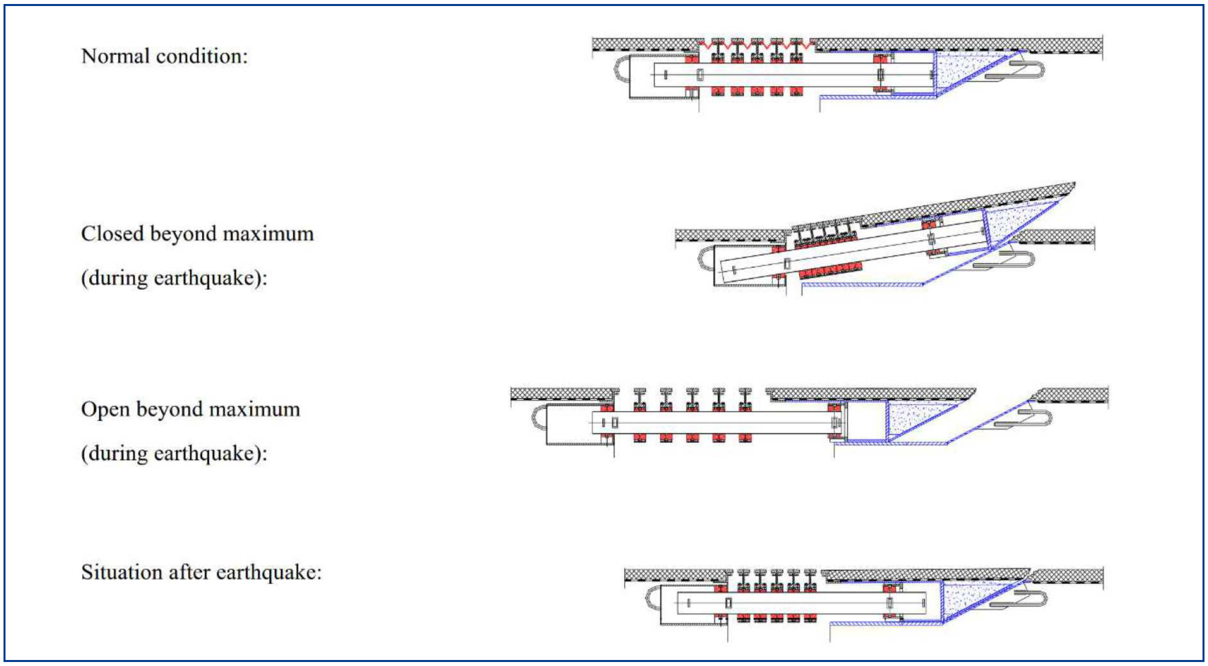

Fig. 19 – Principle of the Fuse-Box seismic protection system for expansion joints

4. *Fuse-Box* Seismic Protection for Bridge Expansion Joints

Fuse-Box consists in principle of a triangular steel "nose" at one side of an expansion joint, which rests (with a connection of designed shear capacity) on a steel ramp that is permanently fixed to the main structure. In the event of an earthquake which causes the joint movement capacity to be exceeded, the connection between nose and ramp will fail, allowing the nose (and joint to which it is connected) to break free of the main structure in a controlled manner, causing little damage to the joint or the structure. After the earthquake, the joint will remain in place across the bridge gap, and with little or no effort should be capable of permitting the passage of emergency and evacuation traffic. It can also with relatively little effort be reconnected to the bridge to allow normal traffic flow to resume. The principle of the system is illustrated in Fig. 19.

4.1 Case Study: Fuse-Box protection of Chilina Bridge, Arquipa, Peru

The Chilina Bridge in the Peruvian city of Arequipa, which opened to traffic in 2014, is a segmental continuous pre-stressed concrete viaduct. With an overall length of 562 m, it is the longest urban bridge in the country, with spans of up to 157 m. Its two 11.3 m-wide decks are box girders with variable depths, as shown in Fig. 20, it is in a highly seismic area, requiring large seismic movements to be allowed for in the design.

Fig. 20 – Chilina Bridge, Peru – featuring modular joints with Fuse-Box protection

The bridge is equipped with four modular expansion joints - two at each end, one per structure. Each has seven individual movement gaps in its driving surface, allowing service movements of up to 560 mm (80 mm per gap). To accommodate the yet larger seismic movements that might arise at some point during the bridge's service life, the joints feature Fuse-Box seismic protection, which, similar to seismic isolation bearings, will prevent the transmission of enormous destructive forces from one part of the structure to another in case of an earthquake.

5. Conclusions

The use of seismic protection strategies such as seismic isolation and energy dissipation has proven to be a sensible approach to the challenges presented by the need to make important structures seismically safe in accordance with current seismic design standards. By providing an alternative to conventional earthquake resistance design measures, it saves the major strengthening works which would otherwise be required. The referenced applications of such seismic protection technologies demonstrate the potential they have to significantly reduce seismic risk without compromising the safety, reliability, and economy of structures.

6. References

[1] Ruiz Julian, F. D., "Seismic performance of isolated curved highway viaducts equipped with unseating prevention cable restrainers", *Doctoral Dissertation*, Graduate School of Engineering, Hokkaido University, Japan, 2005.

[2] Mendez-Galindo, C., Hayashikawa T. and Ruiz Julian F. D., "Seismic damage due to curvature effect on curved highway viaducts", *Proc. 14th World Conference on Earthquake Engineering*, IAEE, Beijing, China, 2008.

[3] Mendez-Galindo, C., Hayashikawa T. and Ruiz Julian F. D., "Seismic performance of isolated curved steel viaducts under level II earthquakes", *Journal of Structural Engineering*, JSCE. Vol. 55A, 2009, pp. 699-708.

[4] Mendez-Galindo, C., Majumdar, S. and Das A.: Advances in Elastomeric Isolators. *IABSE-JSCE Joint Conference on Advances in Bridge Engineering-III*, Dhaka, Bangladesh; 08/2015.