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DYNAMIC PERFORMANCE OF LEAD RUBBER BEARINGS AT LOW TEMPERATURE

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Abstract

Nowadays, even in areas that have not been well known for the application of seismic protective measures, there is a growing tendency to design highway bridges, especially curved ones, to withstand strong seismic demands. A commonly adopted earthquake protection strategy consists of using seismic isolation bearings instead of seismically vulnerable conventional bearings, to isolate the supported bridge deck from the ground movements below. Among the great variety of seismic isolation systems available, the lead rubber bearing (LRB), in particular, has found wide application in highway bridge structures. However, conventional LRBs, which are manufactured from standard natural rubber and lead, display a significant vulnerability to low temperatures.

This paper describes the challenge faced in the seismic isolation using LRBs of a curved highway viaduct where low temperatures must be considered in the design. Specifically, the LRBs must be able to withstand temperatures as low as -30 °C for up to 72 hours, while displaying only minor variations in their effective stiffness. This extreme condition required the development of a new rubber mixture, and the optimization of the general design of the isolators. Since the relevant specifications such as AASHTO Guide Specifications for Seismic Isolation Design and EN 15129: Anti-Seismic Devices contain only limited test data relating to low-temperature performance, extensive full-scale low-temperature dynamic testing was carried out. This testing, which sheds new light on the performance of LRBs at low temperatures, will be described, in the context of the overall challenge to seismically isolate curved highway bridges.

Keywords: seismic isolation; full-scale testing; low temperature; lead rubber bearings

1. Introduction

Increasing awareness of the threats posed by seismic events to critical transport infrastructure has led to the need to seismically retrofit highway viaducts and other bridges to improve their ability to withstand a strong earthquake. Continually evolving technology and the improving evaluation of the design abilities of practitioners have also contributed to the need for such solutions, also incentivized by the increasingly stringent national design standards.

In recent years, curved highway bridges have become more widely used, as the most viable option at complicated interchanges or river crossings. Curved structures are more prone to seismic damage than straight ones, and may sustain severe seismic damage owing to rotation of the superstructure or displacement toward the outside of the curve line due to the complex vibrations that arise during strong earthquake ground motions.

2. Seismic Isolation of Highway Bridges

Bridge's bearings have historically been among its most vulnerable components with respect to seismic damage. Steel bearings in particular have performed poorly and have been damaged by relatively minor seismic shaking [1]. Therefore, a strategy of seismically isolating a bridge's superstructure, by replacing such vulnerable bearings with specially designed protection devices, has much to offer.

Seismic isolation systems provide an attractive alternative to conventional earthquake resistance design, and have the potential for significantly reducing seismic risk without compromising safety, reliability, and economy of bridge structures. Furthermore, with the adoption of new performance-based design criteria, seismic isolation technologies are likely to be increasingly used by structural engineers because they offer economical alternatives to traditional earthquake protection measures [2].

Seismic isolators provide the structure with enough flexibility so the natural period of the structure differentiates as much as possible from the natural period of the ground, as shown in Fig. 1. This prevents the occurrence of resonance, which could lead to severe damage or even collapse of the structure.

An effective seismic isolation system should provide effective performance under all service loads, vertical and horizontal. Additionally, it should provide enough horizontal flexibility in order to reach the target natural period for the isolated structure. Another important capability of an effective isolation system is re-centering, even after a severe earthquake, so that residual displacements that could disrupt the serviceability of the structure are minimized. Finally, it should also provide an adequate level of energy dissipation, mainly through high ratios of damping (Fig. 1), in order to control the displacements that otherwise could damage other structural elements.

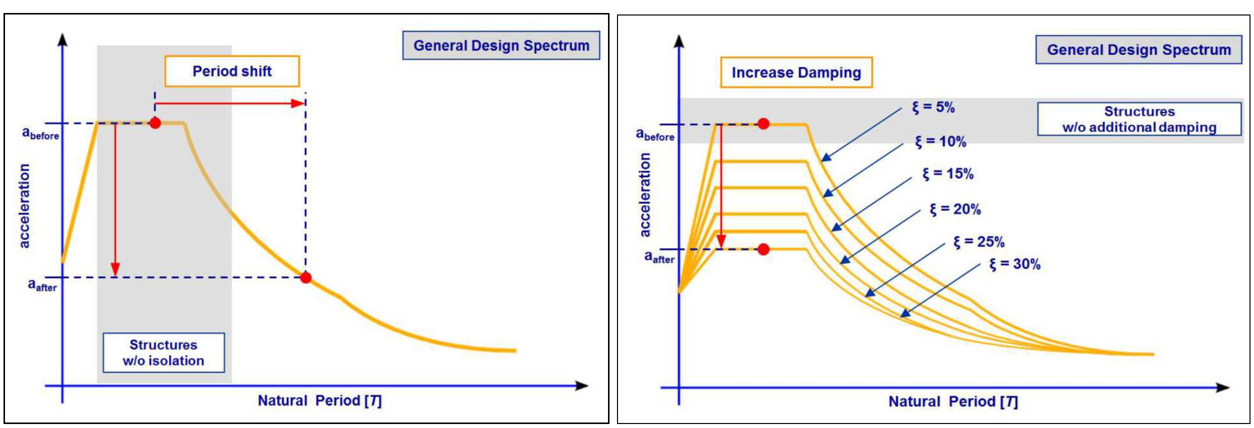


Fig. 1 – Reduction of acceleration by seismic isolation only (left) and then additionally by damping (right)

2.1 Application in bridges

Bridges are ideal candidates for the adoption of base isolation technology due to the relative ease of installation, inspection and maintenance of isolation devices. Although seismic isolation is an effective technology for improving the seismic performance of a bridge, there are certain limitations on its use. As shown in Fig. 1, seismic isolation improves the performance of a bridge under earthquake loading partially by increasing the fundamental vibration period. Thus, the vibration period of a bridge is moved away from the high-energy seismic ground period and seismic energy transfer to the structure is minimized. Therefore, the use of seismic isolation on soft or weak soil, where high period ground motion is dominant, reduces the benefits offered by the technology [3].

The seismic isolation system has a relatively high vibration period compared to a conventional structure. Due to the principle of dynamic resonance, a larger difference between the dynamic vibration frequencies of the isolation system and the superstructure results in a minimized seismic energy transfer to the superstructure. Therefore, seismic isolation is most effective in relatively rigid structural systems and will provide limited benefits for highly flexible bridges. Another consideration is related to the large deformations that may occur in seismic base-isolation bearings during a major seismic event, which causes large displacements in a bridge deck. This may result in an increased probability of collision between deck and abutments. Damping is crucial to minimize the seismic energy flow to the superstructure and to limit the horizontal displacements of the bearings [2].

3. Lead Rubber Bearings

Among the great variety of seismic isolation systems, lead rubber bearings (LRB) have found wide application in bridge structures [4]. This is due to their simplicity and the combined isolation and energy dissipation functions in a single compact unit. Using hydraulic jacks, the superstructure of a bridge that requires seismic retrofitting can typically be lifted to remove the original bearings, easily replacing them with suitable LRB bearings.

LRBs consist of alternate layers of natural rubber (NR) and steel reinforcement plates of limited thickness, and a central lead core (Fig. 2). They are fabricated with the rubber vulcanized directly to the steel plates, including the top and bottom connection plates, and can be supplied with separate anchor plates, facilitating future replacement.

LRBs limit the energy transferred from the ground to the structure in order to protect it. The rubber/steel laminated isolator is designed to carry the weight of the structure and make the post-yield elasticity available. The rubber provides the isolation and the re-centering. The lead core deforms plastically under shear deformations at a predetermined flow stress, while dissipating energy through heat with hysteretic damping of up to 30%.

Fig. 2 – Cut-out view of a typical Lead Rubber Bearing

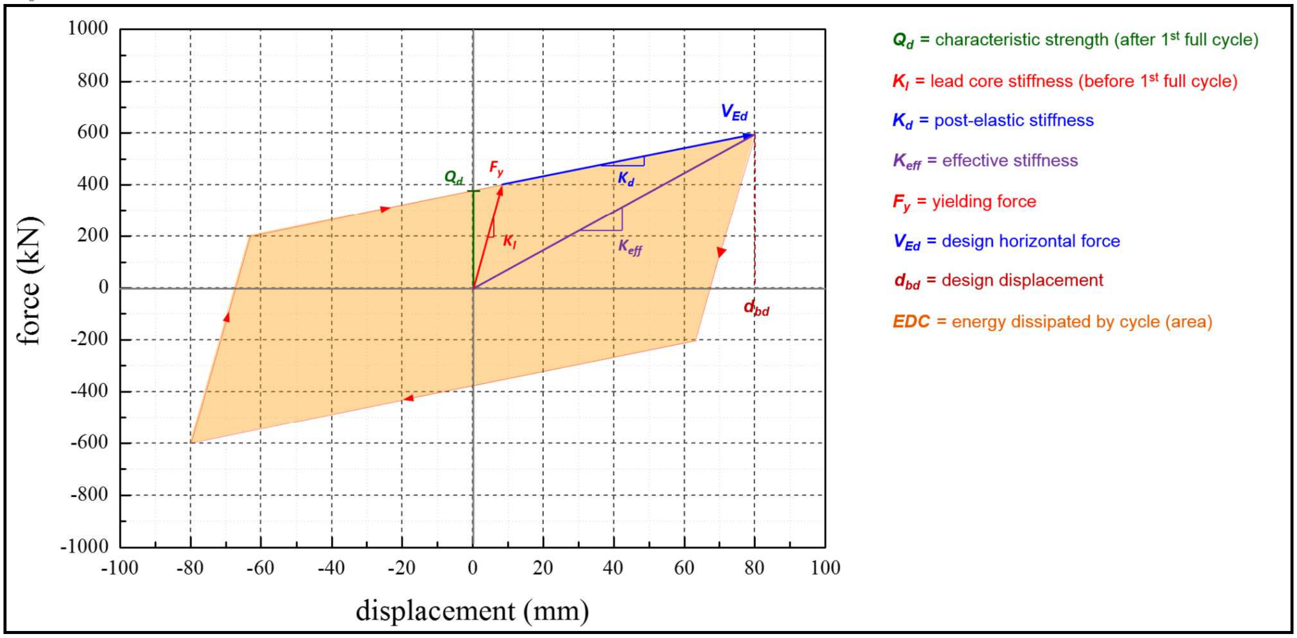


Fig. 3 – Analytical model of an LRB elastomeric isolator

In practice, bridges that have been seismically isolated using LRB bearings have been proven to perform effectively, reducing the bridge seismic response during earthquake shaking. For instance, the Thjorsa River Bridge in Iceland survived two major earthquakes, of moment magnitudes (M_w) 6.6 and 6.5, without serious damage and was open for traffic immediately after the earthquakes as reported by Bessason and Haflidason [5]. LRB bearings of seismically isolated bridges, due to their inherent flexibility, can be subjected to large shear deformations in the event of large earthquake ground motions. According to experimental test results, LRB bearings experience significant hardening behavior beyond certain high shear strain levels due to geometric effects [3].

3.1 LRB analytical model

LRBs have been represented using a number of analytical models, from the relatively simple equivalent linear model composed of the effective stiffness and equivalent damping ratio as formulated by Huang [6] to the sophisticated finite element formulation developed by Salomon [7]. However, the most extensively adopted model for dynamic analysis of seismically isolated structures is the bilinear idealization for the force-displacement hysteretic loop [8]. Due to its simplicity and accuracy in identifying the force-displacement relationship of the isolation devices, LRB bearing supports can be represented by the bilinear force-displacement hysteresis loop given in Fig. 3.

The principal parameters that characterize the model are the pre-yield stiffness K_l, corresponding to the combined stiffness of the rubber bearing and the lead plug, the stiffness of the rubber K_d and the characteristic strength of the lead plug, Q_d. The value of Qd is influenced primarily by the characteristics of the lead plug, but it is important to take into account that in areas of cold temperatures, the use of natural rubber will result in significant increases in force values.

3.2 Full scale testing of LRBs

Prototype testing is frequently required by contracts for the supply of LRB seismic isolators, due to the fact that applications tend to be unique in various ways, considering the structure and the seismic characteristics of the region where it is located. An example of such testing is included in the case study below.

Fig. 4 – View of highway bridge at A40/A73 Interchange in Quebec, Canada

4. Case Study: Highway Bridge at Interchange A40/A73 in Quebec

The seismic isolation of bridges in cold climates is illustrated by the recent retrofitting of seismic isolation bearings to an existing highway bridge, at the A40/A73 interchange, in Quebec, Canada (Fig. 4). Guided LRBs were selected to support the entire bridge superstructure in normal service and to protect the structure during an earthquake by isolating it from the destructive movements of the ground beneath. The LRBs thus ensure the constant serviceability of the structure, even after the occurrence of a strong earthquake, facilitating the passage of emergency vehicles and contributing to the safety of the population. The bridge has a two-span superstructure with concrete girders, with spans of 36m and 42m.

4.1 Design of the LRB

The LRBs (see Fig. 5) are of the guided type, with steel fittings preventing all transverse movements. Each LRB has a vertical load capacity of approximately 3,250 kN – primarily to serve its primary purpose of supporting the deck under normal service conditions. Due to the structure's location, the LRBs were designed for temperatures as high as 40°C (104°F) and as low as -30°C (-22°F). In addition to these severe temperature conditions, the LRBs also had to be designed to fulfil the following requirements:

- Facilitate movements of up to 111 mm in the longitudinal direction
- Prevent movements in the transverse direction
- Provide damping of up to 30%
- Dissipate hysteretic energy up to 58 kN-m per cycle
- Ensure re-centering following an earthquake
- Increase the period of the deck of the bridge to more than 1.7 seconds
- Transmit horizontal loads of up to 414 kN at an ambient temperature of 20°C (68°F)
- Transmit horizontal loads of up to 530 kN at a low temperature of -30°C (-22°F)

These demands presented a significant challenge for design and manufacture, especially in relation to low temperature performance. The bearings were designed to provide optimal performance at 20°C and to minimize variations in dynamic characteristics at very low temperatures. Considering the sensitivity of rubber to low temperatures, this was very difficult to achieve.

Fig. 5 – Guided lead rubber bearings installed in the bridge

However, after a detailed analysis of the effects of temperature on the rubber and the lead, and evaluation of the overall performance of the devices during extensive full-scale testing (as described below), it was possible to develop an optimal solution according to *Canadian Highway Bridge Design Code CAN/CSA-S6*. This solution included design of a new rubber mixture – based on an extensive development program which included testing of a number of rubber samples – and resulted in an optimized LRB design considering all conditions.

4.2 Prototype testing of LRBs

Prototype testing was carried out in accordance with the isolator supply contract, to verify the performance of the LRBs in accordance with their design and the project specifications. The testing included evaluation of the dynamic performance of each device in terms of effective stiffness, damping, energy dissipated per cycle and other parameters such as displacements and forces, as listed above. The testing protocol for room temperature testing is shown in Table 1. Similar testing was required at the specified very low temperature. The test equipment and its configuration, which allows simultaneous testing of two isolators, is shown in Fig. 6. The steel frame holding the isolators was designed to counter the thrust forces that arise during testing of seismic isolation devices.

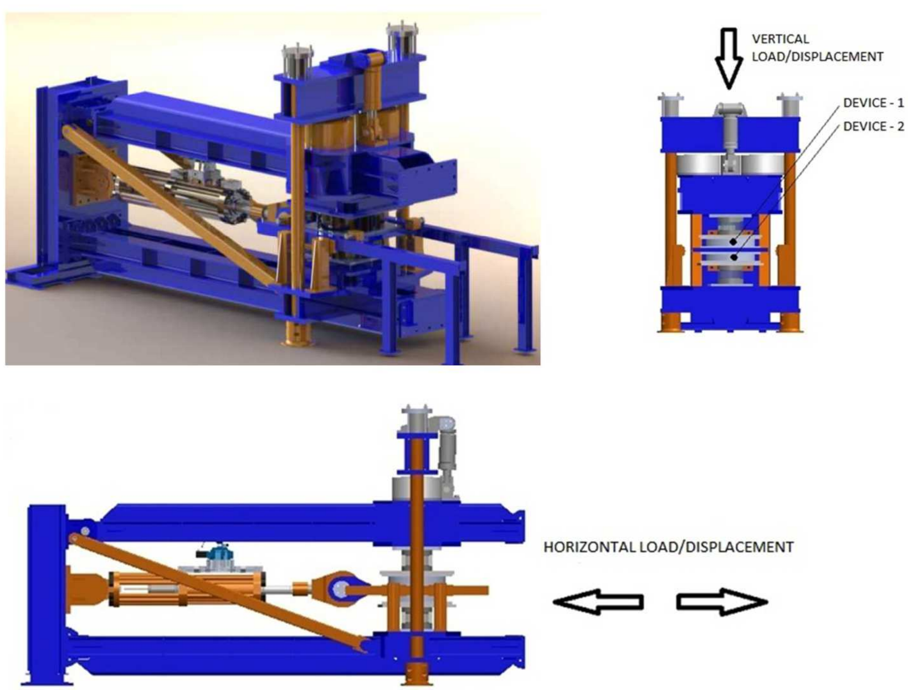


Fig. 6 – Testing equipment and its configuration

Table 1 – Testing protocol required for room temperature performance

Test No.	Test Name	Specification	Main DOF	Amplitude	Cycle Duration	Compression Load	Cycles
			[-]	[mm]	[sec]	[kN]	[-]
1	Thermal / Service	AASHTO 13.2.2.1 CSA 4.10.11.2 (c)(i)	L	± 60	10	1,875	20
2	Wind and Braking: Pre-seismic 1/2	AASHTO 13.2.2.2	L	7	10	1,875	20
	Wind and Braking: Pre-seismic 2/2		V	0	60		0
3	Seismic	AASHTO 13.2.2.3 CSA 4.10.11.2 (c)(ii)	L	± 111	1.5	1,875	3
			L	± 28	1.5		3
			L	± 55	1.5		3
			L	± 83	1.5		3
			L	± 111	1.5		3
			L	± 138	1.5		3
4	Seismic verification	CSA 4.10.11.2 (c)(iii)	L	± 111	1.5	1,875	18
5	Wind and Braking: Post-Seismic 1/2	AASHTO 13.2.2.4	L	7	10	1,875	3
	Wind and Braking: Post-Seismic 2/2		V	0	60		0
6	Stability 1/3	CSA 4.10.11.2 (d)	L	138	60	1,500	loading ramp
	Stability 2/3		L	138	60	2,344	loading ramp
	Stability 3/3		V	0	60	3,250	0

The maximum horizontal load depended on the characteristics of the servo actuators installed, and a nominal value of 1,400 kN was considered. The maximum vertical load of 10,000 kN was provided by two actuators, of 5,000 kN each. The project required consideration of both the AASHTO Guide Specifications for Seismic Isolation Design (AASHTO GSSID) and the Canadian Highway Bridge Design Code (CAN/CSA-S6-06). While AASHTO GSSID requirements are well known and applied, the application of CAN/CSA-S6-06 requirements presented an additional challenge. This code specifies in Section 4.10.11 the main requirements for the testing of seismic isolation devices [9].

The specimens had plan dimensions of 550 x 550 mm and a total height of 236 mm, and were designed for a total design displacement of 111 mm and a test maximum vertical load of 3,250 kN. The samples were subjected to 23 different tests, most of them including dynamic conditions, with frequency and amplitude varying from one test to the next. For all dynamic testing, a vertical load of 1,875 kN was applied to each of the samples.

The testing protocol presented in Table 1 fulfills all specified requirements, incorporating necessary adjustments as required by the project engineer. The following special considerations were taken into account for the prototype testing:

a. Room Temperature Tests (with isolators conditioned at a temperature of 20±5 °C for 48 hours prior to testing):

   i. Three fully reversed sinusoidal cycles at amplitude of 111 mm and peak velocity of 465 mm/s (frequency 0.67 Hz).

   ii. Three fully reversed sinusoidal cycles at amplitudes of 28, 55, 83, 111 and 138 mm (frequency 0.67 Hz).

b. Low Temperature Tests (with isolators conditioned at a temperature of -30 °C for 72 hours prior to testing):

   i. Three fully reversed sinusoidal cycles at amplitudes of 28, 55 and 83 mm and peak velocity of 523 mm/s (frequency 1 Hz).

c. Low Temperature Tests (with isolators conditioned at a temperature of -8 °C for 72 hours prior to testing):

   i. Three fully reversed sinusoidal cycles at amplitudes of 111, 28, 55, 83, 111 and 138 mm and peak velocity of 727 mm/s (frequency 0.83 Hz)

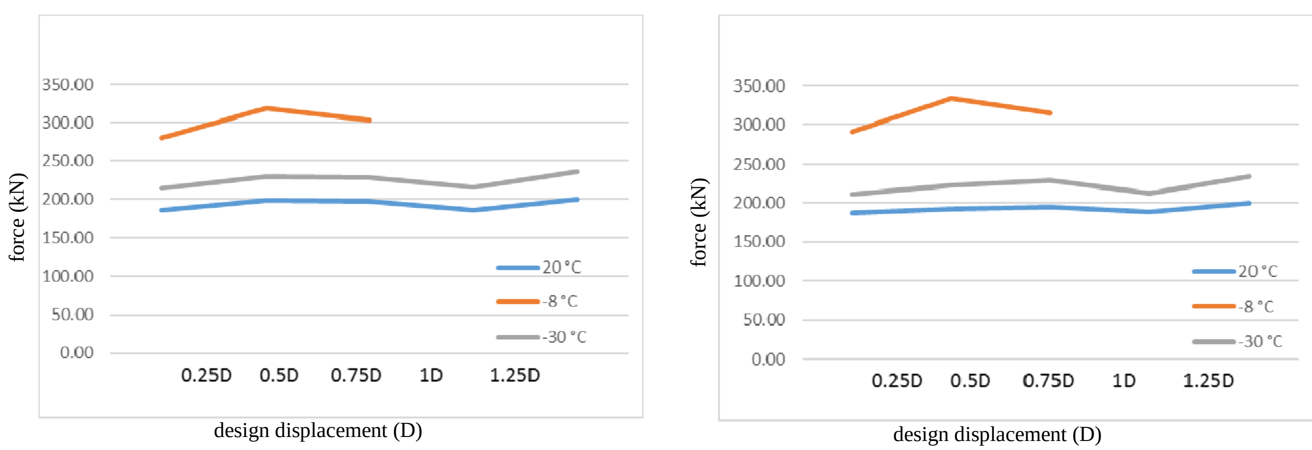
5. Full Scale Test Results

The extensive testing carried out on the two specimens provided a large amount of data. The key performance at room temperature, and a comparison with the performance at low temperature, are presented. The test results are focused on characteristic strength, post-elastic stiffness, effective stiffness, EDC and damping ratio. This results shows the variation on each of these parameter once the isolators are subjected to different temperatures for a period of 72 hours.

5.1 Characteristic strength

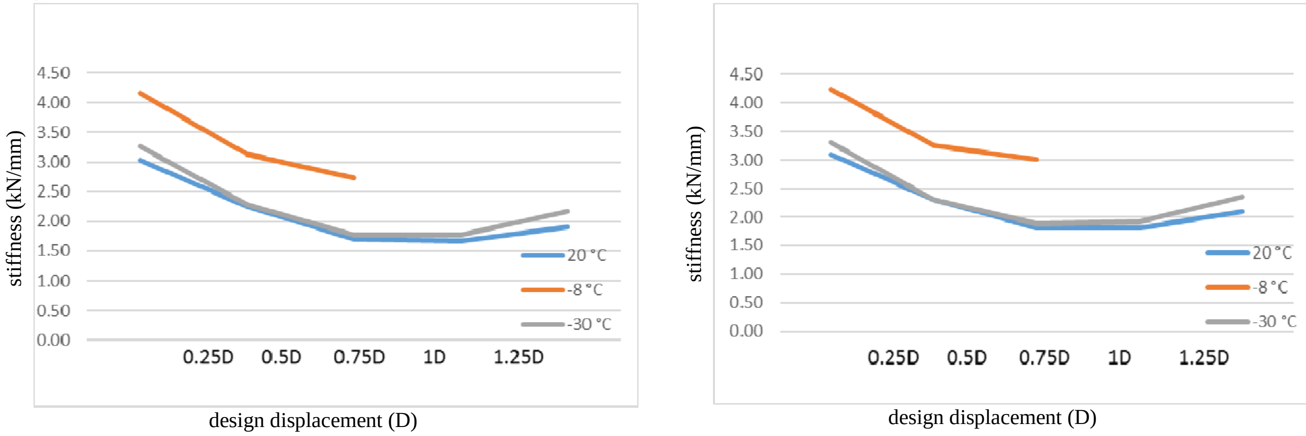
The performance of the two prototypes in terms of characteristic strength is presented in Fig. 7. This specific parameter depends mainly on the lead core performance at different temperatures. The results show that there is an increase on the characteristic strength, particularly in the case of testing at -30 ˚C. In this case, the values increase by a factor of up to 1.7, specifically at a design displacement of 50%. It is also observed that the testing at -8 ˚C does not produce a significant variation, maintaining the performance of the isolator very close to the results at 20 ˚C.

While the values of characteristic strength increase at low temperature testing, it is observed that none of the prototypes show values that could exceed the project expectations, which consider an increase by a factor of 2 in terms of characteristic strength. On the other hand, it can also be observed that the performance of the LRBs is quite consistent among the different shear strains, in all cases, room temperature and low temperature.



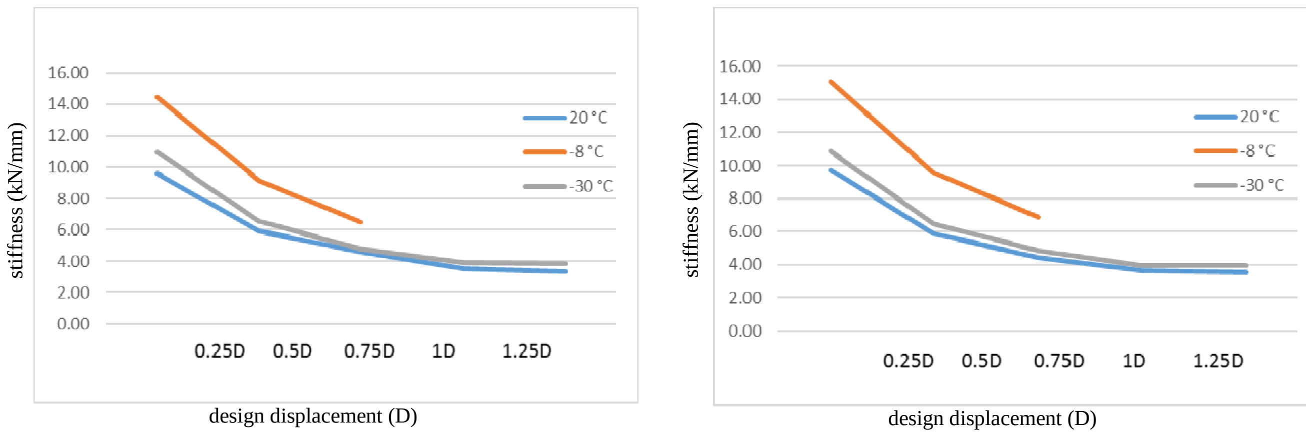
a) Prototype 1 b) Prototype 2

Fig. 7 – Dependence of characteristic strength to different temperatures



a) Prototype 1 b) Prototype 2

Fig. 8 – Dependence of post-elastic stiffness to different temperatures



a) Prototype 1 b) Prototype 2

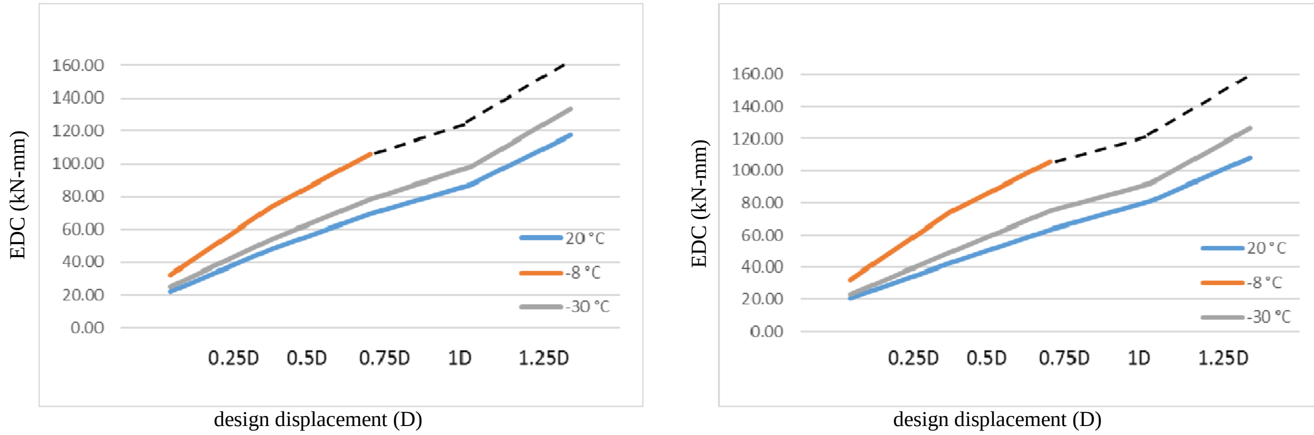
Fig. 9 – Dependence of effective stiffness to different temperatures

5.2 Post-elastic and effective stiffness

In the case of lead rubber bearings, the value of post-elastic stiffness depends entirely on the properties of the rubber and in this specific case, on the dependency to temperature variation. It is naturally expected that the rubber tends to harden when subjected to low temperature, especially the ones specified by this project, where an exposure to -30 ˚C during 72 hours has clearly a direct effect on the increase of the post-elastic stiffness.

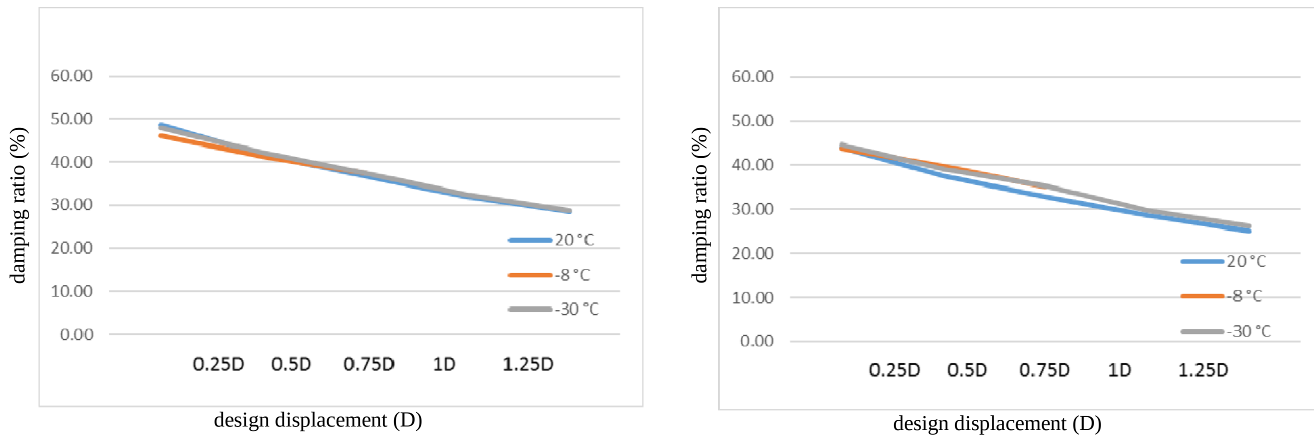
The results presented in Fig. 8 confirm the fact that for lower temperature, the G modulus of the rubber increases, particularly in the results at -30 ˚C. However, it can also be observed that the values shown at such low temperatures actually remain well within the acceptable values by the project specification, which is a key finding due to the expected vulnerability of the rubber to these severe testing conditions. The results also show the consistency of the variation along the different shear strains. The average factor identified in the comparison of room and low temperature is 1.7, the same as the one observed in the characteristic strength results.

Based on the results from the characteristic strength and post-elastic stiffness, it is expected that the results shown in Fig. 9 will be positive as well, especially considering that the effective stiffness will be a resultant of the relationship between the characteristic strength and the post-elastic stiffness. Since both values remained within the acceptable criteria of the project, the results of effective stiffness confirm the compliance of the LRBs.



a) Prototype 1 b) Prototype 2

Fig. 10 – Dependence of EDC to different temperatures



a) Prototype 1 b) Prototype 2

Fig. 11 – Dependence of damping ratio to different temperatures

5.3 EDC and damping ratio

The results presented in Fig. 10 show the clear increase of energy dissipation capacity not only at different shear strains, which is expected, but also at lower temperatures. Since the characteristic strength increases due to the exposure to low temperatures, the energy dissipation capacity therefore increases as well. This is particularly important considering that the force from the earthquake will be defined independently of the temperature. Therefore, the results in Fig. 10 confirms that the LRB will be able to dissipate the same amount of energy, even though the actual displacement at low temperature will be smaller compared to the one at room temperature. This is a key finding, as the energy will be handled by the isolator, and therefore not transferred to the substructure. Fig. 11 shows that in terms of damping ratio, there is no significant effects in terms of temperature variations. This is related to the previous results in terms of EDC. The results also show that for the design displacement, the project requirement of 30% damping ratio is fully provided and therefore the added damping expected for the structure will be ensured during the life cycle of the structure, including the exposure to low temperatures.

5.4 Hysteresis loops at design displacement

The hysteresis loops of the tested LRBs at design displacement are shown in Fig. 12 and 13. These loops clearly show the influence of the low temperature exposure in terms of horizontal forces and actual displacement at room and low temperature conditions.

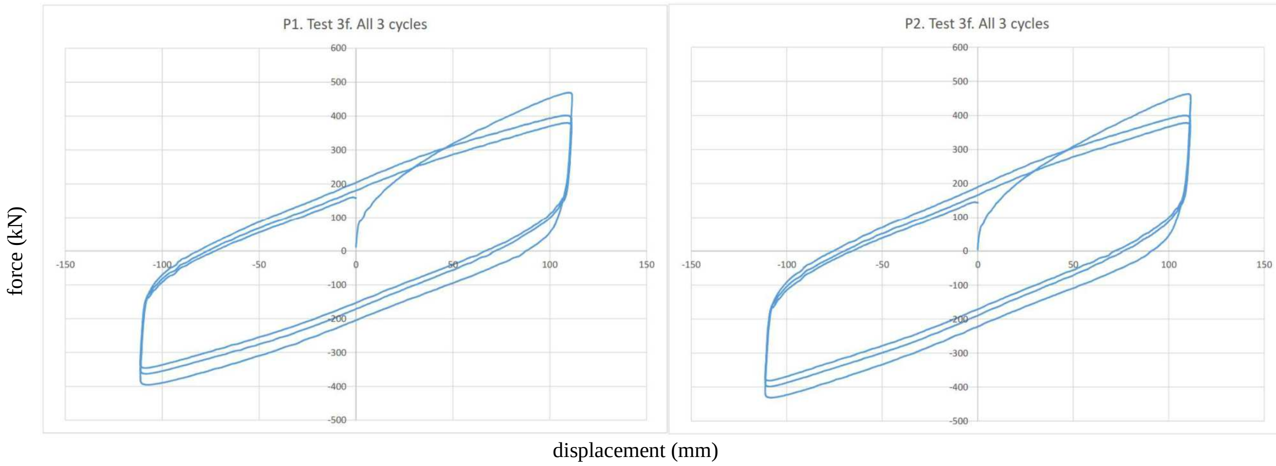


Fig. 12 – Hysteresis loops at room temperature of 20°C (68°F) after 72 hours of exposure

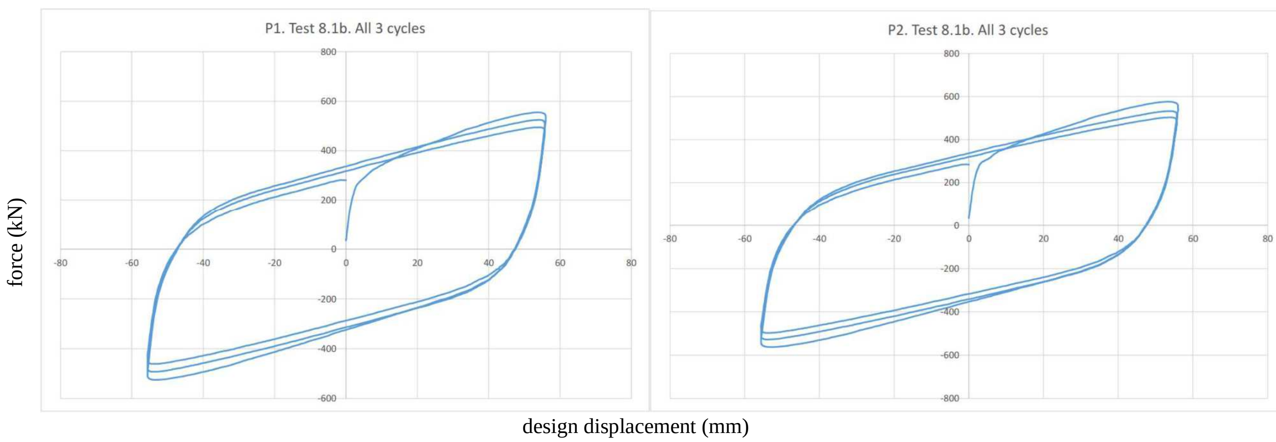


Fig. 13 – Hysteresis loops low temperature of -30°C (-22°F) after 72 hours of exposure

The results in Table 2 demonstrate that the key dynamic parameters such as effective stiffness, horizontal force, post-elastic stiffness and characteristic strength increase by a factor of about two at very low temperatures. However, considering the severe variation of temperature and the strong dependence of rubber's behavior on temperature, these results verified well the effectiveness of these specially developed LRBs at low temperatures, as well as compliance with the project specifications.

Table 2 – Average results of last three cycles of testing, at room and low temperatures

Parameter	Unit	Room Temperature 20°C (68°F)		Low Temperature -30°C (-22°F)	
		Prototype 1	Prototype 2	Prototype 1	Prototype 2
Displacement	mm	111	111	55	55
Horizontal force	kN	392	302	508	533
Post-elastic stiffness	kN/mm	1.7	1.8	3.1	3.3
Effective stiffness	kN/mm	3.5	3.7	9.1	9.6
Characteristic strength	kN	186	188	318	334
Energy dissipated per cycle	kN-m	87	81	73.7	74.2
Damping	%	30	29	30	30

6. Conclusions

Lead rubber bearings, which are widely used to seismically isolate highway bridge structures, display a significant vulnerability to low temperatures (e.g. -30 °C) unless designed and fabricated for such conditions. In particular, their design should ensure that they display only minor variations in their effective stiffness at such temperatures. As in the case study presented, this may require the development of a new rubber mixture, the optimization of the general design of the isolators, and verification of low-temperature performance by means of extensive full-scale prototype testing.

The testing carried out during this study provides enough evidence of the capacity of especially design LRBs to provide and moderate variation in terms of characteristic strength and post-elastic stiffness, which directly leads to lower values of effective stiffness. It is also confirmed that EDC and damping ratios values remain stable even when the LRB have been subjected to severe exposure to low temperature. This provide certainty that eve at low temperature, the LRBs will be able to provide enough energy dissipation capacity and the expected damping ratio.

7. 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] Turkington, D. H., Carr, A. J., Cooke, N. and Moss, P.J., "Seismic design of bridges on lead-rubber bearings", Journal of Structural Engineering, ASCE, Vol. 115, No. 12, 1989, pp. 3000-3016.

[4] Moehle, J. P. and Eberhard, M. O., "Chapter 34: Earthquake damage to bridges", Bridge Engineering Handbook, Boca Raton, CRC Press, 1999.

[5] Bessason, B. and Haflidason, E., "Recorded and numerical strong motion response of a base-isolated bridge", Earthquake Spectra, Vol. 20, No. 2, 2004, pp. 309-332.

[6] Huang, J. S. and Chiou, J. M., "An equivalent linear model of lead-rubber seismic isolation bearings", Engineering Structures, Vol. 18, No. 7, 1996, pp. 528-536.

[7] Salomon, O., Oller, S. and Barbat, A., "Finite element analysis of base isolated buildings subjected to earthquake loads", International Journal for Numerical Methods in Engineering, Vol. 46, 1999, pp. 1741-1761.

[8] 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.

[9] Mendez-Galindo, C., Moor, G, and Miranda, R. "Development and Full Scale Testing of LRB for Bridges Located in Low Temperatures Areas", 14th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures, San Diego, USA; 09/2015.