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Seismic Isolation of Highway Bridges: Effective Performance of LRBs at Low Temperatures

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ABSTRACT: Curved highway bridges are widely used in modern highway systems, often being the most viable option at complicated interchanges or other locations where geometric restrictions apply. 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.

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 and design abilities of practitioners have also contributed to the need for such solutions - as have, of course, increasingly stringent national design standards. In recent years, curved highway bridges (Figure 1) 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.

Figure 1. Construction of a curved highway viaduct.

2. Seismic isolation of structures

A 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 (Ruiz et al., 2005). So a strategy of seismically isolating a bridge's superstructure, by replacing these 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 (Pan et al., 2005). Furthermore, with the adoption of new performance-based design criteria, seismic isolation technologies will be the choice of more structural engineers because they offer economical alternatives to traditional earthquake protection measures (Mendez, 2008).

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 earthquake, as shown in Figure 2. This prevents the occurrence of resonance, which could lead to severe damage or even collapse of the structures. 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 requirement of an effective isolation system is ensuring re-centering capabilities, even after a severe earthquake, so that no residual displacements could disrupt the serviceability of the structure. Finally, it should also provide an adequate level of energy dissipation, mainly through high ratios of damping (Figure 2), in order to control the displacements that otherwise could damage other structural elements.

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 Figure 2, 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 (Turkington et al. 1989). 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.

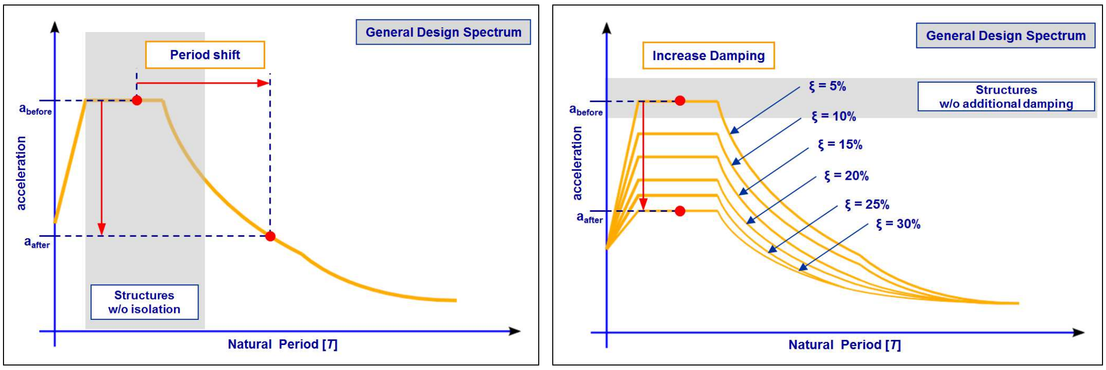


Figure 2. Reduction of acceleration by seismic isolation (left) and by additional damping (right).

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 deck (Pan et al. 2005). This may result in an increased possibility 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 (Mendez, 2008).

3. Lead rubber bearings (LRB)

Among the great variety of seismic isolation systems, lead rubber bearings (LRB) have found wide application in bridge structures (Moehle, 1999). 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 (Figure 3). 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.

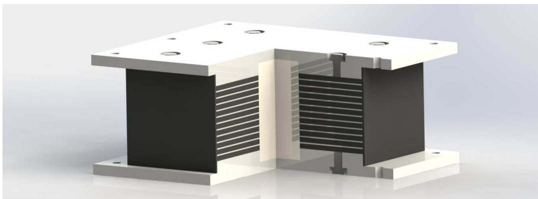


Figure 3. Cut-out view of a multi-directional LRB, showing the lead core at its center.

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%.

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 (Mw) 6.6 and 6.5, without serious damage and was open for traffic immediately after the earthquakes as reported by Bessason and Haflidason (Bessason, 2004).

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 (Turkington et al., 1989).

3.1. LRB analytical model

LRB bearings 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 formulated by Huang (Huang et al., 1996) to the sophisticated finite element formulation developed by Salomon (Salomon et al., 1999). However, the most extensively adopted model for dynamic analysis of seismically isolated structures is the bilinear idealization for the force-displacement hysteretic loop (Ali et al., 1995). 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. 4. The principal parameters that characterize the model are the pre-yield stiffness Kl, corresponding to the combined stiffness of the rubber bearing and the lead plug, the stiffness of the rubber Kd and the yield force of the lead plug Qd. 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.

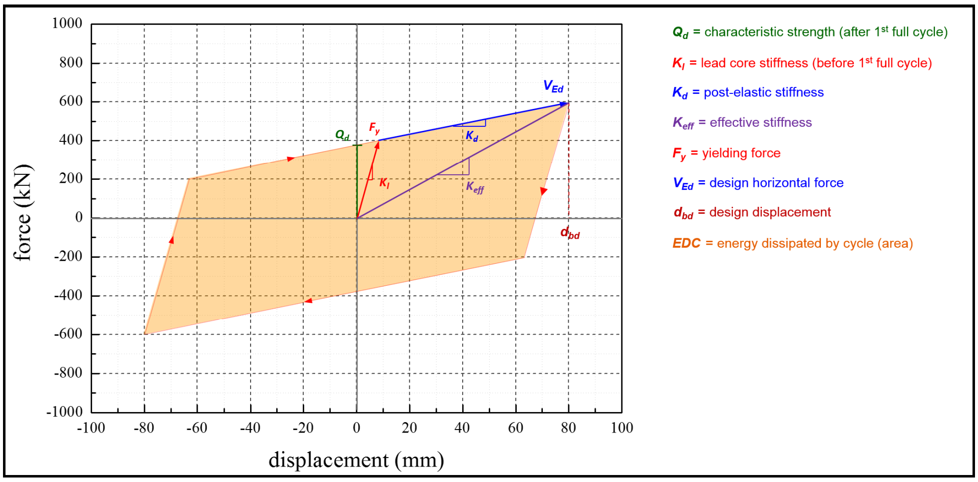


Figure 4. Analytical model of an LRB elastomeric isolator.

4. Testing of LRB seismic isolators

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 both 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.

4.1. Case study: Seismic isolation of New highway viaduct in Quebec

In general, highway bridges in Quebec have not being designed to withstand high seismic demands. However, even though Quebec is not as seismically active as other areas, a certain risk of earthquake damage exists. A recent example of how seismic engineering is now being more widely applied in the design and construction of new structures in Quebec is the seismic isolation of a curved highway viaduct, serving the city of Levis as part of the A20/A73 Interchange.

The new viaduct was constructed adjacent to an existing structure in order to increase highway capacity. LRBs were selected to support the bridge deck 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 viaduct is a six-span structure with a steel girder deck, with spans of between 40m and 60m and a total length of over 300m. With a horizontal radius of 270m, it has a prominent curve which heightens the risk of serious damage during an earthquake and thus increases the need for its deck to be seismically isolated from its supports. The end spans of the deck are supported by conventional pot bearings (at the abutments and on the first pier at each end), while the three internal piers support the deck via LRBs.

Figure 5. Lead rubber bearings installed in the bridge – guided (left) and multi-directional (right).

4.2. Design of the LRBs

Each of these internal piers has six LRBs, one supporting each of the deck's main longitudinal girders. The LRBs at each side of these piers, supporting the outer girders, are multi-directional (facilitating horizontal movements in all directions insofar as these are permitted by deformation of the elastomeric pad and its lead core). The remaining LRBs, supporting the internal girders, are guided, with steel fittings preventing all transverse movements. An LRB of each type is shown in Figure 5. Each LRB has a vertical load capacity of approximately 3,000 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 fulfill the following requirements:

- Facilitate movements of up to 95 mm in the longitudinal direction
- In the case of guided bearings, restrict movements in the transverse direction;
- Provide damping of up to 24%;
- Dissipate hysteretic energy up to 40 kNm per cycle;
- Ensure re-centering following an earthquake;
- Increase the period of the deck of the bridge to more than 2 seconds; and
- Transmit horizontal loads of up to 410 kN at a typical ambient temperature of 20°C (68°F)
- Transmit horizontal loads of up to 600 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. 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, 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.

4.3. 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. 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 the simultaneous testing of two isolators, is shown in Figure 6. The steel frame holding the isolators was designed to counter the thrust forces that are created during testing of seismic isolation devices. The maximum horizontal load depended on the characteristics of the servo actuator installed, and a nominal value of 1400 kN was considered. The maximum vertical load of 10000 kN was provided by two actuators, each 5000 kN.

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.

The specimens each had a plan dimension of 500 x 500 mm and a total height of 284 mm, and were designed for a total design displacement of 95 mm and a test maximum vertical load of 4,677 kN. The samples were subjected to 23 different tests, most of them including dynamic conditions, and with frequency and amplitude varying from one test to the next. For all dynamic testing, a vertical load of 1,715 kN was applied to each of the samples.

Table 1. Testing protocol required for room temperature performance.

Test No.	Test Name	Specification	Main DOF [-]	Amplitude [mm]	Cycle Duration [sec]	Compression Load [kN]	Horizontal Load [kN]	Cycles [-]
1	Thermal / Service	AASHTO 13.2.2.1 CSA 4.10.11.2 (c)(i)	L	± 60	20	1,715	± 190	20
2	Wind and Braking: Pre-seismic 1/2	AASHTO 13.2.2.2	L	7	20	1,715	± 26	20
	Wind and Braking: Pre-seismic 2/2		V	0	60		0	0
3	Seismic	AASHTO 13.2.2.3 CSA 4.10.11.2 (c)(ii)	L	± 95	20	1,715	300	3
			L	± 24	20		75	3
			L	± 48	20		150	3
			L	± 71	20		225	3
			L	± 95	20		300	3
			L	± 119	20		375	3
4	Seismic verification	CSA 4.10.11.2 (c)(iii)	L	± 95	60	1,715	293	10
5	Wind and Braking: Post-Seismic 1/2	AASHTO 13.2.2.4	L	7	20	1,715	± 26	3
	Wind and Braking: Post-Seismic 2/2		V	0	60		0	0
6	Stability 1/3	CSA 4.10.11.2 (d)	L	105	60	1,072	325	loading ramp
	Stability 2/3		L	105	60	2,155	325	loading ramp
	Stability 3/3		V	0	60	4,677	0	0

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 prototypes testing:

- Room Temperature Tests (with isolators conditioned at the temperature of 20±5 °C for 48 hours prior to testing):
  - 5 fully reversed sinusoidal cycles at amplitude of 95 mm and peak velocity of 200 mm/s (frequency of 0.333 Hz).
  - 3 fully reversed sinusoidal cycles at amplitude of 95, 24, 48, 72, 95 and 119 mm and frequency of 0.333 Hz.

- o Low Temperature Tests (with isolators conditioned at the temperature of -30 °C for 72 hours prior to testing):
  - 5 fully reversed sinusoidal cycles at amplitude of 95 mm and peak velocity of 200 mm/s (frequency of 0.333 Hz).

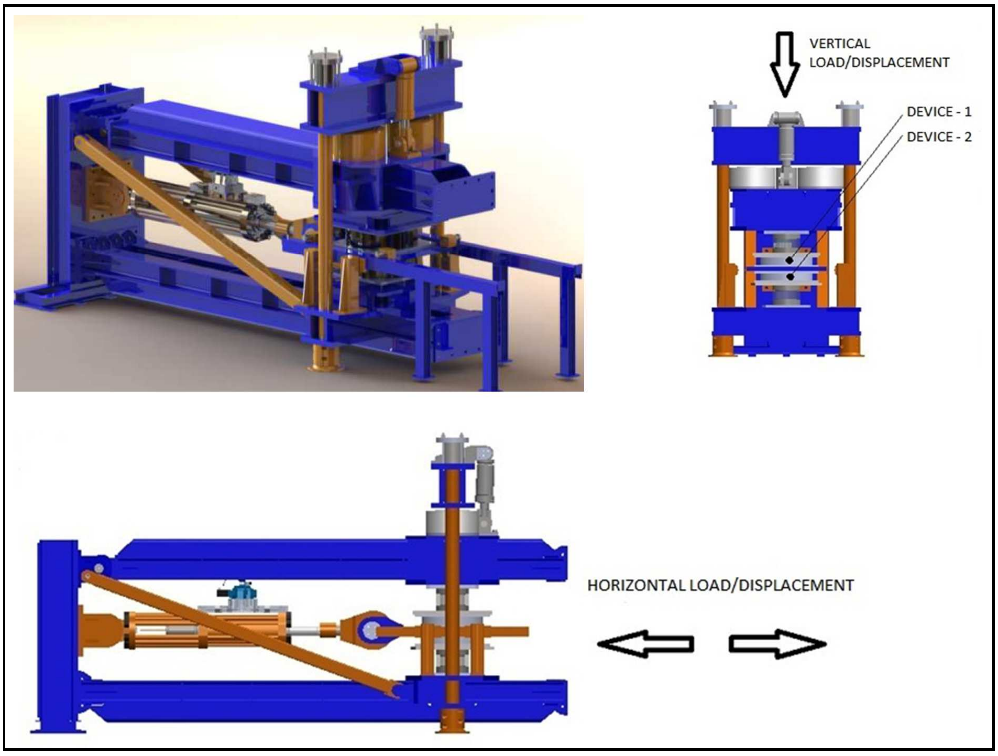
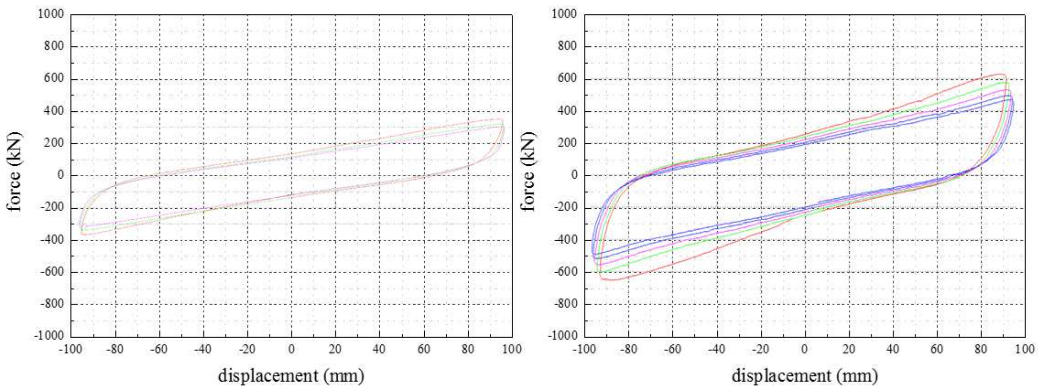


Figure 6. Testing equipment and its configuration.

4.4. Low temperature results

The extensive testing carried out on the two specimens provided a large amount of data. Here, only the key performance at room temperature, and a comparison with the performance at low temperature, are presented. Figure 7 shows the main hysteretic responses at room temperature (a) and low temperature (b).



a) b)

Figure 7. Test results at a) Room Temperature of 20°C (68°F) and b) Low Temperature of -30°C (-22°F) after 72 hours of exposure.

Table 2. Average results of the last three cycles of the prototype testing, at room and low temperatures

Parameter	Unit	Room Temperature 20°C (68°F)	Low Temperature -30°C (-22°F)
Displacement	mm	95	95
Horizontal force	kN	302	589
Post-elastic stiffness	kN/mm	1.91	3.88
Effective stiffness	kN/mm	3.17	6.33
Characteristic strength	kN	120	220
Energy dissipated per cycle	kN-m	43.12	88.06
Damping	%	24	25.6

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.

5. Conclusions

Lead rubber bearings (LRB), 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.

6. References

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