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# Seismic performance of base isolated bridges at subfreezing temperature

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## ABSTRACT

Seismic isolation is one of the most effective ways to minimize structural damage and save lives during and immediately after any seismic event. It is also a cost-effective method to meet performance-based design requirements for minimal or repairable damage. The objective of base isolation is to provide enough horizontal flexibility during seismic excitation while providing adequate performance under all service load. Rubber based isolation systems, such as elastomeric bearing and Lead Rubber Bearing (LRB), have been widely used as seismic isolators for bridges. Due to its superior performance and combined isolation and energy dissipation functions in a single compact unit, LRB has gained much popularity in bridge industry. However, the main constituent of LRB, rubber, is very sensitive to low temperatures and related duration of exposure. The objective of this study is to evaluate the seismic performance of a base isolated bridges at subfreezing temperature. The bridge is seismically isolated using LRB and assumed to be located in Montreal, QC where a temperature variation between +35$^{0}$C to -35$^{0}$C is expected. Using a detailed 3D finite element of the bridge and bearing properties at summer and winter service temperature, the performance of the isolated bridge will be evaluated in terms of isolator force-deformation relationship, force demand in the substructure, and deck acceleration. The outcome of this study will emphasize the necessity of considering low temperature effect on elastomeric seismic isolation system in seismic response analysis.

Keywords: Seismic isolation, Seismic performance, Low temperature, Lead rubber bearing, Flexibility.

## INTRODUCTION

Seismic isolation is a mature technology for seismic protection and decreasing the seismic demand on bridges, buildings, and other civil infrastructures. The benefit of using seismic isolation and other seismic protection devices is well documented [1-4]. The aim of bridge seismic isolation is to decouple the superstructure response from a seismic excitation thus reducing the deck acceleration and force transmitted to the substructure. Seismic isolation limits the load transmitted from the superstructure to the substructure by introducing significant displacement of the superstructure in extreme seismic events. An effective seismic isolation provides the bridge with adequate flexibility to shift the natural period away from the predominant earthquake period. This helps avoiding resonance which could result major damage or even collapse of the bridge.

Elastomeric isolation bearings such as low damping natural rubber bearings (NRB), high damping rubber bearings (HDRB), and lead rubber bearings (LRB) have been widely used in seismic control and damage mitigation of infrastructures [5-7]. Among different seismic isolation systems, LRBs have gained much popularity and have been implemented in numerous new construction and retrofit applications. This can be attributed to the simplicity of LRB system as well as the combined isolation, energy dissipation, and re-centering function provided as a single-compact unit [8].

In 2014, the latest edition of Canadian Highway Bridge Design Code [9] introduced new testing requirements for seismic isolation bearings at low temperature. The code requires that the prototype bearings should be tested under minimum service temperature without displaying major variations in effective stiffness and energy dissipation. However, other relevant specifications, such as AASHTO Guide Specifications for Seismic Isolation Design [10] and EN 15129: Anti-Seismic Devices [11], do not require low temperature testing of isolation bearings. Guay and Bouaanani [12] complied important climatic data and performed relevant analysis for evaluating the low temperature exposure for design and evaluation of elastomeric bridge bearings and isolators in Canada. They concluded that the low temperature testing criteria specified in CHBDC [9] can be too conservative based on geographic location.

However, full scale test results of LRB isolation bearings are very few. Qayyum [13] investigated the long-term behavior of elastomeric seismic isolation bearings subjected to a wide range of temperatures. He found that the effective stiffness of elastomeric bearings increased by 180% at low temperature. Mendez-Galindo et al. [8] evaluated the dynamic performance of isolation bearings at low temperature. They performed full scale tests on LRBs at low temperature of -30$^{0}$C. They reported significant variably in mechanical properties of LRBs at low temperature as compared to ambient temperature. They concluded that special design and fabrication process are required to fulfill the low temperature performance requirements of LRBs as specified in CHBDC [9].

The objective of this study is to evaluate the seismic performance of a LRB base isolated bridges at subfreezing temperature. The bridge is seismically isolated using LRBs and located in Montreal, QC where a temperature variation between +35$^0$C to -35$^0$C is expected. Using nonlinear time history analysis, the performance of the isolated bridge is evaluated under summer (+25$^0$C) and winter (-30$^0$C) conditions. The isolated bridge is analyzed using ten ground motions scaled to Montreal Design spectrum (2475 year return period) with 5% damping. In order to evaluate the seismic performance of the isolated bridges at subfreezing temperature, the base shear in the piers, the acceleration of the bridge deck, and the relative displacement as well as the energy dissipation of LRBs at summer and winter temperature are calculated.

## DESCRIPTION OF THE BRIDGE

A typical four-span continuous highway bridge, isolated by lead rubber bearings (LRB), is used in the current study as shown in Figure 1. The bridge is located in Montreal, QC which is classified as a major route bridge. The bridge is seismically designed following the seismic design guideline of previous edition of the Canadian Highway Bridge Design Code [14]. The bridge is assumed to be located in Site Class-D (stiff soil, average shear wave velocity: 180<Vs<360) according to CHBDC site classification for seismic response. The bridge consists of three piers of 8.5, 6, and 10m high, respectively, and a continuous deck with four identical spans of 30m. The superstructure consists of continuous reinforced concrete (RC) deck and composite steel girder isolated by LRBs. LRB isolation bearings are used at each pier and abutment locations to facilitate the longitudinal and transverse movement of the bridge deck due to thermal loading and earthquake ground motions. The height of the continuous steel girder is 2000mm. The substructures consist of 1500mm circular RC piers supported on concrete drilled shafts (Figure 1b). The circular piers and drilled shafts are reinforced with 32-30M longitudinal bars and 15M spirals at 150mm with 60mm and 100mm cover, respectively (as shown in Figure 1c).

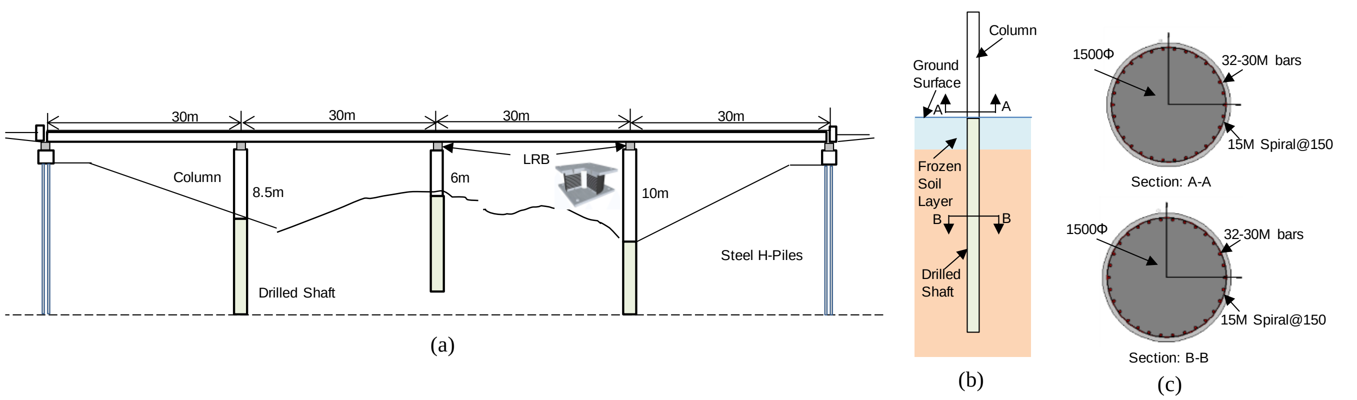


*Figure 1. (a) Elevation of the bridge studied, (b) Details of the soil-foundation system, (c) cross section of column and drilled shaft*

## FINITE ELEMENT MODELING

This section provides detailed information on the analytical modeling of the bridge, soil-foundation system, and isolation bearings used in this study. Using a nonlinear analysis platform, Seimostruct [15], a detailed nonlinear 3-D model of the bridge is developed. 3-D inelastic beam elements have been used for modeling the columns and drilled shafts (Figure 2). Element cross sections are discretized into fibers to represent the distribution of the material's nonlinearity along the length and cross-sectional area of the member (Figure 2a). The Menegotto-Pinto steel model [16] with the Filippou [17] isotropic strain hardening property is used as the reinforcing steel material. The behavior of confined and unconfined concrete is modeled using the non-linear variable confinement model of Madas and Elnashai [18] that follows the constitutive relationship proposed by Mander et al. [19]. The confinement effect of the concrete section is considered on the basis of reinforcement detailing.

Previous research has shown that, plain concrete and reinforcing steel exhibit significant increase in strength when subjected to low temperature [20, 21] without affecting the deformation capacity. In order to account for the effect of subfreezing temperature, the concrete compressive strength and steel strength is calculated using the following two equations proposed by Browne and Bamforth [22] and Montejo et al. [20], respectively.

$$f_c^{'}(T) = f_c^{'}(20^0 C) - Tw/12; \qquad 0^0C > T > -40^0C \qquad (1)$$

$$f_s(T) = 1.1 f_s(20^0 C); \qquad -25^0C > T > -40^0C \qquad (2)$$

The concrete and steel material properties used in the model at summer and winter conditions are provided in Table 1. The superstructure is modeled using elastic beam-column elements with masses lumped along the centerline (Figure 2b). It is assumed that the deck and girder will remain elastic under seismic excitations. Highly rigid beam-column elements, referred to as rigid elements, are used to connect different elements in the model such as piers with cap beams and foundations (Figure 2b). Depending on the sample parameter generated from geometry, materials and mass, the properties of the elastic sections were defined by specifying the values of EA, $EI_2$, $EI_3$ and GJ, where E is the elastic modulus, A is the cross-section area, $I_2$ and $I_3$ are the moments of inertia around local axes (2) and (3), J is the torsional constant and G is the shear modulus.

*Table 1: Material properties for Concrete and Steel*

| Material | Property | Summer | Winter |
|---|---|---|---|
| Concrete | Compressive Strength (MPa) | 35 | 37.5 |
| | Corresponding strain | 0.0030 | 0.0032 |
| | Tensile strength (MPa) | 3.33 | 3.33 |
| | Elastic modulus (GPa) | 26.6 | 27.6 |
| Steel | Elastic modulus (GPa) | 194 | 194 |
| | Yield stress (MPa) | 468 | 515 |
| | Ultimate stress (MPa) | 692 | 692 |
| | Ultimate strain | 0.14 | 0.14 |
| | Plateau strain | 0.016 | 0.016 |

The LRB is idealized using a zero-length spring element with bilinear kinematic behavior in longitudinal and transverse direction (Figure 2c). The bilinear model is defined using the initial stiffness ($K_i$), yield force ($F_y$), and post-yield hardening ratio (r), which are obtained from the experimental test of the LRBs. Table 2 summarizes the mechanical properties of the LRBs used in this study for summer and winter condition. These properties are obtained from the bearing manufacturer based on the tests conducted as per the requirements of CHBDC [9]. However, due to confidential requirements, the bearing manufacturer and test information are not provided in the paper.

*Table 2: LRB Properties at summer and winter temperature*

| Parameter | Summer Temperature ($25^0$C) | Winter Temperature ($-30^0$C) | Unit |
|---|---|---|---|
| Characteristic Strength, $Q_D$ | 187 | 326 | kN |
| Post Elastic Stiffness, $K_d$ | 1.75 | 3.2 | kN/mm |
| Effective Stiffness, $K_{eff}$, | 3.6 | 9.35 | kN/mm |
| Damping, $\xi$ | 30 | 30 | % |
| Yield Force, $F_y$ | 231 | 358 | kN |
| Post-yield hardening ratio, r | 0.19 | 0.089 | |
| Initial Stiffness, $K_i$ | 9.23 | 35.8 | kN/mm |

In order to account for the pounding between abutment and deck, a contact element represented by bilinear gap [23] including the effect of hysteretic energy loss is used (Figure 2d). The impact element is modeled using non-linear springs with the parameters $Kt_1$, $Kt_2$, $\Delta y$, and $\Delta m$ as shown in Figure 2d. In this study, the maximum deformation or penetration $\Delta m$ is assumed to be 25.4 mm and $\Delta y$ is assumed to be $(0.10)(\Delta m)$. The stiffness parameters $Kt_1$, $Kt_2$ are calculated following the model proposed by Muthukumar and DesRoches [23].

Abutments restrain the movement of a bridge superstructure in both longitudinal and transverse directions through the back wall and wing wall, respectively. The seat type abutment is modeled using the simplified bilinear spring using the guidelines prescribed in Caltrans [24]. CHBDC [9] also suggests similar approach for representing abutment lateral stiffness for seismic analysis of bridges with seat type abutments. This model considers three rotational and three translational springs which represent the interaction between abutment, soil, and foundation (Figure 2e). In this study, soil-foundation interaction is considered for the abutment and column foundation without the effect of seasonally frozen soil at low temperature. Spring and dashpot materials represented by zero-length elements are used to model the abutment and column foundation (Figure 2e).

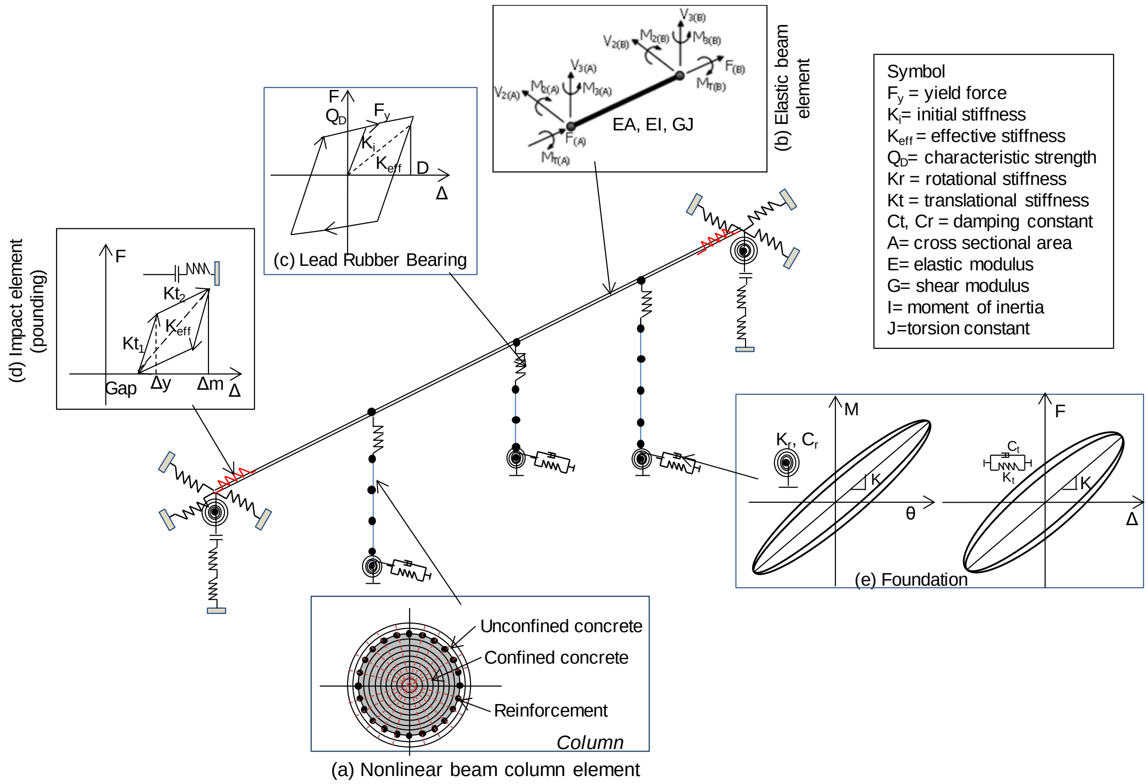


*Figure 2. Details of the finite element model of the bridge*

## SELECTION OF GROUND MOTIONS

Dynamic time history analyses are performed to evaluate the seismic performance of the isolated bridges under summer and winter conditions. Real accelerograms are used for the dynamic analysis of the isolated bridges at different temperatures. These accelerograms are chosen such that they were representative of the seismic motions of the location of the structure. The dynamic analyses are carried out for the 10 selected earthquake records as shown in Table 3. The records selected belong to a bin of relatively large magnitudes 5.3-7.1. The ratio between the peak ground acceleration (PGA) and peak ground velocity (PGV) is an indicator of the frequency content of seismic motion. As reported by Adams and Halchuk [25] and Naumoski et al. [26], ground motions in eastern Canada are typically characterized by high frequency content and high A/V ratios. The selected ground motions have a maximum A/V ratio of 2.63 and minimum A/V of 1.70. These 10 ground motion records were obtained from the PEER strong motion database [27]. Figure 3 shows the acceleration response spectrum (5% damped) for the selected ground motion sets. All the ground motions are scaled using SeismoMatch [28] to match the response spectrum of Montreal, where the bridge is located. Matching is done within the period range of interest, which was $0.2T_1$-$2T_1$ as suggested by CHBDC [9].

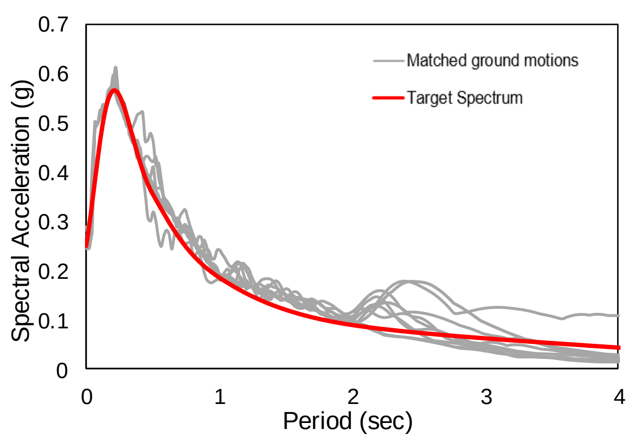


Figure 3. Scaled response spectra of the selected records

*Table 3. Selected earthquake ground motion records. Source: [27]*

| Record ID | Earthquake Name | Year | Station Name | Magnitude | PGA (g) | PGV (m/s) | A/V |
|---|---|---|---|---|---|---|---|
| 1 | Helena_ Montana | 1935 | Carroll College | 6.0 | 0.146 | 0.072 | 2.03 |
| 2 | San Francisco | 1957 | Golden Gate Park | 5.3 | 0.105 | 0.046 | 2.28 |
| 3 | Parkfield | 1966 | Cholame - Shandon Array #5 | 6.2 | 0.434 | 0.255 | 1.70 |
| 4 | Lytle Creek | 1970 | Wrightwood - 6074 Park Dr | 5.3 | 0.198 | 0.096 | 2.06 |
| 5 | San Fernando | 1971 | Lake Hughes #4 | 6.6 | 0.146 | 0.085 | 1.72 |
| 6 | San Fernando | 1971 | Pacoima Dam (upper left abut) | 6.6 | 1.075 | 0.577 | 1.86 |
| 7 | Oroville-01 | 1975 | Oroville Seismograph Station | 5.9 | 0.084 | 0.044 | 1.91 |
| 8 | Nahanni_ Canada | 1985 | Site 1 | 6.8 | 1.101 | 0.462 | 2.38 |
| 9 | Parkfield-02_ CA | 2004 | Parkfield - Temblor | 6.0 | 0.269 | 0.145 | 1.86 |
| 10 | Montenegro_ Yugoslavia | 1979 | Ulcinj - Hotel Albatros | 7.1 | 0.042 | 0.016 | 2.63 |

## RESULTS AND DISCUSSIONS

In order to evaluate the seismic performance of the lead rubber bearings at summer and winter temperature, the base shear in piers, the acceleration at the center of the bridge deck, and the relative displacement and energy dissipation of LRB isolators are evaluated.

### Base Shear in Piers

Seismic isolation bearing is an effective technique for reducing the base shear demand in bridge piers. The function of base isolation is not only to shift the fundamental period away from the predominant earthquake period but also to reduce shear forces acting on the bridge substructure. Figure 4a shows the variation of base shear in the short pier over the time during which the earthquake occurs for ground motion #10. Here ground motion #10 is selected for comparison since it has the largest A/V ratio as shown in Table 3. From this figure, it can be observed that, the shear force in the shortest pier is 685 kN during summer whereas it increases by 27% during winter condition. This can be attributed to the higher stiffness of the isolation bearing as well as the increased concrete and steel strength during winter temperature. Figure 4b shows the comparison of the pier base shear under all ten ground motions considered in this study. From Figure 4b, it is evident that during winter the base shear demand increases significantly with an average increase of 40% as observed in this study. This clearly highlights the importance of considering low temperature performance of isolation bearings in high seismic zones.

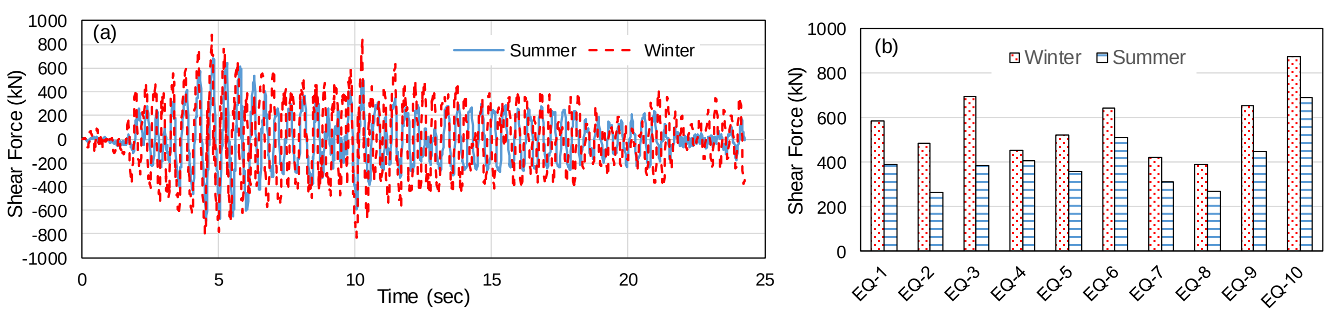


*Figure 4. (a) Base shear-time history of the isolated bridge under EQ#10, (b) Shear force comparison under summer and winter condition*

### Pier top displacement

Figure 5a shows the pier top displacement of the long pier over the time during which the earthquake occurs for ground motion #10. Isolation bearings are known to increase peak displacement responses of the isolated piers, which is a direct consequence of increasing the lateral flexibility resulting from the isolation bearings. Under summer temperature, the bridge pier experienced a maximum deformation of 108mm which reduced to 87mm under low temperature. This can be attributed to the increased stiffness of the LRB systems under low temperature. Evaluation of the pier top displacement under all the ground motions reveal that, there is an average 20% reduction in pier displacement under winter condition as compared to the summer condition.

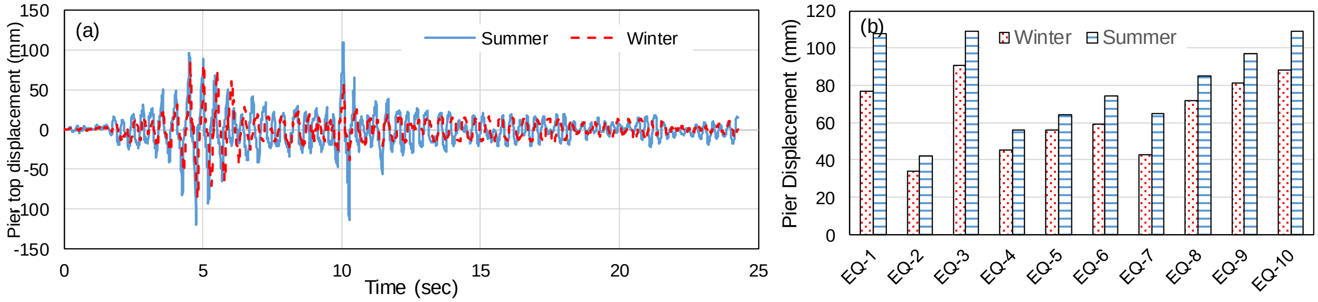


*Figure 5. (a) Pier top displacement-time history of the isolated bridge under EQ#10, (b) Pier top displacement comparison under summer and winter condition*

### Acceleration of the bridge deck

The acceleration of the bridge deck is proportional to the earthquake's forces exerted to the structure. The main responsibility of the LRB isolation system is to significantly reduce the deck acceleration by isolating the superstructure from the substructure. Figure 6a shows the variation of deck acceleration over the time during which the earthquake occurs for ground motion #10. During summer under ground motion #10, the bridge deck experiences a maximum acceleration of 0.36g which is increased significantly up to 0.50g during winter condition. From Figure 4b it can be observed that, irrespective of the ground motions, the deck acceleration demand increased significantly during winter condition at low temperature with an average increase of 45% as observed in this study.

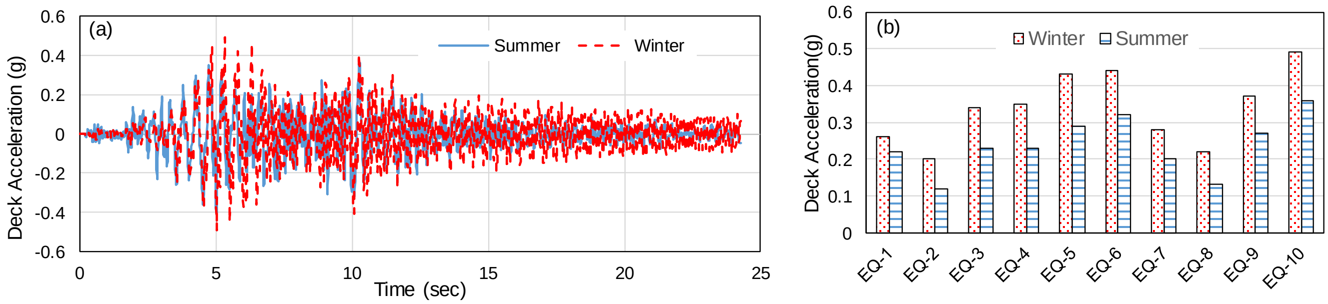


*Figure 6. (a) Deck acceleration-time history of the isolated bridge under EQ#10, (b) Deck acceleration comparison under summer and winter condition*

### Relative displacement of LRBs

Lead rubber bearings should be laterally flexible enough to adequately shift the fundamental frequency of the bridge and, on the other hand, they should have enough horizontal stiffness to control the lateral displacement of the bridge deck caused by the earthquake. In this regard, it is of great interest to determine the shear deformation of LRBs subjected to different ground motions under summer and winter conditions.

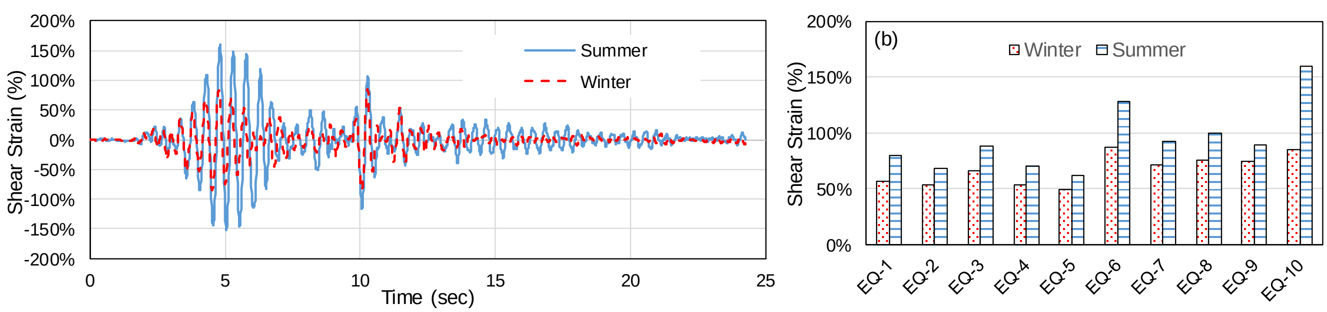


*Figure 7. (a) LRB shear strain-time history of the isolated bridge under EQ#10, (b) LRB shear strain comparison under summer and winter condition*

Figure 7a depicts the normalized relative displacement (i.e. shear strain, γ) of the LRBs under summer and winter condition as a function of time. By comparing peak values of shear strain in two cases, it is observed that the maximum shear strain in LRB exceeds 150% under summer condition while it experiences shear strains lower than 90% under winter condition. This shows that a lower lateral flexibility under winter condition causes the LRB to undergo a lower amount of lateral displacement under same shear forces thus reducing the effectiveness of isolation system. From Figure 7b it is evident that, under winter condition, the LRB experience an average of 26% reduction in shear strain demand.

**Energy Dissipation Capacity**

The effect of low temperature on the hysteretic response of the LRBs are shown in Figure 8 when subjected to ground motion #10. As seen from figure 8, under low temperature, both the bearing deformation and the area of the hysteresis loop decrease significantly. This reduction in hysteresis loop indicates decreased energy dissipation capacity. For the short pier (Figure 8b), the total energy dissipated during summer is 1830 kN.m which is reduced by 24% to 1480 kN.m under low temperature in winter. This effect is more pronounced in the longer pier (Figure 8a) where the energy dissipation is reduced by 42% under low temperature in winter. One of the benefit of using LRB isolation system is to provide substantial amount of additional damping through hysteretic energy dissipation. Under low temperature, this advantage shrinks thus reducing the effectiveness of LRB isolation system. Moreover, due to increased stiffness under low temperature, the period shortens thus increasing the force demand on the isolation bearings.

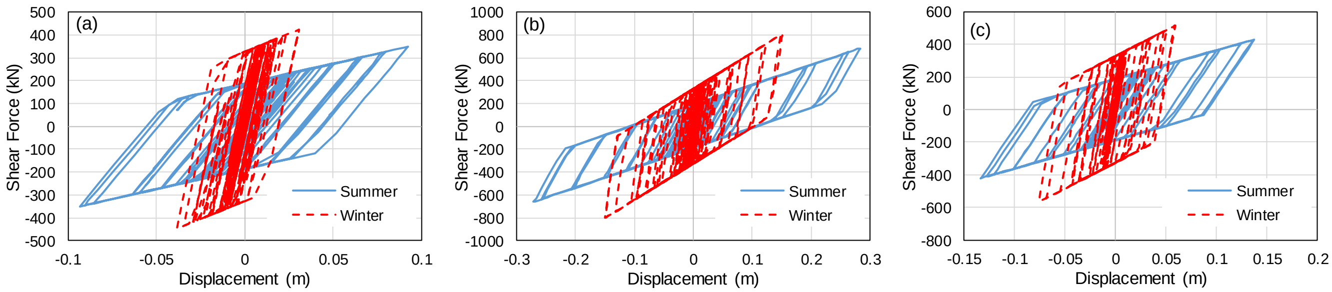


*Figure 8. Hysteretic response of LRBs under summer and winter (a) Long pier, (b) Short pier, and (c) Medium pier*

## CONCLUSIONS

This paper assessed the seismic performance of LRB isolated bridges in terms of pier displacement, shear force, deck acceleration, and energy dissipation considering variability in bearing properties during summer and winter condition. Using nonlinear time history analyses, the effect of subfreezing temperature on the response of seismically isolated bridges are evaluated. Based on the outcome of the numerical analysis, the following conclusions are drawn:

- As observed from LRB property test under low temperature, it is evident that the desirable mechanical properties of LRB are vulnerable at low temperature.
- Under low temperature, LRB isolated bridge piers are susceptible to significantly higher shear force as compared to summer temperature.
- Increased stiffness of the LRB at low temperature reduces the deformation capacity of the bridge thus reduces the effectiveness of using isolation bearings.
- Energy dissipation capacity of the LRB isolation bearings reduces significantly at subfreezing temperature.
- More experimental testing is required to evaluate the performance of LRB isolated bridges at low temperature.
- When designing isolation bearings in regions susceptible to low temperature along with moderate to high seismic demand, the effect of elastomer crystallization should be taken into account.

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