Canadian Conference - Pacific Conference on Earthquake Engineering 2023

Vancouver, British Columbia

June 25th – June 30th, 2023

Earthquake Protection of Bridges Using Seismic Isolation: Case Studies Worldwide

Mohammed S. Mohammed[1*], Scott C. Darling[2], Ahmed F. Ibrahim[2], Javier L. Gimenez[3], Luis Crisanto[4]

[1]Vice President/Director of Engineering, Dynamic Isolation Systems Inc, Reno, NV, USA
[2]Engineering Manager, Dynamic Isolation Systems Inc, Reno, NV, USA
[3]Deputy General Manager/Seismic Engineer, Kawakin Core-Tech Co., Japan
[4]Project Engineer, CDV Ingenieria Antisismica, Peru
[*]mmohammed@dis-inc.com (Corresponding Author)

ABSTRACT

Seismic isolation is a highly effective method of mitigating earthquake hazards. Typically, seismic isolation bearings are placed in a bridge between its substructure and superstructure. These bearings physically separate the superstructure from the horizontal components of a ground motion, reducing the forces on the substructure and superstructure during an earthquake. This results in inelastic deformations occurring in the isolation bearings, allowing the substructure and superstructure to remain elastic and preventing permanent damage to the bridge, which is a common issue with conventionally designed bridges. The primary three design objectives for a seismically isolated bridge are to elongate the fundamental period, which significantly reduce forces in the substructure and superstructure, to further reduce forces through additional hysteretic damping in the isolation bearings, and to redistribute the seismic forces between the piers and the abutments. The first seismically isolated bridge was built in New Zealand during the 1970s. There are more than a thousand bridges around the world, including over 200 in the United States, employ seismic isolation as a cost-effective method for earthquake damage protection. This paper showcases case studies of seismically isolated bridges from various countries, such as the United States, Mexico, Colombia, Turkey, Peru, Japan, and Chile. It also features examples of conventionally designed bridges that suffered damage in seismic events. Additionally, it presents projects with unique challenges and obstacles that required the development and attachment of elastic restraint systems to the isolation bearings. Finally, it includes a case study of a bridge in Mexico that demonstrates the cost-saving advantages of using seismic isolation instead of traditional designs.

Keywords: seismic isolation, earthquake, lead-rubber bearings, seismic mitigation, bridge engineering.

INTRODUCTION

Principles of seismic isolation

The modern concept of seismic isolation began in the 1970's in New Zealand [1]. Many studies have shown the benefits of seismic isolation for the mitigation of damage in structures during severe ground motion shaking [2-3]. The basic concept of seismic isolation is quite simple: seismic isolation bearings (isolators), which are structural elements with high vertical stiffness and low horizontal stiffness, are typically placed between the substructure and superstructure and physically decouple the superstructure from the horizontal components of a ground motion. Consequently, when a seismically isolated bridge is subjected to an earthquake, the inelastic deformations occur in the isolation bearings, reducing forces/accelerations in the substructure and superstructure, allowing them to remain elastic. In contrast, conventionally designed bridges rely on the inelastic response in selected structural elements to dissipate the earthquake energy [4-9]. Figure 1a shows a comparison between a conventional and a seismically isolated bridge. In general, a seismic isolator that is used for a bridge application should have the following three characteristics as a minimum:

- Flexibility from the low horizontal stiffness of the isolators, leading to lengthening the period of vibration of the bridge to reduce the seismic forces in the substructure elements (see Figure 1b).
- Energy dissipation from the introduction of significant level of hysteretic damping to absorb some of the energy of the earthquake. This limits relative displacements between the superstructure and substructure to acceptable levels (see Figure 1b).

- Sufficient initial rigidity to resist service loads, such as wind and braking forces, without activating the isolation system.

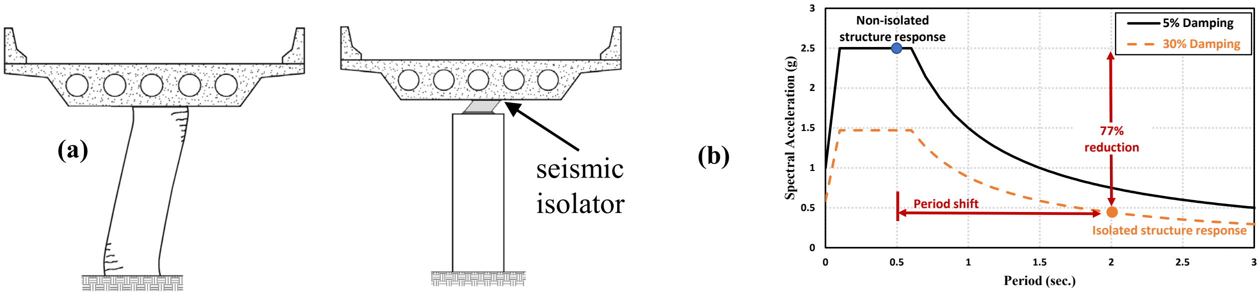

Figure 1. (a) Comparison of a conventional and seismically isolated bridge, (b) Effect of isolator flexibility and damping on bridge performance.

Seismic isolation bearings (isolators)

Seismic isolators or seismic isolation bearings are generally classified into two categories:

- Sliding bearings
- Elastomeric-based isolation bearings:
    - Lead-rubber bearing (LRB): low-damping natural rubber elastomeric bearing with a central lead core to dissipate the earthquake energy during lateral displacements.
    - Low-damping rubber bearing (LDRB): low-damping natural rubber elastomeric bearing without a central lead core. LDRBs can be used alongside with LRBs or with mechanical energy dissipators such as viscous dampers for energy dissipation.
    - High-damping rubber bearing (HDRB): The rubber compound of HDRB has a special composition that increases its energy dissipation capacity without the use of lead cores. HDRBs are more common in Japan [10].

The majority of bridge isolators around the world are elastomeric based bearings, and the most common elastomeric isolator in bridges globally is the lead-rubber bearing [2 and 10], which is the focus of this paper. LRBs have been extensively tested, both in research and in situ, and there are comprehensive guidelines on their design and modelling [11]. Figure 2a shows the main components of an LRB. The LRB is made from layers of vulcanized rubber and steel shims. The rubber layers provide flexibility in the lateral direction, while the steel shims prevent bulging due to axial loads, creating high vertical stiffness. The bearing is fitted with a central lead core which is confined by the steel shims. The lead core provides resistance to service loads, then yields and dissipates energy under earthquake lateral movements. Steel mounting plates are placed on top and bottom of the bearing to connect to the substructure and superstructure. Finally, a resilient rubber compound is used as a cover rubber to protect the bearing's internal components from environmental effects. Figure 2b shows an idealized bilinear force-displacement relationship for an LRB. Figure 2c shows an actual force-displacement test loop for an LRB that was used in a bridge located in the United States.

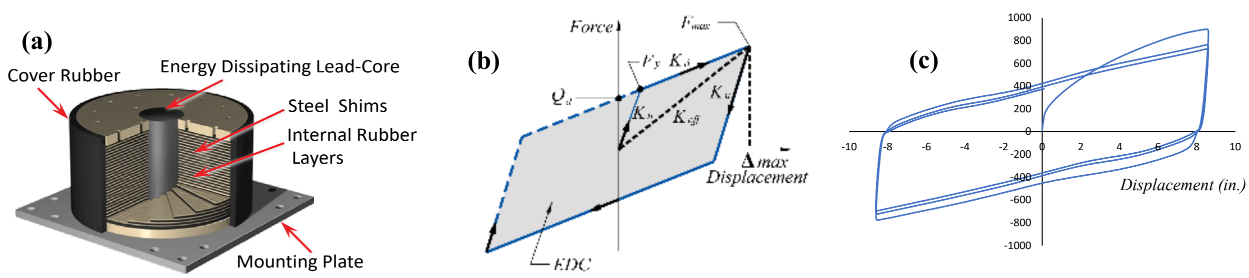

Figure 2: (a) Main components of lead-rubber isolators, (b) Bilinear force-displacement relationship for an LRB, (c) Actual force-displacement test results for an LRB.

Principles of seismic isolation

Using seismic isolation to design bridges can lead to significant improvements in performance under lateral loads. Appropriate selection of bearing properties enables a designer to direct loads away from weaker substructures, and into those substructures with the capacity to resist them. In conventionally designed bridges, the impact of unavoidable variations in column height or foundation conditions on the lateral stiffness of a bridge can be changed, altering the makeup of the substructures. For example, changing a single column support to a wall pier will substantially increase the transverse forces resisted at that location. In this way, the site constraints can be counterbalanced to some extent; however, there is a limit to the extent that altering the pier section properties can help. A better strategy is to introduce isolation bearings to the design. The inherent flexibility of these devices can be used to achieve a more uniform load distribution, or direct forces to or away from certain substructures. The horizontal stiffness of these bearings can vary over a wide range, from near zero to almost rigid by the design parameters of the bearings. Control of load distribution is then feasible despite widely varying substructure properties. Figure 3 shows a simple example of lateral stiffness (K) ratios for short and long columns within the same bridge.

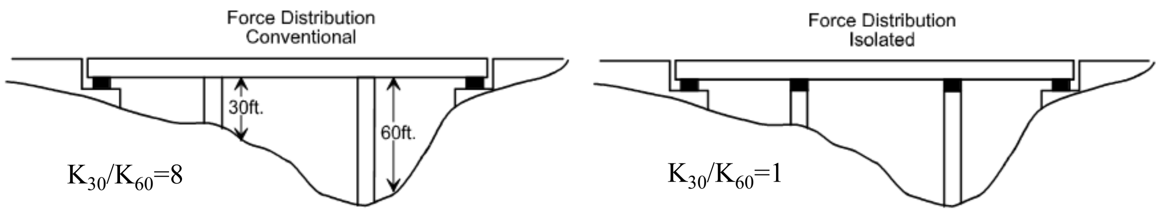

Figure 3: Comparison of lateral force distribution for conventional and isolated bridge designs

CODE PROVISIONS FOR SEISMIC ISOLATION OF BRIDGES

The design of seismically isolated bridges in the United States is governed by the *Guide Specifications for Seismic Isolation Design* (GSID-4) [12] published by the American Association of State Highway and Transportation Officials (AASHTO 2014). The GSID-4 is a supplemental document to the *AASHTO LRFD Bridge Design Specifications* and incorporates the generic requirements for seismic isolation design for bridges. It is the most comprehensive document for seismic isolation of bridges and is being used by engineers in other countries to design seismically isolated bridges. The GSID-4 covers the seismic hazard, analysis procedures, design properties and requirements for isolation systems, property modification factors for different isolator types, and the required tests for validation of the isolation bearings. In the United States, many departments of transportation (DOT) such as Caltrans, Oregon DOT and Washington DOT are adopting seismic isolation in their seismic design guidelines.

In Canada, the Canadian Highway Bridge Design Code (CAN-CSA S6-14) [13] incorporates seismic isolation in the seismic design section. What is presented is very similar to the AASHTO GSID-4 and follows the same design requirements. Other countries like New Zealand, Peru, Chile and Turkey have developed or are in the process of developing seismic isolation guidelines. However, these guidelines are mainly for buildings and not specific for bridges.

PERFORMANCE OF CONVENTIONALLY DESIGNED BRIDGES IN PREVIUOS EARTHQUAKES

This section highlights the structural performance of conventionally designed bridges during previous earthquakes. Countries like Japan, Chile, and New Zealand have been significantly affected by damages to their transport infrastructure during seismic events. Large and damaging earthquakes drive professionals and academia to implement changes to their design philosophy to build structures that can perform beyond code-minimum requirements. The proper use of seismic isolation in designing structures will mitigate or eliminate earthquake damages and will assure continuous functionality after a seismic event.

Performance of conventionally designed bridges in Japan

Considerable bridge damage was observed after earthquakes in the 1980s and 1990s in Japan. Most of the damage was related to insufficient ductility of columns and premature failure of non-seismic bridge pads (non-isolation) which led to unseating of superstructures and total collapse of bridges [10]. [14] presented the performance of steel bridges during the 1995 Kobe earthquake. Many bridges suffered extensive damage as shown in Figure 4. Because of this considerable and extensive damage, seismic isolation was recommended in the design guidelines for the reconstruction of bridges damaged during the 1995 Kobe earthquake, and in the Revised Specifications for Highway Bridges issued in 1996 (Japan Road Association, 1996) [15].

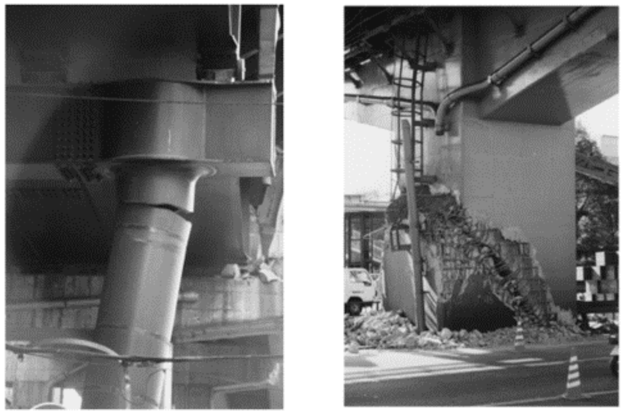

Figure 4: Damage and failure examples for bridges in the 1995 Kobe earthquake in Japan [14]

Performance of conventionally designed bridges in Chile

[16] presented the performance of bridges in the 2010 Maule earthquake in Chile. Out of nearly 12,000 highway bridges in Chile, approximately 300 were damaged in the earthquake, including 20 with collapsed spans. While different failure modes were observed, the failure of super-to-substructure connections was the most common. The extensive damage that occurred during the Maule 2010 earthquake resulted in a review of the seismic codes in Chile and a shift to more seismic isolation. As an example, seismic isolation was used in the replacement of the Rio Claro bridge that collapsed in the earthquake [3] (see Figure5).

(a)

(b)

Figure 5: (a) Rio Claro bridge collapsed in the 2010 Maule earthquake, (b) Rio Claro bridge replacement using seismic isolation.

Performance of conventionally designed bridges in New Zealand

[17] presented the structural performance of bridges in the 2016 Kaikoura earthquake in New Zealand. Different levels of damage were observed along the transport infrastructure as a result of the seismic event (see Figure 6). At the time of the initial inspection, the bridges were assessed and were only open to emergency traffic. Temporary repair work allowed some public access; however, long-term repair and replacement strategies were considered. While these bridges performed as intended under conventional design philosophy, protecting life safety through ductile detailing, the continued use of the structures was significantly impacted following the earthquake. This showed how one earthquake can affect the economy of a country significantly by affecting the transport infrastructure. The authors of the study recommended further investigation into more improvements to the current bridge design philosophy.

Figure 6: Damage examples for bridges in the 20160 Kaikoura earthquake in New Zealand [17].

SEISMIC ISOLATION BRIDGE APPLICATIONS AND CASE STUDIES

The **South Rangitikei Rail Bridge,** constructed in 1974 in New Zealand, is considered one of the earliest applications of seismic isolation. Seismic isolation was achieved by allowing the bridge piers to rock. The rocking period was significantly longer than the fixed base period and the seismic forces were considerably reduced [2]. Before 1991, forty-two bridges have been seismically isolated in New Zealand [18]; however, since then, the use seismic isolation for bridge applications has not been as common compared to other countries around the world. The **Sierra Point Overhead** was the first isolated bridge in the United States. The bridge was constructed in the 1950s and went through retrofit in the 1980s. Seismic isolation was selected as the preferred retrofit technique and the steel bearings were replaced by lead-rubber bearings. The bridge was subjected to shaking during the 1989 Loma Prieta earthquake and showed no damage, signs of cracking, or residual displacement [2].

Sample applications in North America

The **AirTrain Light Rail** System in New York that serves JFK International Airport (see Figure 7a), is a 10-mile viaduct constructed to relieve traffic congestion and improve airport access. The design used continuous multi-span concrete box girders supported on lead rubber bearings (LRBs). Seismic isolation was the preferred system to protect the box girder bridge against earthquakes and proved to be the most economical solution. Since the specified service/non-seismic displacements were limited to 1/8th of an inch in the transverse direction, an Elastic Restraint System (ERS) was developed and attached to the seismic bearings. The ERS was designed to withstand non-seismic loads, then break away at a design level earthquake. More details about the design of the structure, the LRBs and the ERS is presented in [19].

The 32-span **San Diego-Coronado Bay Bridge** (see Figure 7b), considered a critical link for Caltrans' transport infrastructure in Southern California, carries more than 75,000 vehicles per day and connects the mainland with the Coronado peninsula. The bridge straddles the seismically active, strike-slip Rose Canyon fault that runs along the San Diego coastline and crosses the bay under the bridge. Consequently, in addition to the ground motion shaking, the bridge needed to be designed to withstand a fault rupture of nearly 1m of relative ground displacements within certain spans. After several design and analysis iterations, seismic isolation was selected as part of the bridge retrofit. LRBs were selected because of their ability to resist uplift forces. Seismic isolation significantly reduced the forces on the columns, reducing the amount of column and foundation retrofitting required. The seismic isolation bearings replaced vulnerable steel rocker bearings and were used for the shorter piers only (piers 2 through 14). With the advantage of seismic isolation, the columns of only seven out of the 31 piers required retrofitting. Seismic isolation using LRBs was the most effective and economical solution to protect a vital bridge and provides continued functionality after a major seismic event with minimum retrofitting [20].

The **Woodrow Wilson Bridge** (see Figure 7c) is a critical bridge that spans the Potomac River near Washington DC and carries over 250,000 vehicles each day. The bridge is in a low-seismic zone; however, the redistribution of forces and performance under service-load conditions made seismic isolation using LRBs an appealing option for the designers.

The **Rio Vista Bridge** (see Figure 7d) across the Sacramento River is a 2890 ft long vertical lift bridge that was built in 1944. The bridge was seismically retrofitted in the 1990s. LRBs are used to support the approach spans and viscous dampers were placed transversely to control rocking of the tower if the anchor bolts were to break.

The **Eel River Bridge** (see Figure 7e) in California was originally constructed in 1940 and retrofitted in 1987 using 12 seismic isolation LRBs. The seismic forces were reduced by a factor of 4 and collapse potential was eliminated. The bridge passed through the 1992 Cape Mendocino Earthquakes (M_w 6.0 to 7.0). The bridge moved 8 inches and completely re-centered after the seismic event.

The **Richmond San Rafael Bridge** in California (see Figure 7f) used LRBs as part of the retrofit plan. Without isolation, the significant height differences of the piers caused the shorter, stiffer piers to attract most of the lateral forces. The designers used seismic isolation to redistribute the lateral forces throughout the structure. In addition, the structure required higher than normal level of initial strength because of high wind loads. The bearing supplier designed and built 55-inch diameter isolators with three 11-inch diameter lead cores to resist the service/non-seismic loads. This bridge is a good example of why thick and high-quality cover rubbers should be used with rubber isolators especially for bridge applications where harsh environmental conditions are found (see Figure 7g)

The **Feather River Bridge** (see Figure 7h) in California is another example where LRBs are used in harsh environmental conditions for seismic protection. An Elastic Restraint System (ERS) is used in combination with the isolators to resist high wind loads. The ERS consists of a notched stainless-steel shear pin placed in a block housing that restrains the bearings from moving under service loads. The shear pin will break away during a design-level earthquake and allows the isolation system to activate (see Figure 7i). This shear pin detail, which can be replaced following the seismic event, was tested at the University of Nevada Reno as a part of the 2/5th scale model of a 3-span curved bridge that was tested on multiple shake-tables (see Figure 7j).

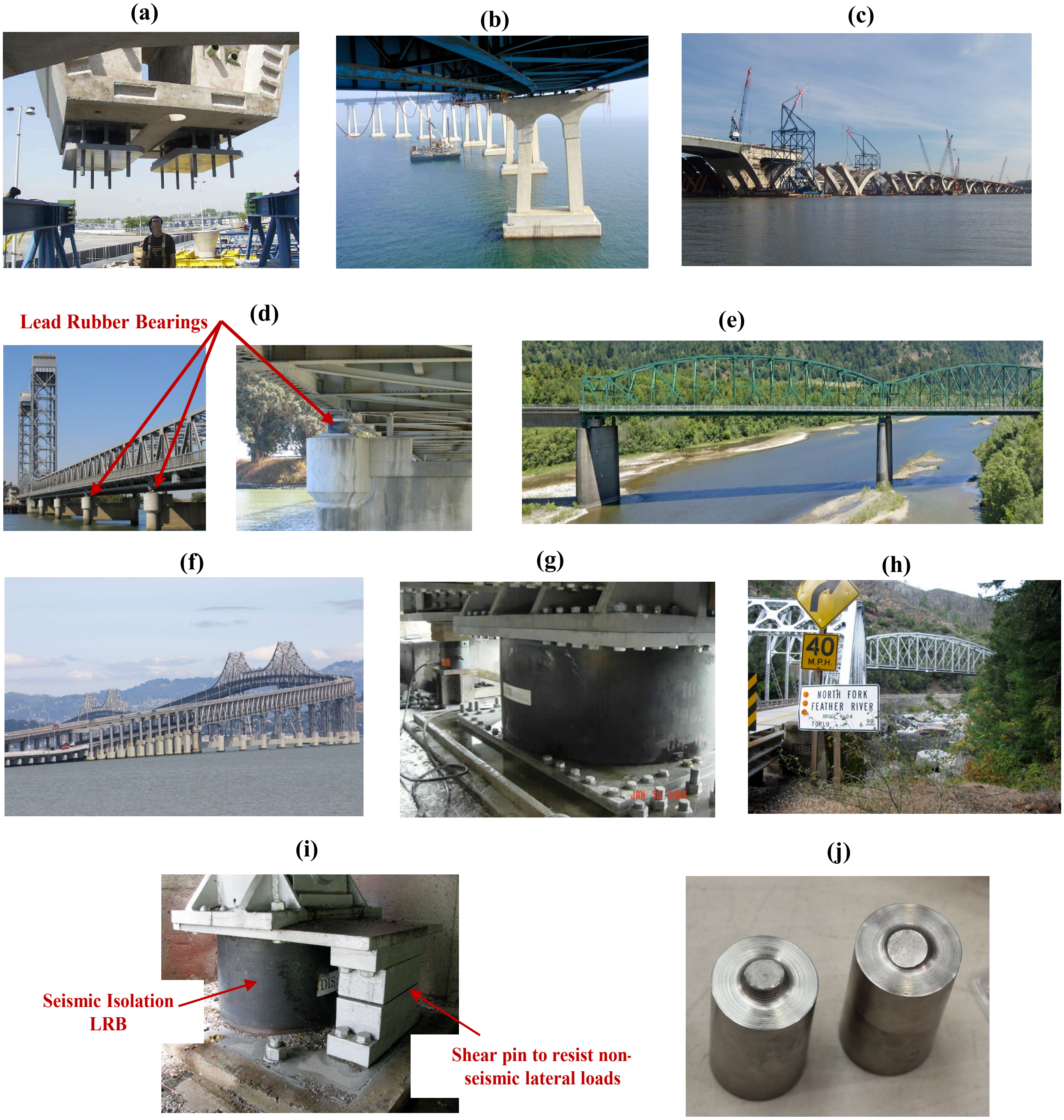

Figure 7: (a) AirTrain Light Rail System serving JFK Airport, (b) San Diego-Coronado Bay Bridge, (c) Woodrow Wilson Bridge, (d) Rio Vista Bridge, (e) Eel River Bridge, (f) Richmond San Rafael Bridge, (g) Installed LRB under Richmond San Rafael Bridge showing the harsh conditions, (h) Feather River Bridge, (i) LRB and shear pin installed under the Feather River Bridge, (j) Broken shear pin after testing.

Replacement of the **US 60 over Tennessee River Bridge** (see Figure 8a) in the New Madrid seismic zone presented challenges for the design team. The primary concern was how to accommodate the new superstructure truss on the previously constructed piers without additional retrofit of those piers, despite being designed for a different superstructure. Seismic isolation using LRBs was selected as the preferred solution because it uncoupled the truss superstructure from the piers. Additionally, it minimized impacts to the foundations and shifted the seismic demands away from the most susceptible components. Thus, the existing piers were utilized without any structural retrofits. Furthermore, the main span of this bridge is 900ft and considered one of the longest continuous truss spans in the world. As a result, LRBs were grouped together to accommodate the high loads (see Figure 8b). More information about the bridge design and construction challenges are presented in [21]. The **Granville Street Bridge** (see Figure 8c) in Vancouver, Canada is a 7-span steel deck truss that was constructed in the 1950s. As part of the bridge retrofit and project development, the design team enhanced the seismic performance of the critical structure through replacement of the existing steel bearings with seismic isolation LRBs (see Figure 8d).

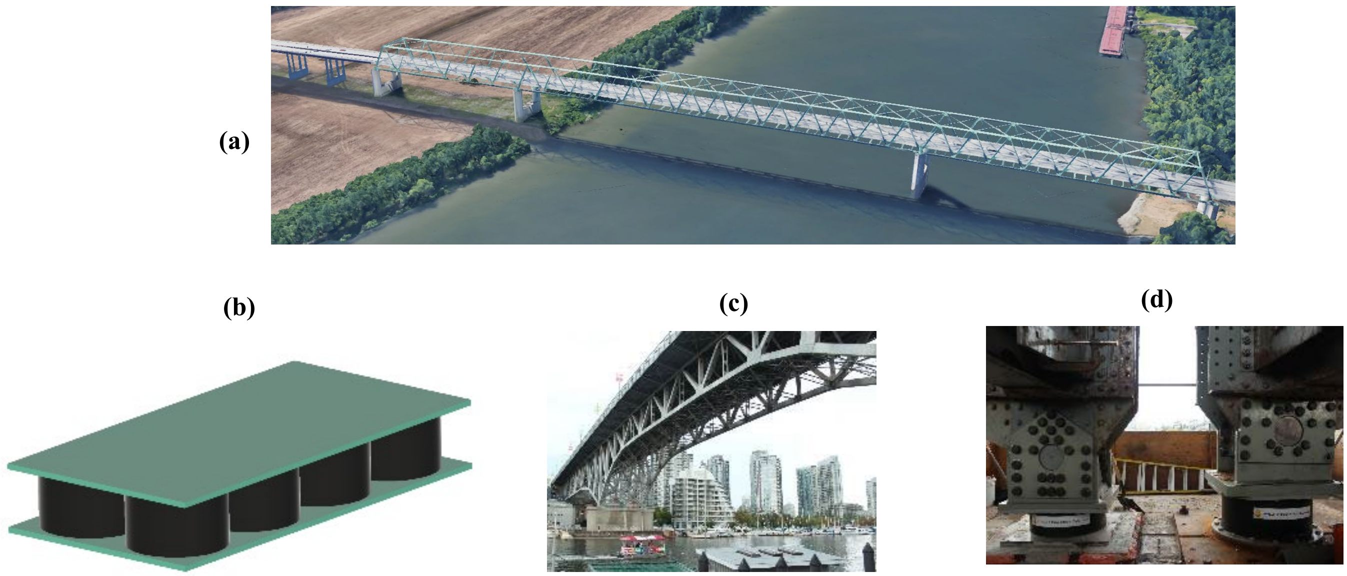

Figure 8: (a) US 60 over Tennessee River Bridge, (b) Eight LRBs combined to accommodate high axial loads, (c) Granville Street Bridge, & (d) LRBs after installation under the Granville Street Bridge.

The design team and construction company for the **Mexicali bridge** in Mexico (see Figure 9) developed a comparison between a conventional and seismically isolated design for the piers of the bridge [22]. The piers are formed of four steel columns filled with reinforced concrete with diameters from 80 cm to 120 cm. The fundamental period of the bridge isolated with LRBs is 1.83 seconds compared to 0.76 seconds for the conventional design. This period shift resulted in a significant reduction in lateral demands. The conventional design required 3 times the volume of concrete and 2.85 times the volume of steel with respect to the seismically isolated design. The total cost of the substructure (columns, foundations and isolators) of the seismically isolated bridge was estimated at around $2,800,000. The cost of the isolators was about $940,000. The estimated total cost of the substructure (columns and foundations) for the conventionally designed bridge was about $5,350,000, or 1.92 times the cost of seismically isolated design. [23] presented the performance of different structures during the 2010 Cucapah M_w 7.2 earthquake. The Mexicali bridge showed an excellent performance with no damage and was functional after the earthquake.

Figure 9: Mexicali bridge in Mexico.

Sample applications in South and Central America

Many countries in South and Central America, such as Chile, Peru, Colombia, Nicaragua and Ecuador, experience frequent significant earthquakes. This motivates the engineers in these regions to utilize seismic isolation to protect their structures and keep them functional after a seismic event.

In the last 5 years, the engineers in Peru have been very active in using seismic isolation to protect their bridges. The Ovalo Monitor Viaduct in Lima used 36 LRBs to mitigate seismic damage. Figure 10 shows the bridge during construction. Intercambio Vial Armendariz bridge, also located in Lima, utilized 26 LRBs for seismic isolation (see Figure 11). Juan Pablo II bridge in Piura, Junin bridge in Lima, and Leoncio bridge in Lima used seismic isolation LRBs to ensure continuous functionality after seismic events (see Figure 12). Figure 13 shows Corredor Honda- Manizales bridge in Colombia and the first seismically isolated bridge in Nicaragua, where the design teams decided to use LRBs to save costs and improve performance.

Figure 10: The Ovalo Monitor Viaduct during construction in Lima, Peru.

Figure 11: Intercambio Vial Armendariz bridge during construction in Lima, Peru.

(a) **(b)** **(c)**

Figure 12: Three bridges during construction in Peru (a) Juan Pablo II bridge, (b) Junin bridge, (c) Leoncio bridge

(a) **(b)** **(c)**

Figure 13: (a) Corredor Honda-Manizales bridge in Colombia, (b) Nicaragua bridge during construction, (c) Nicaragua bridge after construction is completed.

Sample applications in Asia and the Middle East

Japan's vulnerability to seismic activity due to its position along the Ring of Fire is evident from the 2011 Tohoku earthquake, which triggered a massive tsunami and caused widespread damage to the Miyagi Prefecture's Kesennuma city. Despite this, Japan continues to construct structures that can withstand earthquakes, such as **the Kesennuma Bay Bridge** [24], a cable-stayed bridge opened in the area in March 2021 and equipped with seismic isolation bearings. Unlike conventional seismic isolation designs that concentrate all functions in a single device, the Kesennuma bridge has a separation of functions. Pot bearings are installed to support vertical loads and accommodate rotations, while high-damping rubber (HDR) bearings are designed to maximize energy dissipation capacity, resulting in better seismic performance and more economic design. Figure 14 shows the photos of the bridge during construction.

In April 2016, two consecutive earthquakes with M_w 6.5 and M_w 7.3 struck Kumamoto region in Japan and caused significant damage to bridges. [25] presented analyses to evaluate several retrofit strategies for one of the damaged bridges and concluded that seismic isolation devices with large energy dissipation capacity was the optimal solution. A combination of high-damping rubber bearings with and without lead cores and viscous dampers were used to reduce the seismic demands in the truss bridge superstructure such that the main structural members remain within the elastic range.

The **Suginazawa Daiichi Viaduct** [24] in Japan required the design and manufacture of 96 HDR bearings that had to factor in large displacements caused by concrete shrinkage. The continuous prestressed concrete girder superstructure has a total length of 852m, with 23 spans averaging 35m in length. To reduce the size and cost of the seismic isolation bearings, a post-slide mechanism was implemented to counteract the displacement caused by concrete shrinkage. This mechanism involved an initial shear deformation, which would bring the bearing back to vertical alignment after the deformation of the girder due to concrete shrinkage. Traditional installation methods would have required larger bearings to accommodate both shrinkage and earthquake-induced displacements, increasing the isolation device's cost.

[10] showed a case study for the first isolated bridge in Bangladesh (the **2nd Meghna Bridge**) where HDR bearings were used to allow even distribution of seismic forces among the different piers. Figure 15a shows LRBs attached to the pier of a bridge in Azerbaijan where the bearings are close to the water and in the splash zone. The resiliency of the cover rubber and lack of mechanical moving parts within the bearings ensure durability and longevity in these harsh environments. In the **Gebze-Izmir highway** project in Turkey (shown in Figure 15b), 4,874 LRBs were utilized to protect 11 out of the 30 viaducts that were in high seismic regions.

Figure 14: Kesennuma Bay Bridge during construction in Japan.

(a) **(b)**

Figure 15: (a) LRBs installed on a bridge pier in Azerbaijan, (b) An isolated bridge on Gebze-Izmir Highway in Turkey

CONCLUSIONS

Large and damaging earthquakes drive professionals and academia to implement changes to their design philosophy to build structures that can perform beyond code-minimum requirements. The proper use of seismic isolation in designing structures mitigates or eliminates earthquake damage and assures continuous functionality after a seismic event. Seismic isolation provides flexibility to the structure, energy dissipation, and rigidity to resist service loads while also allowing for the redistribution of the seismic lateral loads among bridge piers. The majority of bridge isolators around the world are elastomeric-based bearings, and the most common elastomeric isolator is the lead-rubber bearing (LRB). LRBs are highly durable against the harsh environmental conditions around bridges due to the resiliency of the cover rubber. The case studies presented for conventional designs highlight that even proper ductile detailing in main structural members can have significant impact on the continued functionality of the bridge after a seismic event. The seismic isolation case studies show the benefits of design flexibility, construction costs, and continuous functionality that proper seismic isolation provides.

REFERENCES

[1] Skinner, R.I., Robinson, W.H. & McVerry, G.H. (1993). “An Introduction to Seismic Isolation”. Wiley, England.
[2] Buckle, I., Constantinou, M, Dicleli, M. & Ghasemi, H. (2006). “Seismic Isolation of Highway Bridges”. Report No. MCEER-06-SP07, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY.
[3] Eriksen, K.B., Mohammed, M.S. & Coria, C.B. (2018). “Seismic Isolation in North and South America”. 2018 NZSEE Conference, New Zealand.
[4] Saiidi, M.S., Vosooghi, A. & Nelson, R.B. (2013). “Shake-Table Studies of a Four-Span Reinforced Concrete Bridge”. Journal of Structural Engineering 139(8), 1352-1361.
[5] Vosooghi, A. & Saiidi, M.S. (2012). “Experimental Fragility Curves for Seismic Response of Reinforced Concrete Bridge Columns”. ACI Structural Journal, 109, 825-834.
[6] Mohammed, M.S., Sanders, D. & Buckle, I. (2015). “Shake Table Tests of reinforced Concrete Bridge Columns Under Long Duration Ground Motions”. 6th International Conference on Advances in Experimental Structural Engineering.
[7] Mohammed, M.S. (2016). “Effect of earthquake Duration on Reinforced Concrete Bridge Columns”. Ph.D. Thesis, University of Nevada Reno.
[8] Biasi, G., Mohammed, M.S. & Sanders, D. (2017). “Earthquake Damage Estimations: ShakeCast Case Study on Nevada Bridges”. Earthquake Spectra 33(1), 45-62.
[9] Mohammed, M.S., Sanders, D. & Buckle, I. (2017). Reinforced Concrete Bridge Columns Tested Under Long and Short Duration Ground Motions”. 16th World Conference on Earthquake Engineering.
[10] Gimenez, J.L. & Himeno, T. (2018). “Seismic Iolation of Bridges: Devices, Common Practices in Japan, and Examples of Application”.4th International Conference on Advances in Civil Engineering, Bangladesh.
[11] Naeim, F. & Kelly, J.M. (1999). “Design of Seismic Isolated Structures: From Theory to Practice”. John Wiley & Sons, Inc.
[12] AASHTO (2014). “Guide Specifications for Seismic Isolation Design”. 4th Edition, American Association of State Highway and Transportation Officials, Washington, DC
[13] CAN-CSA S6-14 (2017). “Canadian Highway Bridge Design Code, Update No. 2”. Canadian Standard Association.
[14] Bruneau, M. (1998). “Performance of Steel Bridges During the 1995 Hyogoken-Nanbu (Kobe, Japan) Earthquake – A North American Perspective”. Engineering Structures, Vol. 20, No. 12, 1063-1078.
[15] Japan Road Association (1996). “Specifications for Highway Bridges, Part V, Seismic Design”. Maruzen, Tokyo (In Japanese).
[16] Buckle, I., Hube, M., Chen, G., Yen, W. & Arias, J. (2012). “Structural Performance of Bridges in the Offshore Maule Earthquake of 27 February 2010”. Vol. 22, No. SI, S533-S552.
[17] Palermo, A. et al. (2017). “Performance of Road Bridges During the 14 November 2016 Kaikoura Earthquake”. Bulletin of the New Zealand Society for Earthquake Engineering. Vol. 50, No.2, 253-270.
[18] Skinner, R.I., Robinson, W.H. & McVerry, G.H. (1991). “Seismic Isolation in New Zealand”. Nuclear Engineering and Design, 127, 281-289.
[19] Englot, J.M. & Bakas, P.T. (2002). “Performance/Design Criteria for the Airtrain JFK Guideway”. Arema 2002 Annual Conference and Exposition Washington, DC.
[20] Ashley, M. et al. (2001). “Holding Steady”. Article, Civil Engineering Magazine.
[21] Klusman, C.R., Corda, D.N. & Hunley, C.T. (2014). “Clean Exchange: New Kentucky Bridge Replaces Cluttered Span”. Article, Roads and Bridges Magazine.
[22] Cautín (2010). “Construcciones con aislamiento sísmico en México”. Informe Interno, Constructora Cautín, Guadalajara, México.

[23] Nunez, J. L., Colunga, A.T. & Bernal, A.G. (2011). "Comportamiento Observado En Estructuras Y Subsuelo Del Valley Y Ciudad De Mexicali Durante El Sismo El Mayor-Cucupah Del 4 De Abril Cel 2010". Revista Internacional de Ingenieria de Estructuras. Vol. 16, No.1.
[24] Lopez Gimenez, J., (2020) - Construction - In extremis. Bridge Design and Engineering – Special Issue (Bridges in Extremis).
[25] Gimenez, J.L., Himeno, T. & Eriksen, K.B. (2018). "Retrofit of a Bridge Damaged in Kumamoto Earthquake with High Energy Dissipation Devices". 2018 NZSEE Conference, New Zealand.