Seismic response analysis of curved viaduct with Neoprene bearing

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1. INTRODUCTION

Earthquake is a natural phenomenon that occurs every day all over the world. The occurrence of important earthquakes in any countries cannot be discarded due to the random nature of occurrence of seismic events recently in the world. Civil infrastructure, such as a bridge is an important link in surface transportation network. When structure is subjected to strong ground motion, severe damage, or even collapse of structure, it may be caused by seismic energy. Therefore, infrastructure such as bridge needs to be prepared to withstand this natural disaster.

Bridge is composed of superstructure (girder and deck) and, substructure (pier and abutment) and in between of these components is bearing, a connection element that transfers forces between superstructure and substructure. Elastomeric bearings are the most widely used bridge-support systems. It has been started to be used in bridges in 1950s to control the lateral movements due to shrinkage and creep, temperature difference, lateral forces acting on structure, such as wind load [1]. To enhance seismic performance of highway system, Lead Rubber Bearing that is slightly modified form with a solid lead plug embedded in rubber has been applied to bridges. However, in countries that do not have strong historical earthquake incidents bridges are designed without consideration of ground motion load, and bridges are mostly designed with non-seismic bearings, such as Neoprene Bearing or Natural Rubber Bearing.

The objective of the present research is to evaluate the performance of Neoprene bearing under seismic load, with the intention of verifying whether bridge structure with Neoprene bearing is possible to withstand medium and strong earthquakes. Therefore, the seismic response analysis of curved highway viaduct equipped with Neoprene bearing under three different types of earthquake, Kobe Earthquake, Maule Earthquake, and Illapel Earthquake are investigated in this research.

2. ANALYTICAL MODEL OF VIADUCT

In order to obtain the structural response of bridge, three-dimensional analytical model of typical three-span highway bridge is adopted in this research as shown in Fig. 1. The bridge is discretized into 71 nodal points. Superstructure and piers are modelled as beam-column elements, and bearing supports are represented by spring elements. The overall viaduct length of 120 m is divided into equal spans of 40 m. The bridge alignment is horizontally curved, and curvature radius is 200 m.

This model allows for the evaluation of the combined effect of longitudinal, transverse, and vertical seismic ground motion.

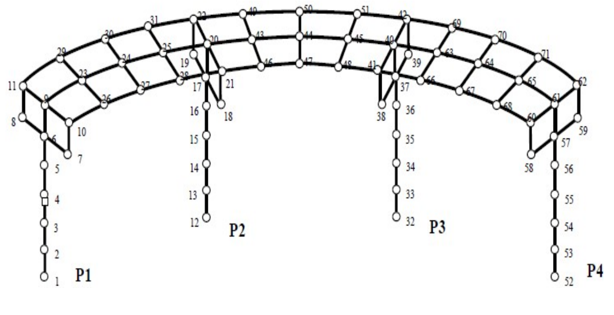


Fig. 1 Detail of analytical model of curved viaduct

2.1 Superstructure and pier

The bridge superstructure consists of a reinforced concrete deck slab that rests on three I-section steel girders, equally spaced at an interval of 2.1 m. The girders are interconnected by end-span diaphragms as well as intermediate diaphragms at uniform spacing of 5.0 m. The viaduct is supported on four box section steel piers of 20 m of height. The width of box sections is 2.4 m, while the thickness is 0.05 m. Cross-sectional properties of girders and piers are summarized in Table 1.

Characterization of the non-linearity of piers is based on the fiber flexural element modelling, as shown in Fig. 2. The element is divided into 5 longitudinal parts, and into 12 transverse divisions. The stress strain behaviour is described by bilinear model. The yield stress is 235.4 MPa, the modulus of elasticity is 200 GPa and the strain hardening in plastic area is equal to 0.01.

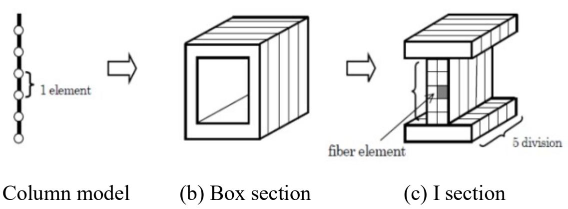
2.2 Bearing supports

Elastomeric bearings are designed to be stiff and strong in the vertical direction, but flexible in the horizontal direction. Vertical rigidity assures that the isolator will support the weight of the structure, and low horizontal stiffness provides isolation function between superstructure and substructure under lateral forces [2]. In the present study Neoprene bearing with 430 x 430 mm of size, and 38 mm of height is considered for the analysis. Neoprene bearing is formed by horizontal layers of synthetic rubber (Polychloroprene) bonded between steel plates.

This research considers one particular restraint configuration, which was presented the most effective restraint configuration in previous study [3]. Pier P1 and P4 are isolated in longitudinal direction and fixed in transverse direction, whereas pier P2 and P3 are isolated in both directions. Fig. 3 shows the restraint configuration of the viaduct in details.

Table 1 Cross-sectional properties of girders and piers

Element	A (m^2)	I_x (m^4)	I_y (m^4)
Pier	0.47	0.4329	0.4329
Girder	0.18	0.1166	0.0305



(a) Column model　(b) Box section　(c) I section

Fig. 2 Cross section fiber element

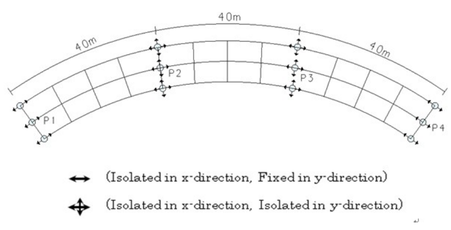


Fig. 3 Restraint configuration of viaduct

Under normal load condition, lateral loads are usually small compared with vertical load. However, in a seismic design, the shear force is very important to be analyzed.

Neoprene bearing is represented by the bilinear shear force-displacement hysteresis loop as shown in Fig. 4, and structural characteristics of the bearing are summarized in Table 2. Three parameters are adopted in the analytical model of the bearing. The parameters k_1 and k_2 corresponds to pre-yield stiffness and post-yield stiffness of the bearing respectively, and the parameter F_1 correspond to yield force of the bearing. The stiffness ratio (k_1/k_2) is 1.5, which does not provide a good energy dissipation capacity by bearing due to the small hysteresis loop. This is the main characteristics that differentiate from the seismic bearing such as LRB and HDR.

2.3 Input earthquake ground motion

In order to evaluate the seismic performance of the viaduct, the bridge model is subjected to the three strong ground motion records measured by the Takatori station during the 1995 Kobe earthquake, Angol station during the 2010 Maule earthquake, and El Pedregal Station during the 2015 Illapel Earthquake. The input ground motion records are shown in Fig. 5. In these earthquake records are included three direction earthquake waves, longitudinal (L), transverse (T), and vertical (V).

Kobe Earthquake ($M_w = 6.9$), occurred on January 17, 1995 in Japan is characterized by high peak acceleration and strong velocity pulses with a long period as well as large displacement.

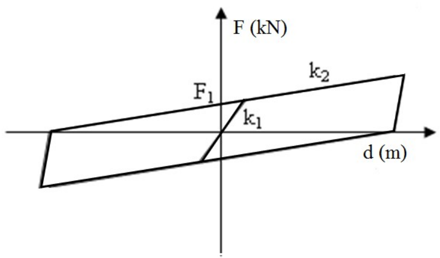


Fig. 4 Shear force – displacement of bearing

Table 2 Shear stiffness of Neoprene bearing - k (kN/mm) F (kN)

Bearing Type	k_1	k_2	F_1
Neoprene	5.320	3.546	106.4

Whereas, Maule Earthquake ($M_w = 8.8$) occurred on February 27, 2010 in south central Chilean region is characterized by high acceleration with short periods. Illapel Earthquake, also occurred in Chile, in 2015 is characterized by high acceleration with short period, but the maximum acceleration is lower than that of Maule Earthquake.

3. NUMERICAL RESULTS

Structural response of the viaduct is investigated by non-linear dynamic analysis. Particular attention is paid to displacement of deck, displacement at top of pier, shear force-displacement response, bending moment at base of pier, and energy dissipation. Central pier (P2) of the bridge model is selected to be analyzed, since it supports double weight, and most severe seismic response is found there [4) 5) 6)].

3.1 Displacement of deck

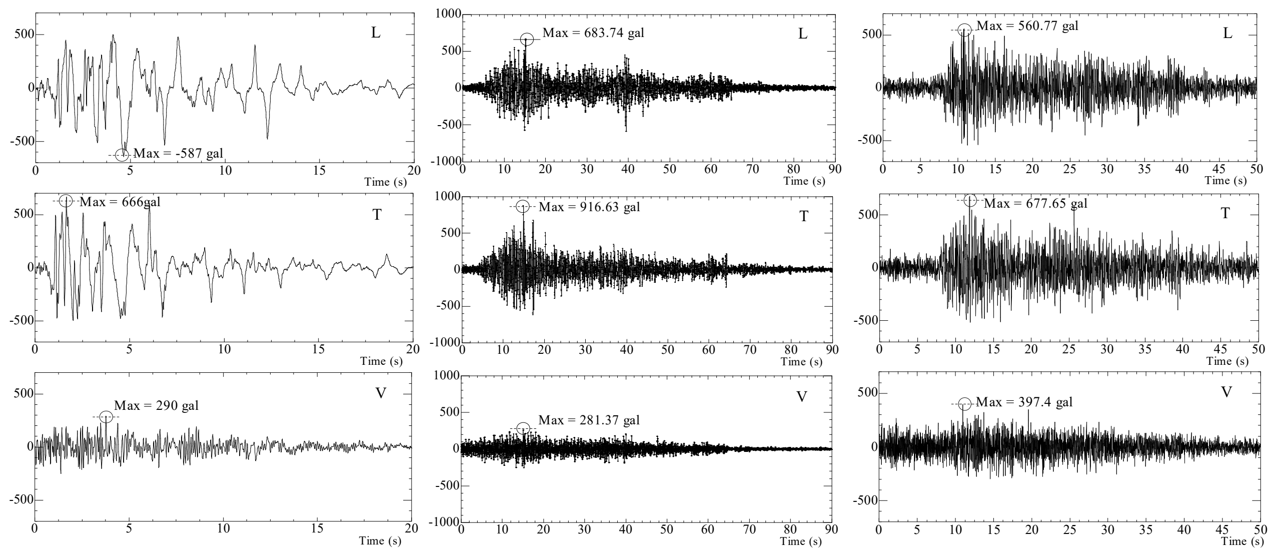
The maximum deck displacement of the bridge model with Neoprene bearing under three different cases of earthquake is evaluated. Table 3 shows the maximum displacement of deck in longitudinal and transverse direction. Result shows that the ground motion of Kobe Earthquake induces the largest displacement in both directions to the bridge structure. In the transverse direction the maximum displacement reaches values > 0.30 m. It may compromise the integrity of the structure by pounding damage or falling down of the deck

Maule Earthquake obtains value close to 0.12 m of maximum displacement of deck. Depending on expansion joint length between superstructure and abutment, it may result in damage to the structure.

The result from Illapel Earthquake ground motion presents 0.05 m of displacement, the lowest displacement among three cases. It is possible to say that the bridge structure is in satisfactory condition under the seismic load.

Table 3 Maximum displacement of deck and top of pier

Earthquake	Displacement of deck (m)		Displacement at top of pier (m)	
	Longitudinal	Transverse	Longitudinal	Transverse
Kobe	0.192	0.301	0.130	0.230
Maule	0.116	0.118	0.098	0.150
Illapel	0.051	0.050	0.048	0.041



(a) 1995 Kobe Earthquake, Japan (b) 2010 MauleEarthquake, Chile (c) 2015 IllapelEarthquake, Chile

Fig. 5 Earthquake ground motion record

3.2 Displacement at top of pier

Piers can be severely damaged or may lose their serviceability when they sustain significant residual deformation. According to the Japan Road Association (JRA), when large displacement is occurred at top of pier, the restoration work may be very difficult, and in some cases irreparable. Due to this fact they impose allowable residual displacement, 1/100 of the height from the bottom edge of the bridge pier to the point where the inertial force acts on the superstructure, or in other words limitation of 1% maximum inclination of the bridge pier height [7)]. The viaduct model adopted in this research has 20 m of pier height, therefore the allowable displacement of the structure model is 0.20 m. Table 3 shows the maximum displacement at top of pier under the seismic load in longitudinal and transverse directions.

In case of Kobe Earthquake, displacement response at top of pier reaches 0.23 m in transverse direction, more than the allowable displacement. This large residual displacement is caused by large impact forces acting to the bearing. In this case due to the displacement at top of pier, large bending moment at base of pier may occur, and severe structural damages may be seen.

The residual displacement for the model under Maule Earthquake is 0.15 m, less than the allowable value. It is a good indicator that Neoprene bearing can function well under the ground motion load with the intensity of Maule Earthquake. The best result is obtained from the model under Illapel Earthquake, only 0.05 m of displacement at top of pier is observed.

3.3 Shear force-displacement response

In order to evaluate the effectiveness of Neoprene bearing, shear force-displacement relationship is considered in this research. This is an important structure response parameter for seismic analysis, because both variables control overall behaviors of the whole bridge system. The effectiveness of the bearing system under seismic loading can be evaluated in terms of hysteretic loops. Shear force-displacement response of pier P2 in longitudinal and transverse direction under three different seismic loads are shown in Fig.6.

In case of the bridge subjected to Kobe Earthquake, the maximum inertial force transmitted to Neoprene bearing support are 155.6 kN in longitudinal direction and 180.5 kN in transverse direction, whereas the maximum displacements are 0.03 m and 0.04 m, respectively. Hysteretic loop area can be observed in both directions, which means that the bearing is dissipating a certain value of seismic energy. The similar behavior occurs in the bridge model under Maule Earthquake only in transverse direction which presents 167.4 kN of shear force transmitted to the bearing, and 0.038 m of displacement.

The structural model under Illapel Earthquake obtains small values of shear force transmitting to the bearing and elastic behavior is observed in both directions. The maximum value of shear force is 80.7 kN, and displacement is 0.015 m. The maximum shear force obtained is less than the yield force F_1 (106.4 kN) of the bearing. It is clear that Neoprene bearing cannot dissipate energy adequately under small earthquake intensity.

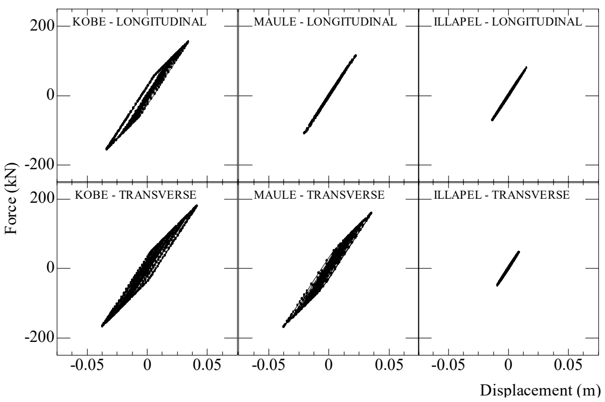
3.4 Bending moment-curvature response

Bending moment at base of pier occurs due to the inertial force transmitted to the bearing supports and the inertial force of pier itself. Analysis of bending moment is considered a good measure to quantify the damage induced in the bridge structure by seismic load, because the bottom of bridge piers is subjected to the maximum loading and consequently, large bending moment. The failure mechanisms usually start with formation of plastic hinges. Fig. 7 shows the bending moment-curvature response of pier P2 under three different earthquake ground motions in longitudinal and transverse direction.

The yield moment of the pier is 8480 kN m. The maximum bending moments obtained from the model under Kobe Earthquake are 9651 kN m and 10140 kN m in longitudinal and transverse direction, respectively. It can be seen that the maximum moment at pier bottom overpasses the yield moment in both directions. It indicates the occurrence of plastic deformation, and structural damage on this substructure element is confirmed by the significant large moment-curvature loop at base of pier. This is already expected due to the large force transmitted to the bearing as shown in Fig. 6 of shear force-displacement response.

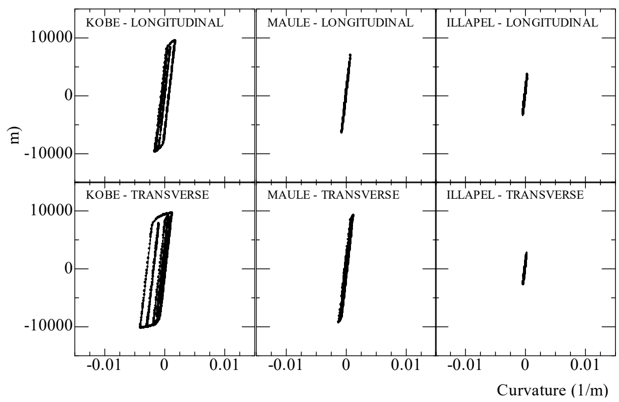
In case of Maule Earthquake, inelastic deformation is observed only in transverse direction, since the maximum moment is 9242 kN m and due to significant moment curvature loop area. In longitudinal direction the maximum moment is 7142 kN m, less than the yield moment. The consistency of this result is confirmed by the shear force-displacement response presented previously which presents large shear force transmitted to the bearing in transverse direction.

Illapel Earthquake induces a very small value of bending moment at base of pier compared to Kobe and Maule Earthquake. The maximum bending moments are less than 4000 kN m in both directions and linear behavior are observed which indicate that the pier remains under elastic range from the top to the bottom, at every nodal point. Therefore, no damage is expected to the pier under Illapel Earthquake ground motion.



(a) Kobe　(b) Maule　(c) Illapel

Fig. 6 Shear force - displacement response



(a) Kobe　(b) Maule　(c) Illapel

Fig. 7 Bending moment - curvature response

3.5 Energy dissipation

Energy is an alternative way to examine the seismic damage effect on bridge. When bridges are subjected to strong earthquake, seismic energy flows from the ground to structures and substantial amounts are dissipated by damping mechanisms and by plastic deformation which is responsible in part for structural damage. A great amount of seismic energy dissipated at bearing level implies that the isolation system provides effective protection against earthquakes. In this analysis energy dissipation is considered by kinetic energy, damping energy, and strain energy. Kinetic energy includes the effects of the rigid body translation of the structure. However, the effect of this energy can be ignored, because a very small value of energy dissipation close to zero is observed. Damping energy is the consumed energy due to damping mechanism of the system, and strain energy corresponds to the absorbed energy by the hysteresis loops of steel bridge piers and the hysteretic energy dissipated by the bearings [8].

The performance of the bearing system under the three different earthquake ground motions are shown in Fig. 8

In case of the structure model under Kobe Earthquake, total input energy is 1730 kN m, whereas damping energy is 1182 kN m and, strain energy is 547 kN m which amounts to 31.6% of total energy dissipation. Dissipation by damping mechanism represents the major part of dissipation. Also, significant value of strain energy can be observed, while it does not happen in other two cases of ground motion condition.

The obtained results from Maule Earthquake shows that almost all the seismic energy inputted to the viaduct (2321 kN m) is dissipated by damping energy (2223 kN m), and energy dissipation by strain energy (96 kN m) amounts to only 4.1 % of total energy dissipation.

Illapel Earthquake obtained the lowest total input energy, 505 kN m. This result is already expected due to the small shear force transmitted to the bearing, and small value of maximum bending moment at base of pier. However, the strain energy obtained is only 0.82 kN m, value close to zero. It means that in this case dissipation by the capacity of bearing does not occur. By this result and seismic response results presented previously in this research it is confirmed that Illapel Earthquake is not strong enough to induce damage to the structure.

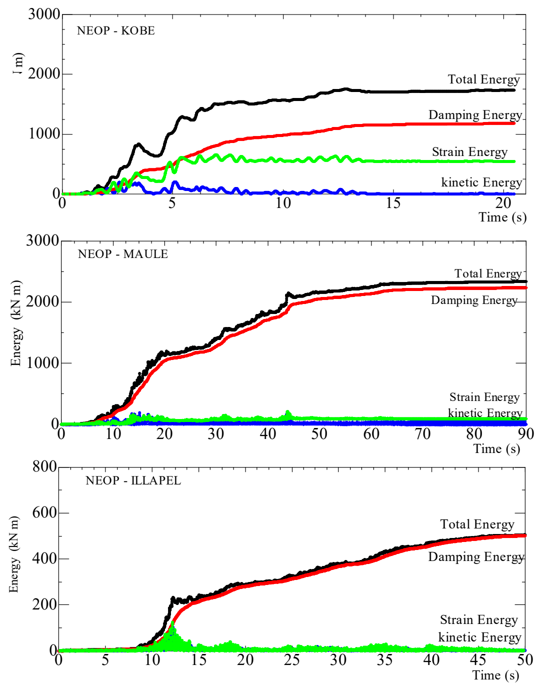


Fig. 8 Energy – time history

4. CONCLUSION

In this research, nonlinear dynamic analysis of a finite element model of highway viaduct with Neoprene bearing under three different earthquakes, 1995 Kobe Earthquake, 2010 Maule Earthquake, 2015 Illapel Earthquake is carried out. Seismic responses are studied and evaluated to investigate the performance of Neoprene bearing under seismic ground motion. The investigation results provide sufficient evidence for the following conclusions:

(1) Among the three earthquakes analyzed, the bridge structure with Neoprene bearing adopted in this research was able to withstand Illapel Earthquake ground motion. Significant response that may implicate in damage to the structure was not observed. Piers remained under elastic range during the earthquake, since the maximum bending moment at base of piers was lower than the yield moment. Small values of shear force transmitted to the bearing, and linear behaviour was presented. Besides that, small value of maximum displacement of deck was observed, as well as displacement at top of pier.

(2) The structure under Kobe Earthquake presented the worst seismic response results, such as large deck displacement, displacement at top of pier higher than the allowable value by JRA specification, and large bending moment at base of pier. Significant structural damage at superstructure and substructure can be confirmed by these results. Therefore, it is possible to conclude that Neoprene bearing cannot withstand under this level of earthquake.

(3) Maule Earthquake ground motion induced a little damage to the bridge structure model with Neoprene bearing. In case of this intensity of earthquake, special attention needs to be paid to deck displacement and the bending moment at base of pier.

(4) Neoprene bearing is very stiff compared to seismic bearing such as LRB and HDR. The input seismic energy is predominantly dissipated by damping mechanism of the system. Considerable dissipation by strain energy was observed only under Kobe Earthquake ground motion which had large shear force transmitted to the bearing, and hysteresis loops area.

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