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Performance Evaluation of Seismically Isolated Bridge

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Abstract

This research aims at the performance evaluation of bridge seismically isolated with high damped rubber isolators. The responses of both seismically isolated and non-isolated bridges are studied to determine the effectiveness of the seismic isolators. To carry out this procedure, the finite element modeling of a two-span bridge is done with and without isolator and the non-linearity associated with high damped rubber isolator is modeled using the hysteretic Bouc – Wen model. The global finite element model of the bridge is analyzed using a suite of spectrum compatible ground motions. The maximum possible acceleration at deck level and maximum pier base shear corresponding to various seismic loading are assessed using time history analysis. Also, the maximum isolator displacement is evaluated for physical design parameters for the isolation system. The results obtained show a considerable decrease in seismic response parameters after the use of an isolation system.

Keywords

Seismic Analysis, High Damping Rubber Isolators, Seismic Isolation, Bridges

1. Introduction

Bridges are an integral part of mankind for everyday amenity services. The importance of bridge structures is even increased during natural calamities like earthquakes, for the provision of emergency relief activities or the post-earthquake rehabilitation programs. Bridges are vulnerable structures due to their structural simplicity. Also, the natural frequency of bridge lies within the predominant frequencies of most earthquakes, which makes them even more vulnerable to seismic events. Seismic isolation can be a promising approach to ensure the structural safety of the bridges during a seismic event.

The major principle of seismic isolation is to decouple the superstructure from the damaging effects of earthquake ground accelerations. Due to seismic isolation, the fundamental frequency of a structure is shifted away from the dominant frequencies of earthquake ground motion whilst providing sufficient rigidity for quasi-static loads and support for the superstructure load. The other attribute of an isolation system is to provide an additional energy dissipation offered by seismic events. Various theoretical, analytical, and experimental studies in the past have supported the idea of seismic isolation in buildings and bridge structures for various types of isolators such as elastomeric isolators, sliding isolators, etc. These isolators can be conveniently provided in place of conventional bridge bearings. Abe et. al.[1] studied three bridges that are isolated by lead rubber bearings, high damped rubber bearings, and natural rubber bearings. The seismic response reduction is obtained for all types of isolators used. Tongaonkar and Jangid[2] conducted a parametric variation in elastomeric bearing properties and studied the effects of the variation in the seismic response of bridge structures. It is seen that the seismic response is dependent on parameters such as stiffness and damping parameters. He suggested selecting the optimum mechanical parameters is important for obtaining the maximum seismic isolation. Pandey and Srivastav[3] studied the response of an isolated and non-isolated bridge using the Lead Rubber Bearing (LRB) and Friction Pendulum System (FPS). For a given period and damping value, the LRB is more efficient in reducing the seismic forces than FPS. The elastomeric isolators (lead rubber isolators, low, and high damped rubber isolators) are most commonly used due to ease in manufacturing, economy, durability, and efficiency. Among them, lead rubber isolators have been extensively used in the past, as they have high energy dissipation provided by lead core, even though the production of lead has adverse effects on the environment. It is studied that high damped rubber isolators can be an environment-friendly alternative for lead rubber isolators when provided with extra damping. This research focuses on the study of dynamic behavior and evaluation of the seismic response of bridges isolated with high damped rubber isolators.

2. Research Objectives

The general objective of this research is to study the efficiency of the high damped rubber isolation system in the bridge during various earthquake events.

The specific objectives of this research include:

- Evaluation and comparison of seismic response parameters such as deck acceleration, base shear due to various earthquakes for both the isolated and non-isolated bridge models.

3. Modeling of Isolator

High damped rubber isolators consist of an alternate layer of rubber and steel vulcanized together with additional viscous damping properties. A typical high damped rubber isolator is shown in Figure 1. The rubber layer gives horizontal flexibility for the earthquake events, steel plates provide support for the superstructure and vehicle load and the viscous damping causes seismic energy dissipation. The ideal force deformation behavior of high damped rubber isolators is defined by non – linear characteristics. The hysteretic Bouc – Wen model can sufficiently represent the non – linearity considered with these isolators.

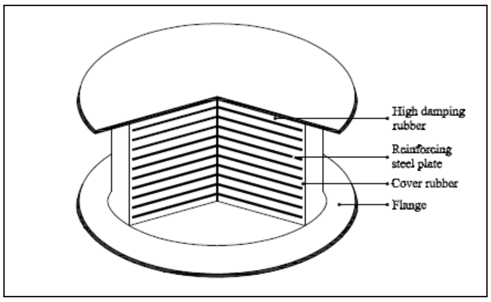

Figure 1: A Typical High Damped Rubber Isolator[4]

The restoring force developed in the isolation system is given by Bouc[5] and Wen[6].

$$F_b = c\dot{x} + \alpha kx + (1-\alpha)F_y\dot{z} \tag{1}$$

where x is the nonlinear oscillator displacement, c and k are the system damping and the elastic-initial stiffness respectively, $\dot{z}$ is an internal variable governing the hysteretic behavior and satisfying the differential equation:

$$q\dot{z} = A\dot{x} - \gamma|\dot{x}||z|^{n-1}z - \beta\dot{x}|z|^n \tag{2}$$

where q is yield displacement, n controls the smoothness of transition from elastic to plastic response, dimensionless parameters A, γ, β, n is selected such that the predicted model closely matches the experimental results Jangid[7].

The schematic diagram of high damped rubber isolator is shown in Figure 2.

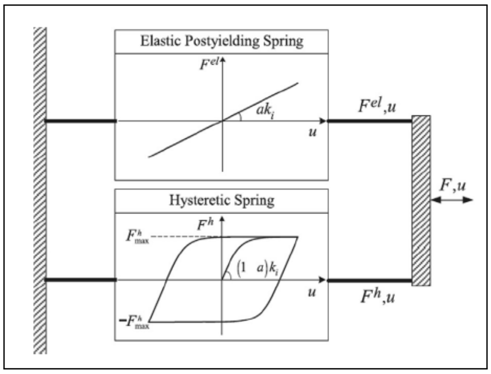

Figure 2: Schematic Diagram of High damped Rubber Isolator[8]

The hysteretic properties of high damped rubber isolators are calculated using equation (1) and (2) of the Bouc – Wen model and the mechanical properties considered are presented in Table 1.

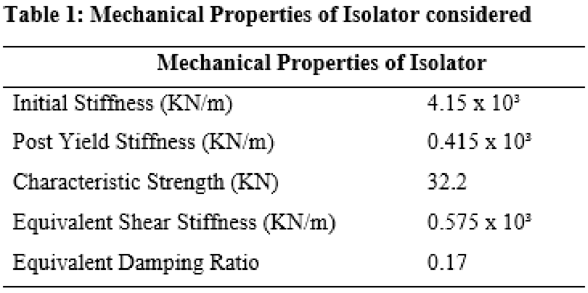

Table 1: Mechanical Properties of Isolator considered

Mechanical Properties of Isolator	
Initial Stiffness (KN/m)	4.15×10^3
Post Yield Stiffness (KN/m)	0.415×10^3
Characteristic Strength (KN)	32.2
Equivalent Shear Stiffness (KN/m)	0.575×10^3
Equivalent Damping Ratio	0.17

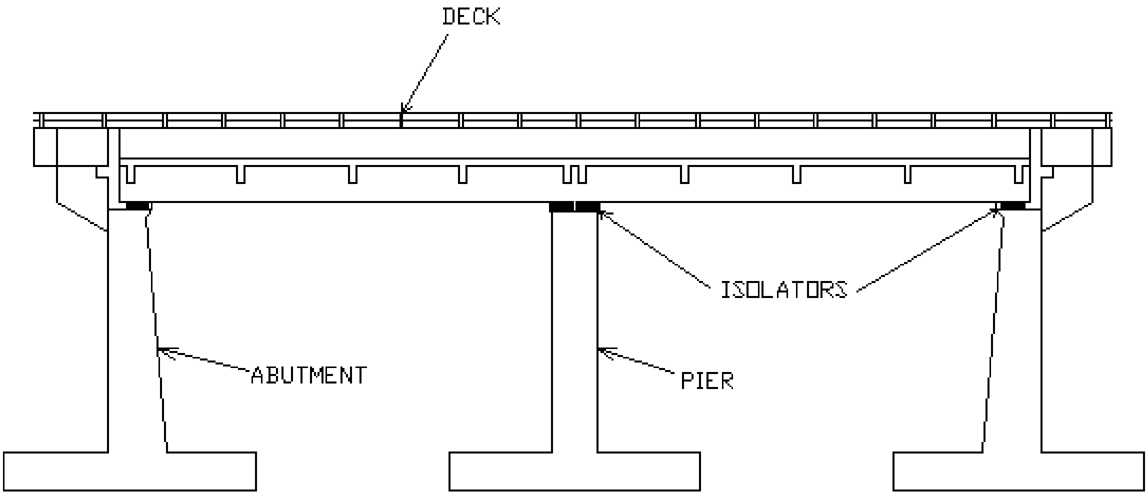

Figure 3: Longitudinal Section of Model Bridge Provided with High Damped Rubber Isolators

4. Finite Element Modeling of Bridge

To evaluate the efficiency of seismic isolation system, a Reinforced Concrete Tee beam bridge (Figure 3) is considered for the analysis. The example bridge is the Manohara Khola Bridge over Manohara Khola located in Kurthali Village in Kathmandu Valley. It is a two-span reinforced concrete Tee-beam bridge with having a total length of 41.24 m. It is a single lane bridge with a carriageway width of 4.25 m supported over a pier cap, each span is 20.56 m. The superstructure consists of two longitudinal girders with a dimension of 1400 mm x 400 mm. On each span, there are five cross girders of 1000 mm x 300 mm equally spaced at 5 m. Deck slab of thickness 220 mm is constructed monolithically with the longitudinal and cross girders. In the model, only the flexibility of the pier is taken into account whereas deck and abutments are considered rigid. The finite element tool SAP2000 v14 is used to develop the 3-D model of the bridge including the boundary condition. Eight isolators are used in place of conventional bearings and modeled as non-linear link elements.

5. Analysis

The time-history analysis is the most realistic method for the assessment of the behavior of structures subjected to seismic loads. Earthquake acceleration time history and response spectra design are needed as a basis to determine the earthquake loading that can be used to design and assess the seismic response of structures. Each ground motion records have a different response spectrum depending upon their origin type of earthquakes, local site responses. The ground motion time histories used in structural analyses need to accurately reflect the behavior of earthquake patterns in the study area.

In this research, the SeismoMatch(2020) application is used to adjust the considered earthquake accelerograms to match a target response spectrum specified in IS 1983: 2016. This application uses the wavelet algorithm proposed by Abrahamson[9] and Hancock et. al.[10] to provide the matched response spectrum. The elastic spectra are computed utilizing the time-integration of the equation of motion of a series of single-degree-of-freedom systems, from which the peak displacement, velocity, and acceleration response quantities are then obtained and plotted in the period, frequency or displacement vs. amplitude graphs. Seven spectrum compatible earthquakes are utilised for the time history analysis. The ground motion parameters of various earthquakes considered are shown in Table 2. Figure 4 and Figure 5 shows the response spectra of considered earthquakes along with the target response spectrum before and after matching respectively.

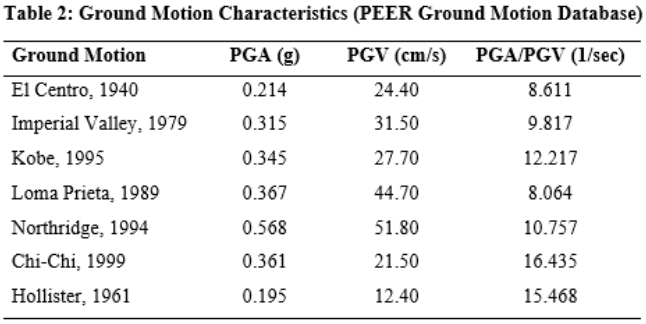

Table 2: Ground Motion Characteristics (PEER Ground Motion Database)

Ground Motion	PGA (g)	PGV (cm/s)	PGA/PGV (1/sec)
El Centro, 1940	0.214	24.40	8.611
Imperial Valley, 1979	0.315	31.50	9.817
Kobe, 1995	0.345	27.70	12.217
Loma Prieta, 1989	0.367	44.70	8.064
Northridge, 1994	0.568	51.80	10.757
Chi-Chi, 1999	0.361	21.50	16.435
Hollister, 1961	0.195	12.40	15.468

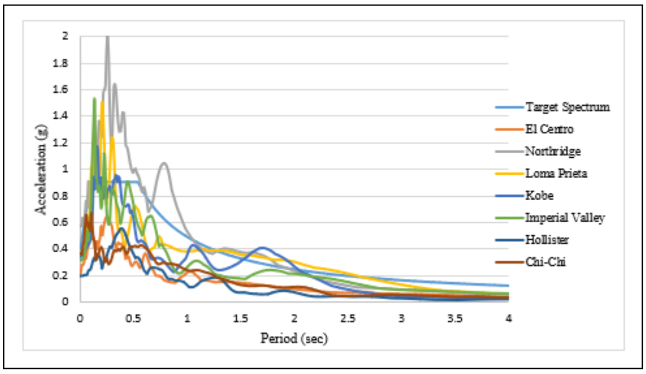

Figure 4: Target Spectrum and Response Spectrum of Considered Earthquakes before Spectral Matching

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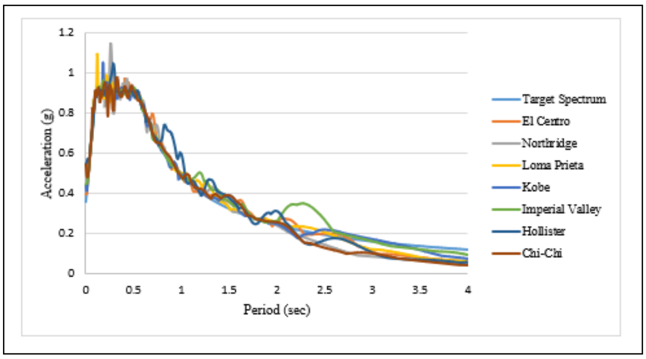

Figure 5: Target Spectrum and Response Spectrum of Considered Earthquakes after Spectral Matching

6. Results and Discussion

Modal analysis is carried out in the global finite element model of the example bridge to evaluate the dynamic characteristics. Twelve modes of vibration are considered for the modal analysis. The fundamental period of the non-isolated bridge is observed to be 0.467 seconds whereas the isolated one has 1.587 seconds. The period of the isolated bridge is found to be extended by almost 3.39 times the fundamental period.

To study the seismic performance of high damped rubber isolators, the percentage reduction in seismic response parameters such as base shear and deck acceleration are evaluated.

Table 3 shows the reduction in base shear for various time histories considered and the % control in the base shear after the bridge isolated using high damped rubber isolator. A maximum reduction in base shear is obtained as 62.12% for the Hollister earthquake and the minimum reduction obtained as 21.17% for the El Centro Earthquake. An average reduction in base shear of 37.81% is obtained which can be used in seismic design procedure for these typical isolator properties.

Figure 6 shows the bar diagram for the close comparison of base shear for non – isolated and isolated bridge for various earthquakes considered.

Table 3: Variation of Base Shear in Non – Isolated and Isolated Bridge Model

Ground Motion	Base Shear (KN)		
	Non-Isolated	Isolated	% control
Chi-Chi, 1999	501.713	329.097	34.40
El Centro, 1940	599.709	472.741	21.17
Hollister, 1961	1047.751	396.868	62.12
Imperial Valley, 1979	697.066	417.812	40.06
Kobe. 1995	622.979	466.503	25.19
Loma Prieta, 1989	771.54	431.52	44.07
Northridge, 1994	627.888	390.512	37.80

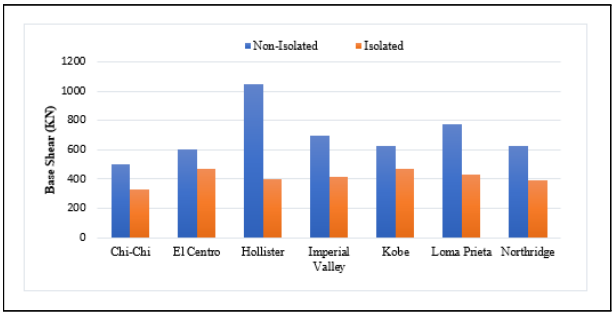

Figure 6: Base Shear Variation for Non – Isolated and Isolated Bridge in Bar Chart.

From Table 4, it is seen that the deck acceleration parameter is controlled considerably for all earthquakes with a maximum reduction of 57.67% for the Hollister Earthquake and the minimum reduction of 28.2% for the El Centro Earthquake. The average reduction in deck acceleration for seven considered earthquakes is 44.75%, which also can be used as a seismic design parameter when these typical isolator properties are used.

Figure 7 shows the bar diagram of deck acceleration variation for various earthquakes considered.

Table 4: Variation of Deck Acceleration in Non – Isolated and Isolated Bridge Model

Ground Motion	Deck Acceleration (m/s^2)		
	Non-Isolated	Isolated	% Control
Chi-Chi, 1999	2.615	1.18	54.87
El Centro, 1940	2.12	1.522	28.20
Hollister, 1961	3.383	1.432	57.67
Imperial Valley, 1979	2.45	1.51	38.36
Kobe. 1995	2.471	1.638	33.71
Loma Prieta, 1989	3.41	1.56	54.25
Northridge, 1994	2.953	1.589	46.19

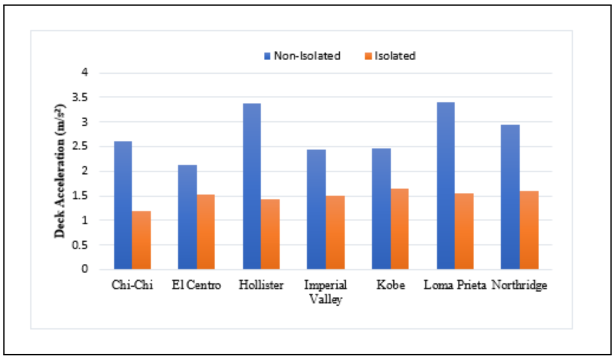

Figure 7: Deck Acceleration Variation for Non – Isolated and Isolated Bridge in Bar Chart.

Table 5 shows the maximum isolator displacement suffered by isolators for the considered earthquake scenarios. A maximum isolator displacement of 99.28 mm is obtained for the Kobe Earthquake.

Table 5: Isolator Displacement for Different Earthquakes considered

Ground Motion	Isolator Displacement(mm)
Chi-Chi, 1999	69.94
El Centro, 1940	89.08
Hollister, 1961	88.06
Imperial Valley, 1979	90.21
Kobe. 1995	99.28
Loma Prieta, 1989	88.20
Northridge, 1994	82.97

For the clear representation, the plot function of isolator displacement and deck acceleration is shown in figures below. The plot function gives a clear picture of seismic parameter variation during the event.

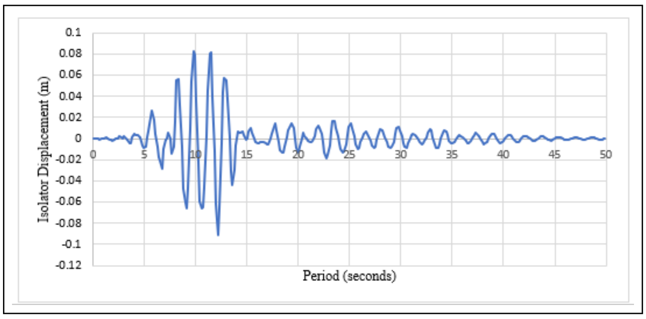

Figure 8: Plot Function showing Isolator Displacement for the Northridge Earthquake.

Figure 8 shows the isolator displacement time history for the Northridge Earthquake. Figure 9 shows the deck acceleration time histories for both isolated and non – isolated cases for the Northridge Earthquake.

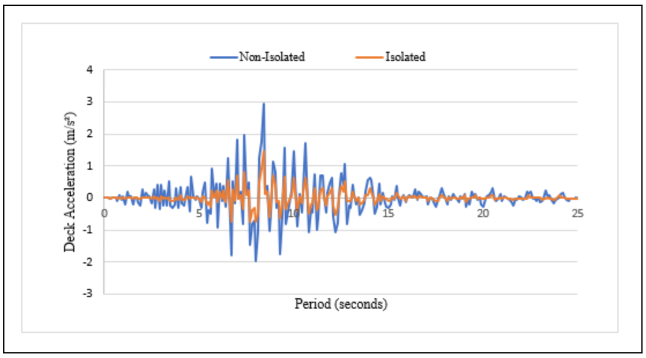

Figure 9: Variation of Deck Acceleration of Non – Isolated and Isolated bridge for the Northridge Earthquake.

7. Conclusions

In this paper, the seismic response of a two-span reinforced concrete bridge isolated by high damped rubber isolators is analyzed. The modal analysis and time history analysis for both isolated and non-isolated cases have been carried out in the present study. The seismic response namely isolator displacement, deck acceleration, pier base shear of example bridge is studied for seven ground excitations.

- The fundamental period of the bridge is increased considerably due to seismic isolation, which avoids the risk of resonance during the seismic event.
- The high damped rubber isolator is effective in reducing the seismic response parameters like base shear and deck acceleration. However, the seismic control amount is dependent upon the parameters like ground motion characteristics of the earthquakes and isolator properties considered.
- This procedure can be a useful tool in seismic damage mitigation facilitating the economical design. This can also be a beneficial approach in the seismic retrofit of old bridges constructed with conventional design practices.

Future Enhancements

The amount of seismic isolation is mostly dependent on the properties of isolators used. For the precise mechanical characterization of the seismic isolators, the parametric variation of properties like stiffness and damping can be studied for a wide range. The optimum mechanical parameter combination should be selected afterward to obtain the maximum seismic isolation.

Due to the flexible nature of seismic isolators, displacement at the deck level is increased during a seismic event. This may result in the pounding between the intermediate decks. The chances of deck failure can also be studied for new design as well as for retrofit of old bridges.

The longitudinal, transverse, and vertical components of earthquakes can be considered in the seismic analysis of the bridge. The contribution of various components of earthquakes on the response can be analyzed.

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