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Abstract

The use of seismic isolators such as Lead Rubber Bearings in bridges can considerably contribute to the reduction in forces acting on the substructure, especially in the event of near-field strong earthquakes. However, relatively large superstructure displacements necessitate the use of special expansion joints with larger dimensions at the end of bridge and also larger seats width on the piers. This research aimed to study the effect of using additional elastic stiffness in Seismic Isolated Bridges (SIB) to reduce superstructure displacements by keeping the substructure forces in the reasonable ranges. To this end, an elastomeric bearing was installed as a sample conventional Supplement Elastic Devices (SED) in parallel with seismic isolators in the space between the superstructure and substructure of a typical bridge. In order to evaluate seismic performance and compare of seismic behavior of systems, non-linear dynamic time history analyses were performed on the models of bridge using strong near-field records. Results indicated the positive effect of the application of SEDs to decrease the isolator displacements by keeping forces of substructure in control ranges in structures with seismic isolators. Moreover, by controlling the superstructure displacements and substructure forces simultaneously, the more appropriate piers may be used with smaller seats width.

Keywords: Seismic isolator; Lead Rubber Bearing; Elastomeric bearing; Near-field; Non-linear dynamic time history analysis.

Introduction

Near-field earthquakes are different from far-field earthquakes because of having more limited frequency contents at higher frequencies [1]. Due to the concentration of shear waves on the path of fault rupture, when these waves diffuse toward the station or site at a velocity as fast as ground structure rupture, a long-period pulse-like motion is caused in the beginning of near-fault record [2]. A lead rubber bearing dissipates a part of earthquake energy by keeping the structure away from the resonance ranges and another part by using a yield mechanism [3]. Generally, displacements of isolated bridges in far-field earthquakes are delimited to a control range [4]. Displacements of superstructures in isolated bridges in the vicinity of powerful faults are considerable and may necessitate installation of large special expansion joints at the bridge ends. As a result, the seat width of piers grows leading to an increase in the dimensions of piers. This is in contrast with the application of seismic isolators in economic and practical projects [5]. Hence, the use of Conventional Supplement Elastic Devices (SEDs) is useful for delimiting isolator displacements to the control ranges while also keeping substructure forces in the range suiting Seismic Isolator Bridges (SIBs) in the vicinity of fault motions in medium to large distance earthquakes. In addition, the overall behavior of a SIB with SED is similar to that of an elastic structure with a period equal to the bridge post-elastic period under near-fault ground motions. Therefore, stiffness of SED can be determined in a relation with the velocity pulse period (or magnitude) of near-fault ground motions with minimum isolator displacements regardless of the resonance response [6]. Warn et al. indicated that the maximum horizontal displacement of isolator determined by the equation in the AASHTO code yields an underestimated value despite using conservative values (or small) of damping coefficient and assuming the linear increase in displacements in periods higher than 1 second [7]. As compared to viscous dampers, SEDs combined with SIBs generate higher forces on the substructure. Hence, although SEDs are not as effective as dampers for reducing substructure forces, they can be now incorporated into seismic designs and rehabilitation of near-fault SIBs situated on areas intended larger design earthquake magnitudes [6]. Sahasrabudhe et al. studied the effect of active energy absorption devices sush as magnetorheological (MR) dampers to control the sliding isolator displacements in bridges. They figured out that the use of MR dampers in the controlled modes reduces bearing displacement more than the passive low- and passive high-damping cases through keeping forces at a level equal to passive low-damping cases [8].

This research studied the effect of using elastomeric bearings as supplement elastic devices on decrease in superstructure displacements in seismic isolated bridges. To this end, a typical three-span bridge with a deck consist of precast prestressed concrete girders and concrete slabs, was selected. This bridge was designed in accordance with AASHTO. In order to compare the efficiency of SEDs in SIBs, different models with varying SED stiffness values were created. Non-linear dynamic time history analyses were carried out on the models using strong near-field records.

Bridge Specifications and Modeling

Models were formed of a typical three-span bridge with a deck composed of precast prestressed concrete girders and concrete slabs. The models differed in the type of bearings and stiffness of SEDs they employed. Lengths of spans were 33, 33 and 33 meters. Figure (1) shows an elevation and plan view of the typical bridge. The nominal gap between the deck ends and abutments was 5 cm and the width of the concrete deck was 12.5 m. Each pier included 3 columns with a diameter of 1.2 m and 10m height. Besides, the distance between piers was 5 m. The cross-section of deck on the middle pier with the position of SEDs and isolators are shown in Figure (2). Isolators were designed based on the $Q_d/W=0.065$, where Q_d denotes isolator characteristic strength and W denotes the effective deck weight imposed on each isolator. The total weight of the deck due to dead load is equal to 16500 KN and the effective weight on each isolator in the middle pier was calculated to be 1200 KN. Equation (1) shows the relationship of lead core area (A_l) and core allowable compressive stress (σ_l) with characteristic strength. Hence, the diameter of the lead core (D_l) was determined to be 18 cm and the external diameter of the isolator (D_b) was determined to be 50 cm. The thickness of the isolator was also selected equal to the rubber diameter.

$$Q_d = \sum A_l \sigma_l \tag{1}$$

Post-elastic stiffness (K_d) was determined using the diameter and thickness of the isolator by assuming 15 cm of displacement in the earthquake design level (D_d). The effective stiffness of the isolator (K_{eff}) was also obtained using Relation (2) [9].

$$K_{eff} = K_d + Q_d / D_d \tag{2}$$

In addition, by assuming the yield displacement (Y) equals 1 cm, the yield strength (Fy) and elastic stiffness (K) values for the isolator were obtained using relations (3) and (4);

$$F_y = K_d \cdot Y + Q_d \tag{3}$$

$$K = F_y / Y \tag{4}$$

SEDs were installed on the middle piers in the distance between the diaphragm and seat of pier and placed between isolators (Fig. 2). Gravity loads were imposed on isolators while SEDs only provided lateral stiffness. In this system, isolators and SEDs acted such as parallel springs and the equivalent stiffness of the system equaled the sum of their stiffness. The effective stiffness of SEDs (k_e) was determined as the ratio of post-elastic stiffness of isolators (K_d) in the models. Figure (3) depicts the bi-linear hysteresis model of isolator force-displacement, stiffness of supplement elastic devices, and equivalent stiffness of combined system.

Figure 1. *Base Bridge Prototype*

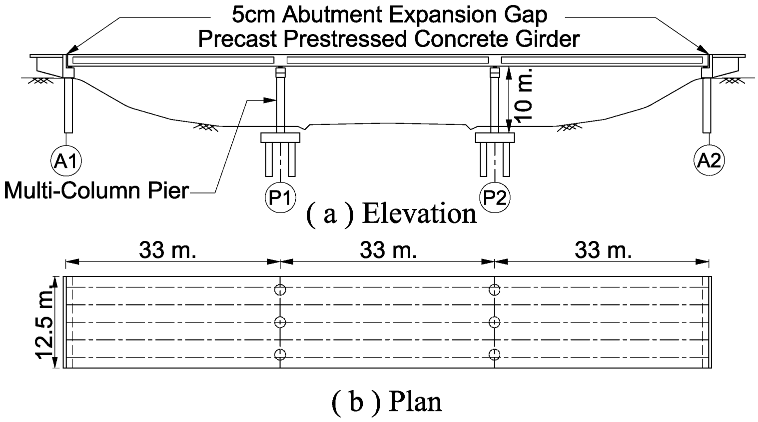


Figure 2. *Typical Configuration of Deck Transverse Section above Piers*

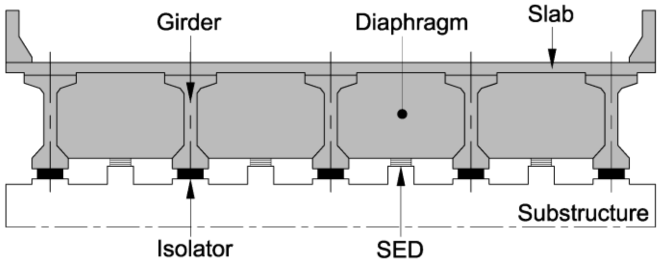
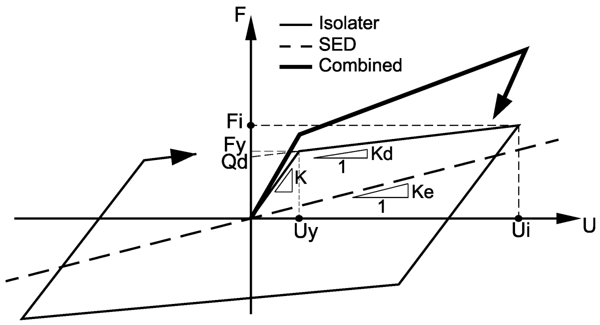


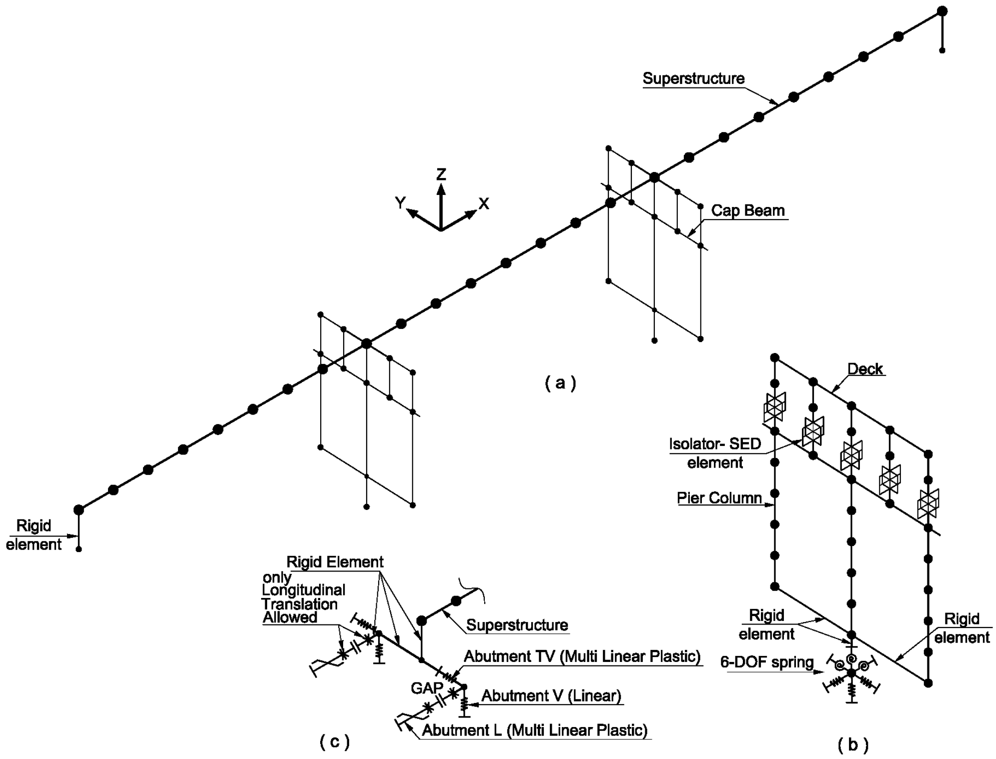
Figure 3. *Force-displacement Relationships of Isolator, Supplemental Elastic Device and their Combination [6]*



In the study models, it was assumed that the substructure remained in the linear range, which complied with the design assumption of isolators [10]. Stiffness of soil springs at middle piers in all six degrees of freedom was modeled using the method introduced for spread footings assuming that $\nu=0.35$ and $G=1180\ KN/m^2$[11]. Figure (4) shows the allocation of the springs.

Abutments were seat-type abutments. Moreover, their seats were covered with a row of isolators embedded under each beam. In modeling the seat-type abutments, realistic behavior that covered all of the components and mechanisms of strength (such as mass and non-linear hysteresis behavior) was considered. The soil-structure strength curve for abutments was obtained based on SDC2004 in the longitudinal and transverse directions while the primary stiffness of the embankment behind abutments was assumed to be Ki=11.5 KN/mm/m and the maximum passive pressure was 239 KPa [12]. The abutment model for the study (Figure 4) included a rigid element with a length of d_w (concrete superstructure width). The element was connected to the center of superstructure using rigid connections. Non-linear response was also defined along the longitudinal and transverse directions at both ends.

Figure 4. *Configuration of Model for Nonlinear Analysis; (a) Three Dimension Model, (b)Detail of Middle Pier Model, (c)Detail of Abutment Model*



In the longitudinal direction, the series system (Figure 4) was comprised of a rigid element with releasing shear and moment at ending, a gap element, which was only able to move along the longitudinal direction (the movement only applied to the expansion joint and soil strength acted immediately after closing the gap), and a zero-length elastic-completely plastic backbone curve element with abutment stiffness (K_{abt}) and ultimate strength (P_{bw}) were defined based on SDC2004. In the transverse direction, there was a non-linear zero-length element at both ends of the rigid element of abutment. It was in the form of an elastic-completely plastic resistant curve, which reflected the response of the embankment and foundation. The resistance of shear keys as well as distribution of bearings at the abutment was neglected in modeling. In order to consider the vertical stiffness of isolator bearings at two ends of the rigid element of the abutment, elastic springs with the vertical stiffness of bearings (K_v) were used [13].

The characteristic strength of concrete used in piers and deck was f’c=35 MPa and the yield stress of rebars in use was assumed to be f_y= 400 MPa. Models were created as three-dimensional models using the SAP 2000 (v.14.2.4) software [14]. The Rubber Isolator link in the program was used in order to bi-linear model of the lead rubber bearings.

Earthquake Records

In order to assess the behavior of the structure under actual strong earthquakes, the non-linear time history analysis was performed for the designed bridge model by using the near-field earthquakes records. Since this research studied the longitudinal movement of bridge, only horizontal records perpendicular to the fault line were used.

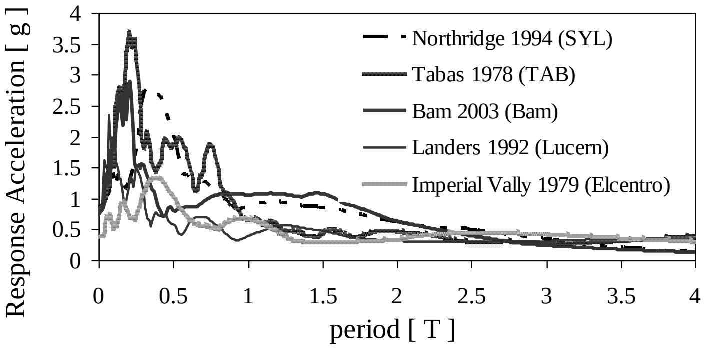
In selecting near-field records the following two criteria were used as the inclusion criteria: the distance from the fault rupture plane and the presence of high-amplitude long-period velocity pulses. Therefore, according to Table (1), near-field earthquakes included the 1994 Northridge earthquake (Sylmar Station), the 1978 Tabas earthquake (Tabas Station), the 2003 Bam earthquake (Bam Station), the 1979 Imperial Valley earthquake (Elcentro Station), and the 1992 Landers earthquake (Lucerne Station). Accelerogram data was obtained from the Peer website, which is affiliated with the University of California, Berkeley [15]. Figure (5) depicts the response spectra of the aforementioned accelerograms.

Table 1. *Specifications of selected Near-field Earthquakes Records*

Earthquake (Station)	Magnitude (M_w)	Distance (km)	PGA (g)	PGV (cm/s)
			Horizontal	Horizontal
Northridge-1994 (Sylmar)	6.7	6.4	0.843	129.36
Tabas-1978 (Tabas)	7.4	3	0.852	121.22
Bam-2003 (Bam)	6.6	1	0.778	121.47
Imperial Vally-1979 (Elcentro, Array #5)	6.5	1	0.38	90.5
Landers -1992 (24Lucerne)	7.4	1.1	0.720	97.6

Accelerogram of the corresponding earthquake were applied to the structures by their real values without applying coefficients for scaling to the standard design spectrum. This is important, especially for the accelerograms registered in the near-field of a fault. It means that such accelerograms are registered at the near distances to the ground failure surface and they indicate real behavior of ground at the time of fault fails.

Figure 5. *Response Acceleration Spectra of selected Records*



Dynamic Responses of Bridges

Models were prepared based on the criteria enumerated in section 2. According to the design of isolators, the post-elastic stiffness of isolators was obtained to be K_d=1200 KN/m. In this research, the following 6 models were examined: 1) a typical bridge with elastomeric bearings (conventional); 2) seismic isolator bridge (SIB); 3) SIB and SED with $k_e=2K_d$; 4) SIB and SED with $k_e=4K_d$; 5) SIB and SED with $k_e=6K_d$; 6) SIB and SED with $k_e=8K_d$. Non-linear dynamic time history analyses were performed on the models using the input near-field accelerograms introduced in section 3.

Fundamental periods in models (1) to (6) were 0.64, 2.77, 1.82, 1.55, 1.42, and 1.34, respectively.

Figures (6), (7) and (8) show superstructure displacements, base shear and isolator displacements in longitudinal direction, respectively, for the models under the study earthquakes. Moreover, the average values of these functions in various near-field earthquakes are shown in these figures.

Results revealed the positive effect of reducing superstructure displacement using SEDs while also keeping substructure forces in the control ranges.

Results obtained showed around 25-50% reduction in superstructure displacements by using SEDs with varying stiffness compared with a SIB without SEDs. This was ascribed to the fact that they keep substructure forces in the reasonable ranges. Depending on different stiffness values of SEDs, base shear forces were on average about 51-70% of than those of the typical conventional bridge without the seismic isolator based on SEDs stiffness.

Moreover, results of isolator displacements also indicated that about a 26-52% reduction in isolator displacement was obtained depending on the stiffness of SED compared to the SIB without SED.

A decrease in the displacement of isolator and superstructure in SIBs in the vicinity of strong faults led to a decrease in the width of seats at piers. For example, using an SED with stiffness of $8K_d$ the superstructure displacement was reduced from 28.14 cm to 14.24 cm on average. Hence, the minimum seat width required for piers was reduced from 2×28.14=56.28 cm to 2×14.24=28.48 cm. However, by considering the dimensions of isolator connection plates and providing the minimum distance between the isolator gusset plate and seat edges, the minimum seat width in the absence of SED was increased from 56.28 cm to 110 cm. Therefore, the dimensions of piers by using supplemental elastic stiffness shall be modified and may be reduced. Moreover, this reduction in displacements provides for the use of smaller expansion joint at bridge ends.

Figure 6. *Superstructure Displacement in Longitudinal Direction*

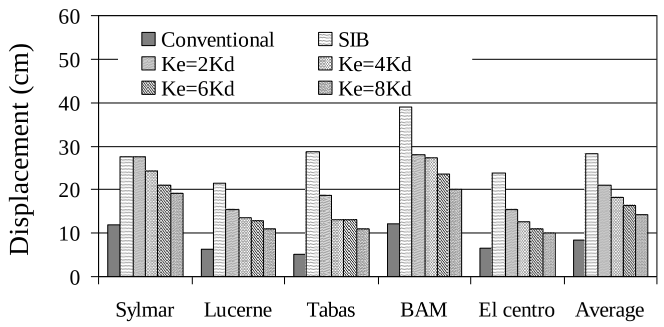


Figure 7. *Base Shear Forces in Longitudinal Direction*

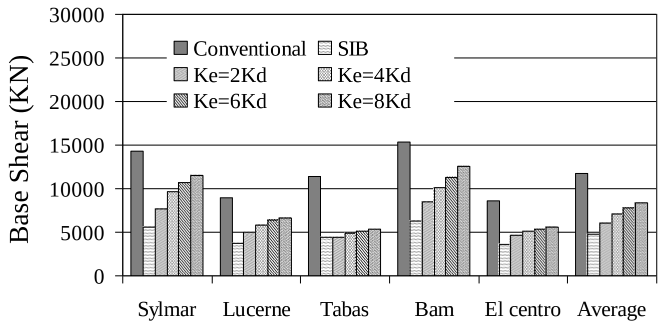
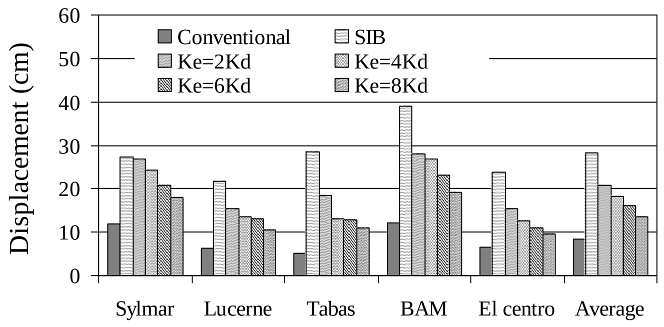


Figure 8. *Isolator Displacement in Longitudinal Direction*



Conclusion

This manuscript focused on the study of the incorporation effect of supplement elastic devices into seismic isolator bridges on reduction in isolator displacement by delimiting substructure forces to the reasonable and control ranges. To this end, typical SED bearings such as elastomeric bearings with varying stiffness values were emplaced in parallel with seismic isolators into the space between superstructures and substructures. The following results were obtained with the use of the SEDs:

Such additional stiffness can be used effectively for seismic rehabilitation of SIBs near strong ground motion and also for effective control of superstructure displacement. In addition, it was found out that supplement elastic devices also keep substructure forces in the rational and control ranges.

The effect of using SEDs is important, especially in near-field earthquakes affected by forward rupture directivity (which lead to large displacements in superstructure of seismic isolated bridges). However, in far-field earthquakes, displacements of SIBs fall in the control ranges and thus there is no need for SEDs.

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