16th World Conference on Earthquake Engineering, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 3788
Registration Code: : *S-E1463857855*

SEISMIC RETROFIT OF OLD BRIDGES WITH SEISMIC ISOLATION

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Abstract

A standard highway bridge has usually multi simple spans supported over piers by elastomeric bearings in Turkey. The bearings usually do not provide a positive connection but in contact with girder and pier by only gravitational forces. In this study, a model test bridge of about ½ scale have been shaken under low to moderate earth quakes to determine the change in response of the bridge with different seismic isolation configurations. Three configurations of bearings are elastomeric bearings, lead core bearings and ball rubber bearings. The bridges supported with lead rubber or ball rubber bearings' deck displacements are dampened out in a short period of time compared to the tests of bridges with elastomeric bearings as expected. The seismic retrofit goals can be defined for the old bridges based on the target structural response in terms of displacements and forces.

Keywords: bridge; seismic; isolation; retrofit

1. Introduction

The old bridges in Turkey usually have an elastomeric bearing support which can provide a response isolation between substructure and superstructure during an earthquake. These bearings do not inherit high damping characteristics as their advanced types such as lead rubber or ball rubber bearings. The aim of this study is given identify the variation in response of bridge superstructure thru bridge shake tests and provide recommendations for the seismic retrofit of old bridges.

The elastomeric bearings placed under the bridge girders stay at their position by gravity forces and usually no mechanical connection of the bearing to the substructure or superstructure is made as shown in Figure 1. In some cases, these free bearings can walk out from their position even if there is no earthquake mostly due to cyclic service load cases at bridges on slope or with high skewness as shown in Figure 1.

(a) (b)

Figure 1. (a) Shear key damage during an earthquake (b) walkout during service

The seismic isolation systems has known to minimize the earthquake induced force effects while controlling the increased displacements by use of proper damping characteristics [1,2,3,4,5,6]. Agrawal et al [5] concluded that the elastomeric bearings and lead rubber bearings can significantly improve the vulnerability of bridges to the seismic events.

2. Test Bridge and Isolation System

The material tests of the bridge support systems under cyclic loads at a predetermined compression is followed by bridge shake tests. The three types of rubber based bridge supports have the same geometry in terms of shape. The shear modulus of the rubber is determined to be around 0.8 MPa. The internal layer of rubber is 10 mm and the diameter of the supports are 150 mm. The total thickness of the rubber is 50 mm.

The inner hole diameter for lead rubber and ball rubber bearing is set to 50 mm. The inner hole is either filled with pure lead plugs or 1.65 mm diameter steel balls. The lead plugs are forced to get into the hole in the case of lead rubber bearings and balls are just freely poured into the hole until the hole is filled to the top in the case of ball rubber bearings. The steel shims of having a yield strength of 235 MPa has a thickness of 2 mm. The geometric details of the tested systems are given in Figure 2 for lead rubber bearings. The only difference between lead rubber, ball rubber and elastomeric bearings is that the lead and ball rubber ones have the internal hole filled with additional material.

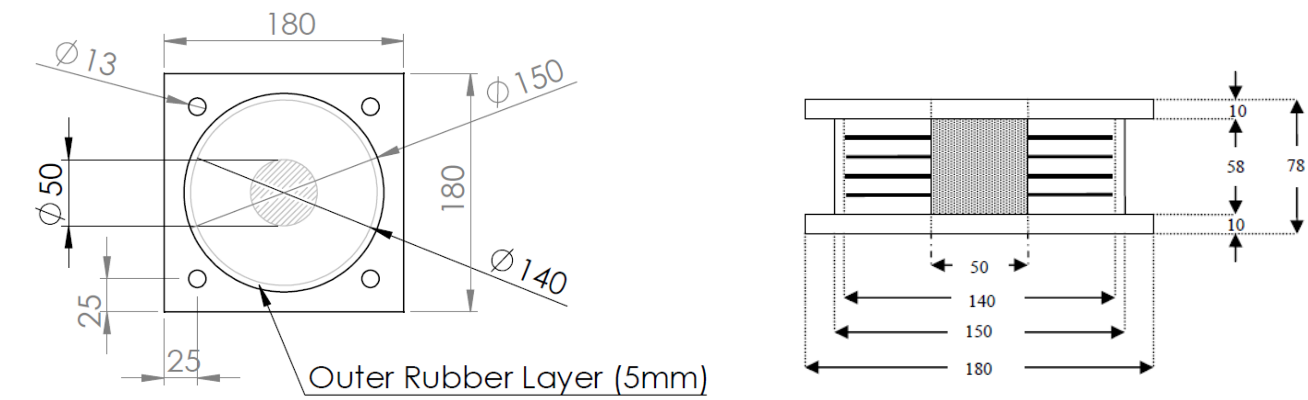

Figure 2. Lead Rubber Bearing Design Details

The individual cyclic load tests of bearings conducted using two pairs of bearings at the same time [7]. These tests are performed to determine the lateral cyclic load deformation characteristics of the bearings under a predetermined compression. The testing machine is capable of applying 4000 kN in vertical direction and 1000 kN in lateral direction. The maximum lateral displacement can change between +/- 250 mm having a total cylinder course length of 500 mm. The bridge support systems can be tested in lateral direction with use of cosine function that can cycle between positive and negative values of target amplitude at a certain frequency that determines the rate of loading. At each test one bearing is placed on top and the other placed at bottom side of pull-push plate attached to the lateral hydraulic cylinder. The target amplitudes selected based on the percent of rubber shear strain for each test. At the extreme displacement test machine adjust itself to apply the same load in vertical direction so that there will be no change of vertical load as the bearings move in lateral direction.

The bridge used in earthquake shake tests has been used in one other research studying the effect of vehicles on bridges during earthquakes [8]. The same bridge setup is used by replacing its support system with the elastomeric bearings, lead rubber bearings and ball rubber bearings. The total weight of the reinforced concrete slab on steel beam type superstructure is 200 kN and the reinforced concrete substructure including the two piers weighs around another 200 kN. The reinforced shake table is supported on six dimpled and oiled teflon plates, sliders, that only create about 1 to 2% friction loss. The earthquake records are applied thru a computer software that controls the hydraulic actuator capable of pushing and pulling the reinforced concrete substructure over the sliders and can excite the structure up to 0.5 g for a certain amplitude in real time. The photos of the test bridge is given in Figure 3. The reinforced concrete has been set to have a 28-day compressive strength of 25 MPa. The steel beams and braces have yield strength of 235 MPa.

Figure 3. Test Bridge and Bridge Bearings

Five earthquake records are applied to the test bridge that are also used in the research of Shaban et al (2015). These amplitude scaled records have the following properties.

Table 1. Selected Earthquake Records

Name	Earthquake	M_w	Station	Applied Scaled PGA (g)	Site Type	Epicentral Distance (km)	Scale Factor
M1	İzmit 1999	7.4	Sakarya	0.213	C	36	0397
M2	İzmit 1999	7.4	Sakarya	0.107	C	36	0.200
M3	İzmit 1999	7.4	Göynük	0.135	D	81	1.000
M4	Düzce 1999	7.2	Düzce	0.124	D	9	0.370
M5	Düzce 1999	7.2	Düzce	0.067	D	9	0.200

3. Test Results and Discussions

3.1 Individual Bearing Tests Under Combined Compression and Cyclic Shear

The individual tests of three types of bearings reveal that lead rubber bearings are about 10% to 30% stiffer than ball rubber bearings having the same geometry and shape factor for elastomeric bearing with an inner hole filled with either material. The elastomeric bearings have much less stiffness compared to the both lead rubber and ball rubber bearings as expected and shown in Table 2 since the only source of lateral stiffness is the rubber material itself for elastomeric ones. The high stiffness of the lead rubber bearing is due to additional high yield stress of the lead core and the additional high stiffness of the ball rubber bearing is developed due to the friction between the rolling balls under applied lateral effects. The ball rubber bearings and the lead rubber bearings have similar effective damping value. The lead rubber bearing has both higher EDC and K_eff compared to the ball rubber bearing on the same magnitude of order. Therefore, EDC divided by the K_eff results in similar equivalent damping ratio for lead rubber bearing and ball rubber bearing under the same lateral displacement.

Table 2. Bearing Test Results per One Bearing Under 3 MPa Constant Compression

Support Type	Keff (kN/m) 25% Strain	50% Strain	100% Strain	Equivalent Damping (%) 25% Strain	50% Strain	100% Strain
EB	410	375	312	8	9	9
LRB	875	597	383	21	27	27
BRB	769	441	289	24	23	25

Effective stiffness of elastomeric bearings do not change significantly as compared to the lead rubber and ball rubber bearings by the increase of shear strains due to the low damping characteristics of the tested elastomeric material. The effective stiffness measured at 100% strain is about 35% at effective stiffness measured at 25% strain that corresponds to a 65% reduction in effective stiffness.

3.2 Bridge Shake Tests

The bridge shake tests reveal that in some cases the peak deck accelerations are even less than the applied peak ground accelerations for the lead rubber bearings and ball rubber bearings at some instances. The deck accelerations measured at the mid-span of the bridge has a scattered response in terms of comparing minimum and maximum values as shown in Table 3. In tests of M1 and M4 records where relative deck displacements and accelerations are large compared to other cases, the highest deck acceleration is measured at the bridge tests with elastomeric bearings and the lowest deck accelerations is measured at the bridge tests with ball rubber bearings. In these cases, the elastomeric bearings having low damping and stiffness compared to other bearings resulted in large displacements associated with large accelerations not much effectively dampened as in the case of lead rubber and ball rubber bearings. The lead rubber bearing stiffness being larger compared to the ball rubber bearing also resulted in slightly high acceleration compared to the ball rubber bearings. The deck displacements that reached to 50% strain values at bridge tests with elastomeric bearings are reduced by 70% in bridge shake tests with lead rubber bearings and 50% in similar tests of ball rubber bearings due to high stiffness and equivalent damping ratio properties as shown in Table 4.

Table 3. Bridge Deck Accelerations

Support	Peak Deck Acceleration (g)				
	M1 Test	M2 Test	M3 Test	M4 Test	M5 Test
EB	0.257	0.145	0.136	0.293	0.112
LRB	0.241	0.177	0.191	0.238	0.137
BRB	0.204	0.151	0.164	0.217	0.119

Table 4. Peak Bridge Deck Displacements Relative to Cap Beam

Support	Peak Deck Displacement (mm)				
	M1 Test	M2 Test	M3 Test	M4 Test	M5 Test
EB	24.5	9.9	9.4	27.9	8.8
LRB	8.1	6.0	6.4	8.9	4.1
BRB	12.2	7.0	9.2	14.3	3.3

In tests of M2, M3 and M5 records, the deck displacements are less than 25% strain values of bearings and about 65% less than the results of the M1 and M4 bridge tests. In all these three cases, there is not much significant change in deck acceleration results. The relative deck displacements for lead rubber bearing bridge tests resulted in about 50% less deck displacement due to its high stiffness. The lead rubber bearings are only displaced about their yield displacement level where ball rubber bearings exceeded their yield displacement capacity and ended up with smaller stiffness in the cases of bridge tests under M2 and M3 earthquakes. At M5 earthquake bridge test, ball rubber bearings and lead rubber bearings stayed around the yield displacement. Sample deck displacement reduction for M5 earthquake are given in Figure 4.

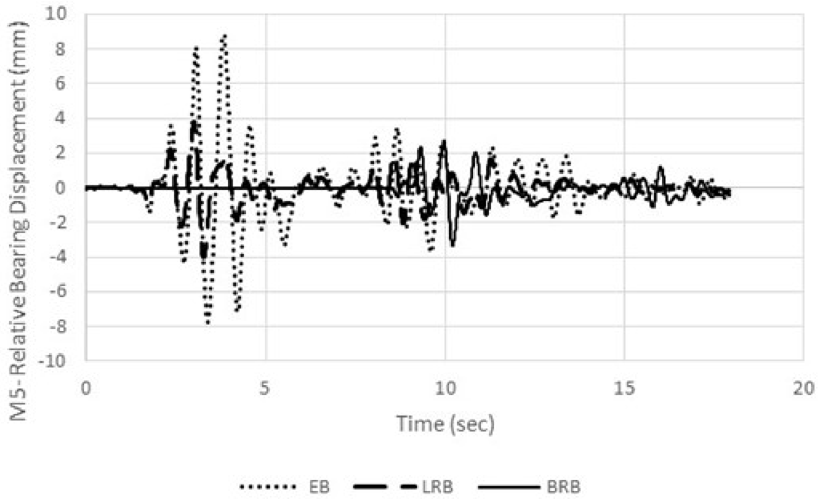

Figure 4. Comparison of Measured Deck Displacements.

3. Case Study

A standard railway bridge has been studied to investigate the seismic performance with different bearing configurations. The multiple-girder-on-slab bridge has ten precast pre-tensioned girders with a height of 1900 mm. The thickness of the slab is taken as 300 mm. The compressive strength of concrete at 28 days is assumed to be 30 MPa for reinforced concrete elements. The sectional properties of the main bridge elements are shown in Table 5 and the 3D bridge model in Figure 5.

Table 5. Sectional Properties

Element	Area (m^2)	Istrong (m^4)	Iweak (m^4)
Girder	0.78	0.34	0.03
Column	9.03	15.99	2.74

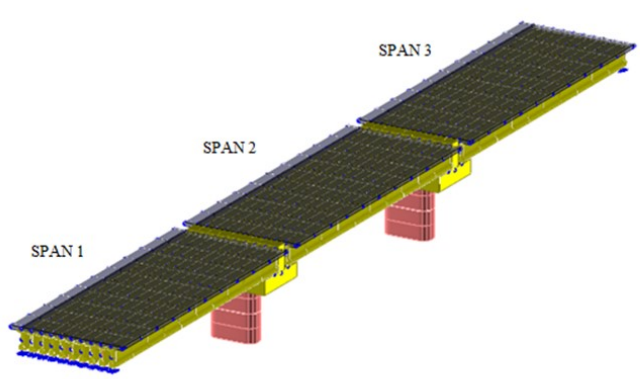

Figure 5. 3D Bridge Model - LARSA

Table 6. Bridge Support Conditions – Longitudinal Direction Effective Stiffness

Case	Span 1 – Bearing Stiffness		Span 2 – Bearing Stiffness		Span 3- Bearing Stiffness	
	Left	Right	Left	Right	Left	Right
Original	3600	Fixed	3600	Fixed	Fixed	3600
Retrofit-Service	4000	Fixed	4000	Fixed	Fixed	4000
Retrofit- Seismic	1500	1500	1500	1500	1500	1500

The original bridge has some fixed and movement bearings as listed in Table 6. The inherent damping of the movement bearings is 5%. In the retrofit case, seismic isolation with 20% damping has been utilized. During the service conditions the original bearing condition has been maintained thru restrainers. The restrainers have been designed to break as a fuse during the design earthquake. Therefore, the stiffness of the retrofit service performance will be significantly different than the retrofit seismic case.

The fundamental period of 0.45 sec in longitudinal direction of the original structure will shift to the 1.43 seconds. The shift in fundamental period of the structure is shown on the design response spectrum curve provided in Figure 6.

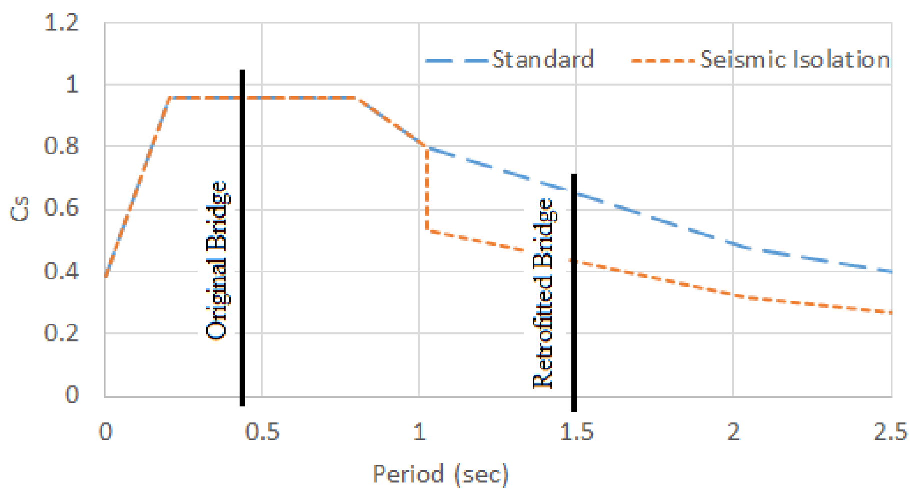

Figure 6. Shift in Fundamental Period

The seismic forces reduced by almost 50 % as the seismic coefficient corresponding to the fundamental period of the original bridge shifted to a new state for the retrofitted bridge case as shown in Figure 6.

4. Conclusions

The tests of three type of bridge supports being elastomeric bearings, lead rubber bearings and ball rubber bearings have clearly indicated that the stiffness and damping characteristics dominate the control of the deck displacements during an earthquake. The tests involved not only individual performance tests but also real time bridge earthquake shake tests. Following conclusions can be drawn from this research:

1. In all tested cases, even after very low earthquakes, the rubber based bridge supports re-centered themselves and came to their original position after each shake test.

2. The deck displacements of the bridges supported with lead rubber or ball rubber bearings are dampened out in a short period of time compared to the tests of bridges with elastomeric bearings, as expected. The individual

tests of lead rubber and ball rubber bearings indicated that the damping characteristics of these bearings are about three times larger than those of elastomeric bearings.

3. The seismic isolation system of using ball rubber can be effectively used to reduce the deck displacements and possibly the substructure forces as expected. In the tests, it was revealed that the reduction in deck displacements can be more than 50% of original value. The seismic isolation can be effectively used to replace the elastomeric bearings to have a better control on mitigation of seismic forces.

4. Use of seismic isolation can significantly reduce the design forces as demonstrated in the case study.

5. Acknowledgements

The authors would like to thank to TUBITAK for their support of the 110G093 research project. The authors would also like to extend their thanks to Turkish General Directorate of Highways (KGM).

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