Journal of Traffic and Transportation Engineering (English Edition) 2018; 5 (6): 480–490

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Original Research Paper

Shake table tests of different seismic isolation systems on a large scale structure subjected to low to moderate earthquakes

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HIGHLIGHTS

- Ball rubber bearings provide the same EDC as lead rubber bearings while having less stiffness.
- Ball rubber bearings transfer smaller forces to substructure elements than lead rubber bearings do.
- Ball rubber bearings have both larger EDC and stiffness compared to elastomeric bearings.
- Ball rubber bearings lead to a more significant improvement in seismic response compared to elastomeric bearings.

ARTICLE INFO

Article history:
Received 15 May 2018
Received in revised form
10 August 2018
Accepted 13 August 2018
Available online 7 October 2018

Keywords:
Shake table test
Seismic isolation
Lead rubber bearing (LRB)
Ball rubber bearing (BRB)
Elastomeric bearing

ABSTRACT

Seismic isolation systems designed for extreme events may likely experience low to moderate earthquakes during the design life of the structure rather than the extreme event itself. In new seismic building design codes, low and moderate earthquakes are also mandatory to be investigated in Turkey and some other countries. One of the main reasons is to protect the integrity of non-structural elements or machines during these types of earthquakes. The selection of appropriate seismic isolation is typically decided based on their force-displacement characteristics and amount of energy dissipation per cycle. The same energy dissipation per cycle (EDC) can be achieved by high force-low displacement or low force-high displacement response. The focus of this research is given to identify the performance of ball rubber bearing isolation systems compared to different or similar EDC units such as elastomeric bearings and lead rubber bearings through a series of shake table tests performed at low to moderate earthquake levels. Shake table tests were conducted on an almost full scale short span bridge. The tests have revealed that the ball rubber bearings are superior to elastomeric bearings in terms of EDC and can match EDC of LRB. However, although LRB and BRB have the same EDC, BRB is more beneficial to use under low to moderate earthquakes since BRB can transmit less force with larger displacement compared to LRB and LRB can sometimes stay in elastic range with an ineffective EDC as a stiffer elastomeric bearing.

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Peer review under responsibility of Periodical Offices of Chang'an University.
https://doi.org/10.1016/j.jtte.2018.10.003

1. Introduction

The seismic isolation systems have been extensively implemented in building and bridge type structures to minimize the adverse effects of earthquakes. Although, the isolation system is designed for the extreme event, it will more likely perform under lower intensity earthquakes which have a higher probability of occurrence. Therefore, performance of structures is always tested before the big event. A representative distribution of earthquake severity for Turkey confirms the statement. Statistical records of peak ground acceleration values of earthquakes for three major cities in Turkey, namely Ankara, Izmir and Bursa, are shown in Fig. 1. The data further elaborated by Yilmaz (2014) shows that moderate earthquakes are the most frequent seismic events for the representative cities which can be generalized for the whole territory of Turkey.

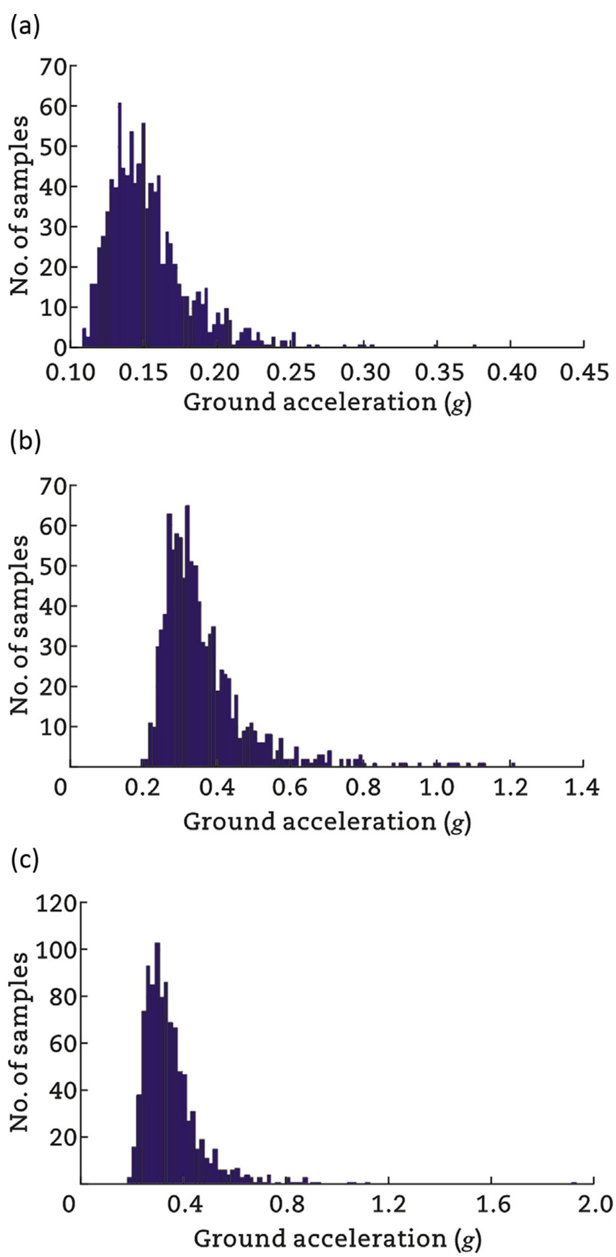

Fig. 1 – Histogram of peak ground accelerations. (a) Ankara. (b) Izmir. (c) Bursa.

In light of this data, the performance of seismically isolated structures needs to be investigated for low and moderate earthquakes other than the extreme event scenario considered in design. This is also required by the new Turkish seismic design code. The code specifies four earthquake levels with the following return periods: DD1 – 2475 years, DD2 – 475 years, DD3 – 72 years and DD3 – 43 years and makes investigation for all of them mandatory. In the current study, devices are interchangeably used as either isolation or bearing.

Seismic isolation usually fits to structural working principles of a bridge rather than a high-rise structure and typically significantly improves the seismic response of bridges that may be subjected to damages induced by earthquakes. The standard bridges in Turkey, usually designed to have a minimum damage level at large earthquakes, and have been tested under the major earthquakes of the past twenty years. In the recent 2012 Van earthquake with Mw 7.1, the only observed minor damage was cracking at substructure elements due to pounding effects of superstructure to the substructure (Akansel et al., 2014; Okuyucu et al., 2012). 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 Fig. 2. 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 Fig. 3.

The seismic isolation systems have been known to minimize the earthquake induced force effects while controlling the increased displacements by use of proper damping characteristics (Agrawal et al., 2012; Avsar and Ozdemir, 2013; Caner et al., 2015; Castaldo and Lo Priore, 2018; Dezfuli and Alam, 2013; Li and Conte, 2018; Liu et al., 2014; Ozkaya et al., 2011). Agrawal et al. (2012) concluded that the elastomeric bearings and lead rubber bearings can significantly improve the vulnerability of bridges to seismic events.

In a recent study, the seismic performance of elastomeric bearings has been reported by Steelman et al. (2013). The seismic performance of these bearings can degrade during slips at multiple large cycles of displacement. Vemuru et al. (2014) and Sanchez et al. (2013) have conducted a series of shake table tests of a mass with four elastomeric bearings under severe ground motions to verify their analytical work. They have concluded that the elastomeric bearings could exceed their theoretical stability limit while sustaining larger horizontal loads than expected.

The individual tests of seismic isolation bearings do not usually address the total structural response of the bridge since they are conducted independent of the structure. In a usual case, the engineers select to perform a series of numerical structural analyses including the non-linear ones to determine the structural performance of the bridge. The structural response predictions of such structural analyses in some cases can be found to be very successful in predicting the real bridge response to earthquakes (Shaban et al., 2015). Shaban et al. (2015) have performed a series of earthquake

Fig. 2 – Minor damage close to the elastomeric bridge bearings after the Van earthquake.

shake tests on a large scale bridge to assess the vehicle presence on a bridge during earthquakes. The conducted time history analyses were in a good agreement with the test results. Similar study has been conducted by Wibowo et al. (2012) to investigate live load effects on seismic response of curved bridges. Both experimental studies indicate that a vehicle acting as a hidden mass damper can reduce the seismic response on substructure. Vehicles, being transient loads, are not a permanent source of response modification for bridges as in the case of seismic isolation.

The main focus of this research is given to compare the effectiveness of different seismic isolation systems on the seismic response of a large-scale bridge model subjected to low to moderate earthquake shake tests. The tested support systems are elastomeric bearings, lead rubber bearings and ball rubber bearings. The present study is aimed to identify the performance of newly introduced ball rubber bearings comparing it with the one of elastomeric and lead rubber bearings that have gained wide acceptance and application. This comparison has not been performed before and is intended to provide the design engineer with comparative performance assessment to clarify the proper area of application of each system considering its outstanding benefits. Another distinguished aspect of this research is the investigated level of earthquake intensity. Although the design is performed for the maximum considered seismic event, the isolation systems are most likely subjected to low to moderate earthquakes, i.e., while a strong earthquake may not happen during the structure, life time, moderate earthquakes may be repetitive events. This qualifies these earthquakes as a must in performance evaluation. Furthermore, the most trustworthy approach for such an evaluation is the full-scale real-time shake test which is another valuable contribution of the presented study.

Fig. 3 – Walkout of a free elastomeric bridge bearing in a regular day.

2. Test bridge and isolation system

The material tests of the bridge support systems under cyclic loads at a predetermined compression are followed by bridge shake tests. The three types of rubber based bridge supports have the same geometry in terms of shape.

The design method derived for ball rubber bearings including the low temperature effects has been developed by Caner et al. (2015) thru a series of experimental research. Similar to lead rubber bearings, the hole inside the bearing is filled with 1.65 mm diameter steel balls on average. During the seismic event, the steel balls roll and develop friction to provide damping. The inner hole temperature does not increase significantly as compared to the lead rubber bearings due to the presence of air pockets between the small size diameter balls.

The shear modulus of the rubber is determined to be around (0.8 ± 0.1) MPa per strain levels defined in TS EN 1337 (2007). The internal layer of rubber is 10 mm and the total thickness of the rubber is 50 mm. The diameter of the supports is 150 mm. The inner hole diameter for lead rubber and ball rubber bearings is set to be 50 mm. The inner hole is filled with either 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 while 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 with a yield strength of 235 MPa have a thickness of 2 mm. The geometric details of the tested systems are given in Figs. 4 and 5.

The individual cyclic load tests of bearings were conducted using two pairs of bearings at the same time as described by the TS EN 1337 (2007). 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

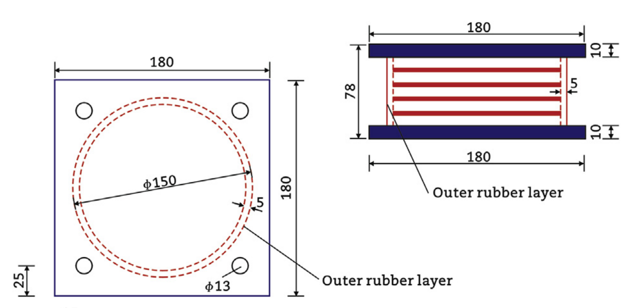

Fig. 4 – Elastomeric bearing design details (unit: mm).

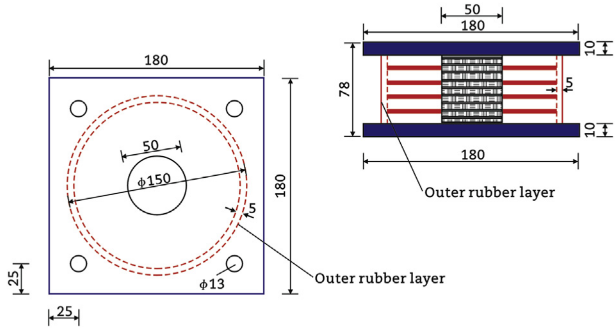

Fig. 5 – Lead rubber and ball rubber bearing design details (unit: mm).

displacement can change between −250 and 250 mm having a total cylinder course length of 500 mm. The testing machine shown in Fig. 6 has a displacement based control system in both directions. The bridge support systems can be tested in lateral direction with use of sine 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 the bottom side of the pull–push plate which is connected to a lateral hydraulic cylinder. Thus, shearing deformation is applied to both bearings at a time as described in double shear test procedure defined in EN and AASHTO. The target amplitudes are selected based on the percentage of rubber shear strain for each test. At the extreme displacement, the test machine adjusts 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 another research studying the effect of vehicles on bridge response during earthquakes (Shaban et al., 2015). The bridge is 12 m long and 3.5 m wide with concrete deck on steel girders. 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 concrete shake table is supported on six dimpled and oiled Teflon plates acting as sliders that create only about 1%–2% friction loss. The dominant frequency of the bridge in the direction of excitation (transverse) is 1.5 Hz. The earthquake records are applied thru a computer software that controls a hydraulic actuator capable of pushing and pulling the reinforced concrete substructure over the sliders and can excite the structure up to 0.5g for a certain amplitude in real time. The hydraulic actuator is connected to the bottom slab at its mid-span and records the applied displacement and force. The transverse deck displacement is measured through linear variable differential transformers (LVDTs) placed at the top and bottom of each bearing. Deck acceleration is recorded through wireless accelerometers positioned at the bridge mid-span. The photos of the test bridge, instrumentation, dimensions of the deck plan and the cross-section are given in Figs. 7 and 8. The reinforced concrete has been set to have a 28 day compressive strength of 25 MPa. The steel beams and braces have a yield strength of 235 MPa.

Fig. 6 – Cyclic lateral load test machine keeping constant compression in vertical direction.

Five earthquake records, also used in the research of Shaban et al. (2015), have been applied to the test bridge in real time. These records were taken from the 17 August 1999 Kocaeli and 12 November 1999 Düzce earthquakes in Turkey. They are particularly selected in order to test the effects of source-to-site distance and local site conditions on the bridge response. The characteristics of these records are summarized in Table 1.

The 5% damped response spectra curves for the tested earthquake records are shown in Fig. 9. The spectral accelerations are presented only for the tested range of periods.

3. Test results and discussions

The individual tests of the three types of bearings reveal that lead rubber bearings are about 10%–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 both the 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 the 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 values. The equivalent damping ratio, ξ, of the individual bearings can be assessed using the following equation.

$$\xi = \frac{\mathrm{EDC}}{2\pi K_{\mathrm{eff}} d^2} \tag{1}$$

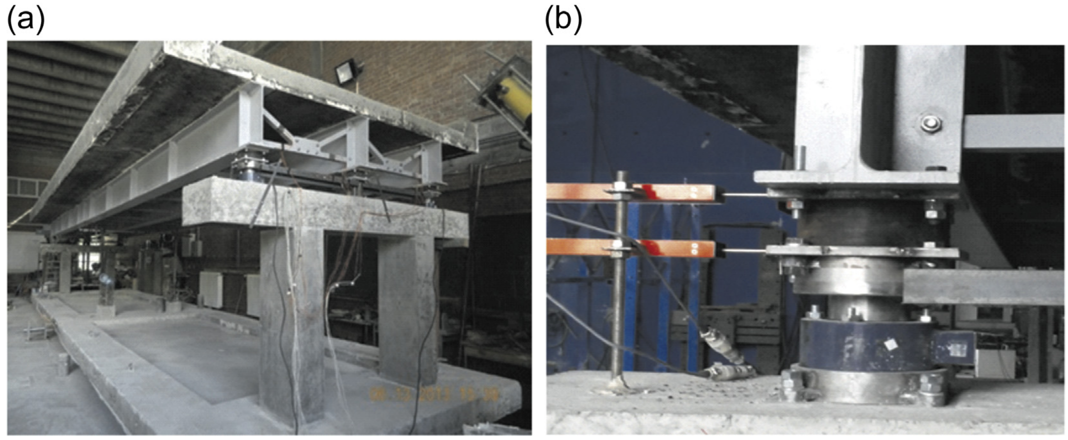

Fig. 7 – The photos of bridge. (a) Test bridge. (b) Bridge bearings.

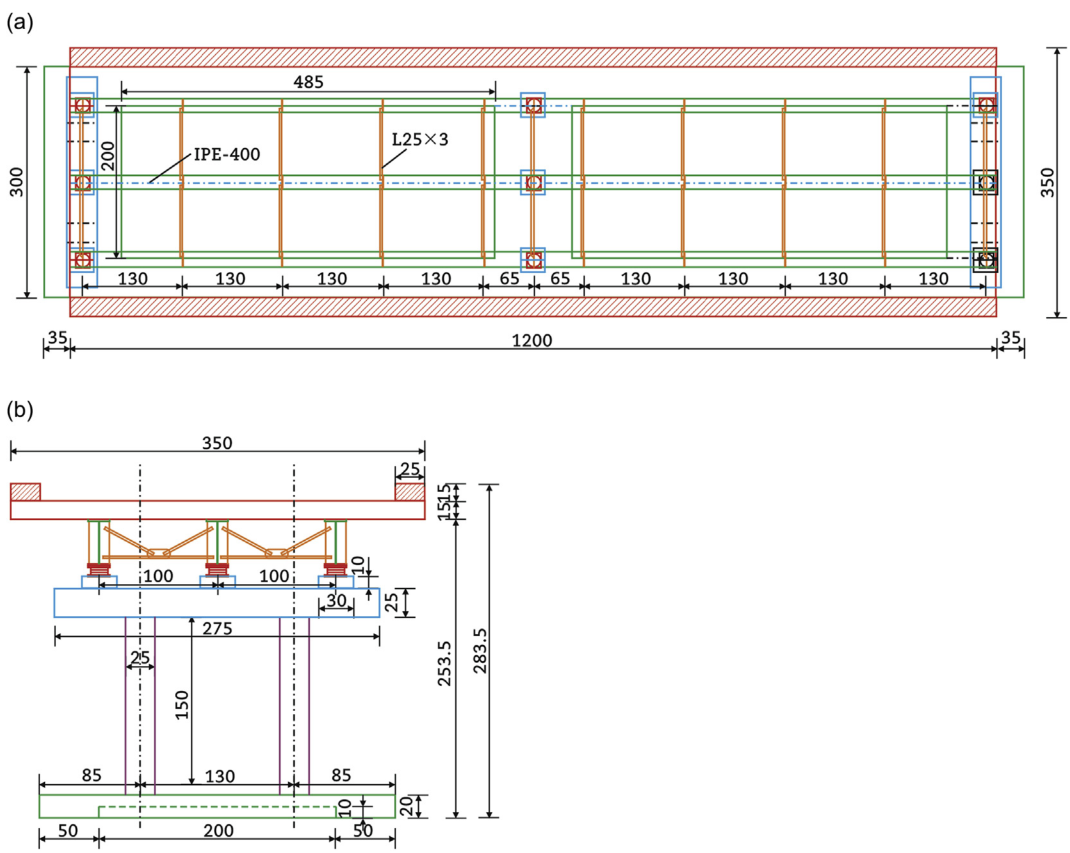

Fig. 8 – Test bridge design (unit: cm). (a) Plan. (b) Cross-section.

Table 1 – 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	0.397
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

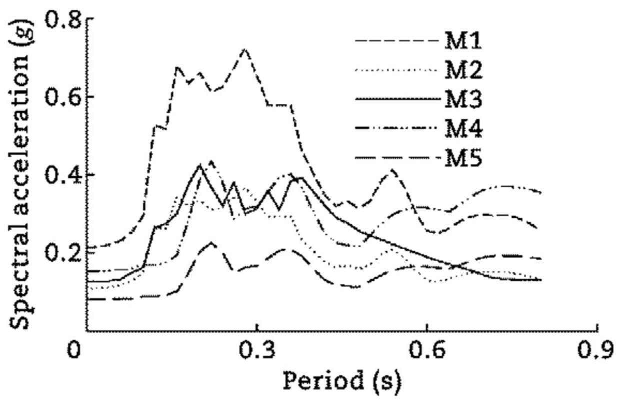

Fig. 9 – 5% damped response spectra curves for the selected earthquake records.

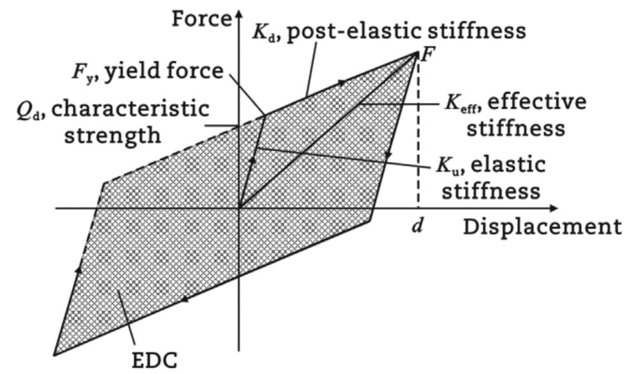

Fig. 10 – Lateral force-displacement characteristics of seismic isolation (AASHTO, 2014).

where EDC is the energy dissipated per cycle (area of the hysteresis loop) as shown in Fig. 10, K_{eff} is the effective stiffness of the bearing at the investigated displacement, and d is maximum lateral displacement.

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 K_{eff} results in similar equivalent damping ratio for lead rubber bearing and ball rubber bearing under the same lateral displacement.

Cyclic load–deformation graphs for the lead rubber and ball rubber bearings are shown in Fig. 11. The lateral force at each test needed to be divided by two to obtain the single response. The displacements shall not be divided by two. The yield displacement for both the lead rubber and the ball rubber bearings is about 6 mm. The idealized cyclic load patterns for all three supports are shown in Fig. 12.

The effective stiffness of the elastomeric bearings does not change significantly by the increase of shear strains as compared to the lead rubber and ball rubber bearings due to the low damping characteristics of the tested elastomeric material (Table 2). The lead rubber bearing effective stiffness measured at 100% strain is about 44% of the effective stiffness measured at 25% strain, which corresponds to a 56% reduction in effective stiffness.

The detailed test results for the elastomeric bearings can be found at the research report of TUBITAK (2014). Again, the elastomeric bearings have much less equivalent damping ratio compared to the two other bearings since the only source of damping is the rubber itself and no additional damping source is present as in the case of lead rubber or ball rubber bearings. Similar reduction in horizontal stiffness has been reported indirectly by Vemuru et al. (2014) under increased shear strains. In their tests they have observed that shear modulus is not constant which has a reflection on the horizontal stiffness.

The bridge supports selected purposely for the bridge shake tests avoided the peak demands of the selected response spectra curves expected in the case of fixed support bridge. Even for 5% damped response spectra curve, the demands just decrease by 60% by shifting the natural periods. The ones that have higher damping ratios even provide an improved seismic performance of the structure.

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 and ball rubber bearings. The deck accelerations measured at the mid-span of the bridge have a scattered response in terms of comparing minimum and maximum values as shown in Table 3.

It can be observed from Fig. 9 that the response spectrum curves for the five earthquake records indicate that M1 and M4 earthquake motions have higher spectral acceleration values compared to the other excitations in the range of periods capturing the natural periods of the test bridge that range between 0.4 s and 0.6 s. That is the main reason the deck accelerations and the deck displacements are higher for these two cases compared to the other earthquake records as shown in Tables 3 and 4. It shall be noted that for the M4 earthquake, the peak deck acceleration is amplified about 2.5 times in the range of observed natural periods.

In the 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

Table 2 – Bearing test results per one bearing under 3 MPa constant compression.

Support	K_{eff} (kN/m)			Equivalent damping (%)		
	25% strain	50% strain	100% strain	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

Note: EB is the elastomeric bearing, LRB is the lead rubber bearing, BRB is the ball rubber bearing.

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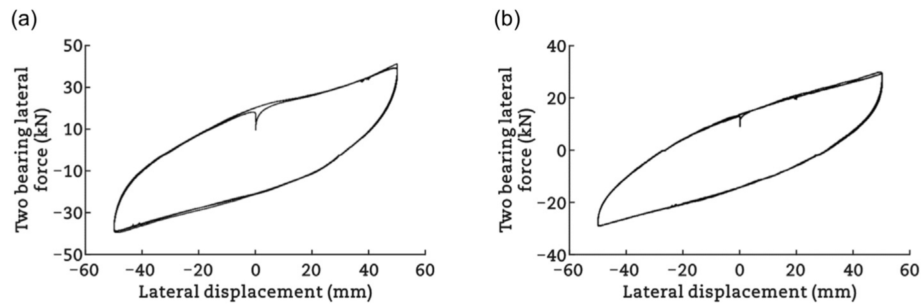

Fig. 11 – Hysteresis loops of double shear tests at 100% cyclic shear strain under sustained 3 MPa compression. (a) Lead rubber bearing. (b) Ball rubber bearing.

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 bearing. The deck displacements that reached up 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.

In the 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 ball rubber and lead rubber bearings are only displaced about their yield displacement level. At M5 earthquake bridge test, ball rubber bearings and lead rubber bearings stayed below their yield displacements. Therefore, the isolation systems did not function due to low demand.

The vertical load readings from load cells indicate that the vertical loads only change by ±15% of the original dead load during the excitations. This fluctuation did not much effect the lateral response of the bridge tests.

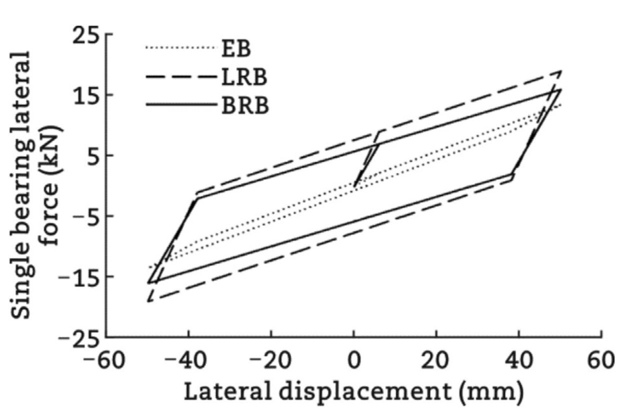

Fig. 12 – Idealized lateral force-displacement response of support systems.

The deck acceleration in time domain indicates that for all cases with low deck excitations the bearings almost responded in a similar way as shown in Fig. 13. At the early stages of excitations, the elastomeric bearings, lead rubber bearings and ball rubber bearings have almost the same pattern and even very similar acceleration amplitudes, an indication of isolation systems with significant damping being not much effective at the early stages of the earthquake. The lead rubber bearing and ball rubber bearing are much more effective at high acceleration levels reducing the accelerations significantly as in the case of M1 and M4 earthquakes.

Observations similar to the case of deck accelerations can be made for the deck displacements as well (Fig. 14). The isolation systems are not much effective at the early stages of the earthquake but more effective at reducing peak displacements. In all cases, the deck displacements dampen in a very short period of time for the bridge tests with lead rubber bearings and ball rubber bearings compared to the bridge tests with elastomeric bearings. The main reason is the high damping properties of the ball rubber and lead rubber bearings.

In all tested three types of bearings, the bridge superstructure re-centered itself after the low to moderate seismic events. Vemuru et al. (2014) have observed the similar response from shake table tests of elastomeric bearings subjected to severe earthquake motions.

The analytical formulations used in design and stability checks have been researched by Naeim and Kelly (1999), Vemuru et al. (2014), and Weisman and Warn (2012) at extreme event. Since low to moderate earthquakes are not expected to develop stability problems, no advanced analytical check for the stability has been made except the

Table 3 – Bridge deck acceleration.

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

AASHTO (2014). The simple approach suggested in AASHTO (2014) has been used to assess the seismic forces and displacements of the structure.

The damping coefficient B_L defined in AASHTO (2014) is investigated to see if the equation can be used to assess the reduction in deck displacements. The damping coefficient can be determined from the following equation.

$$B_L = (\xi/0.05)^{0.3} \tag{2}$$

The equivalent lateral force, F, in the simplified method of AASHTO (2014) can be determined from the below equation.

$$F = C_{sm}(T)W/B_L \tag{3}$$

where $C_{sm}(T)$ is the elastic seismic coefficient determined from 5% damped response spectrum curve corresponding to the structural period, T, and W is the weight.

The structural period can be determined from the classical structural dynamics equation as a function of the acting mass and effective stiffness. The effective stiffness of the structure in lateral direction is amplitude dependent as shown in Table 2. Therefore the fundamental period of the structure is not constant during the excitations. The relevant effective lateral stiffness and damping coefficient are used to assess the analytical deck displacement using corresponding force determined from Eq. (3) and effective stiffness determined from Table 2.

The simplified method cannot predict the deck displacements at low level earthquake demands as presented in Table 5. In the case of high earthquake demands observed in M1 and M4 cases, the simplified equation can provide a more adequate assessment of the deck displacement.

The presented research focuses on the effectiveness assessment and comparison of different elastomeric isolation systems regarding the global structural response to underline the viability of isolation systems along with the importance of proper selection. Detailed analytical and numerical analyses

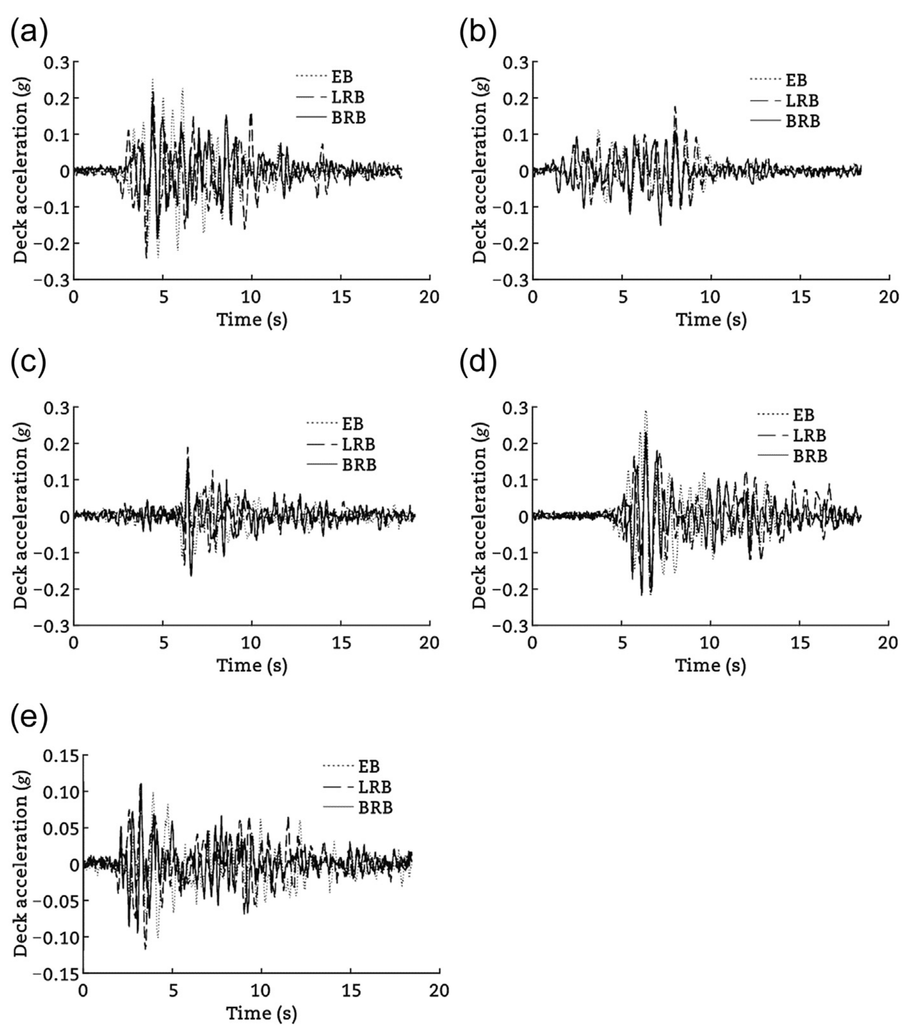

Fig. 13 – Earthquake deck acceleration. (a) M1. (b) M2. (c) M3. (d) M4. (e) M5.

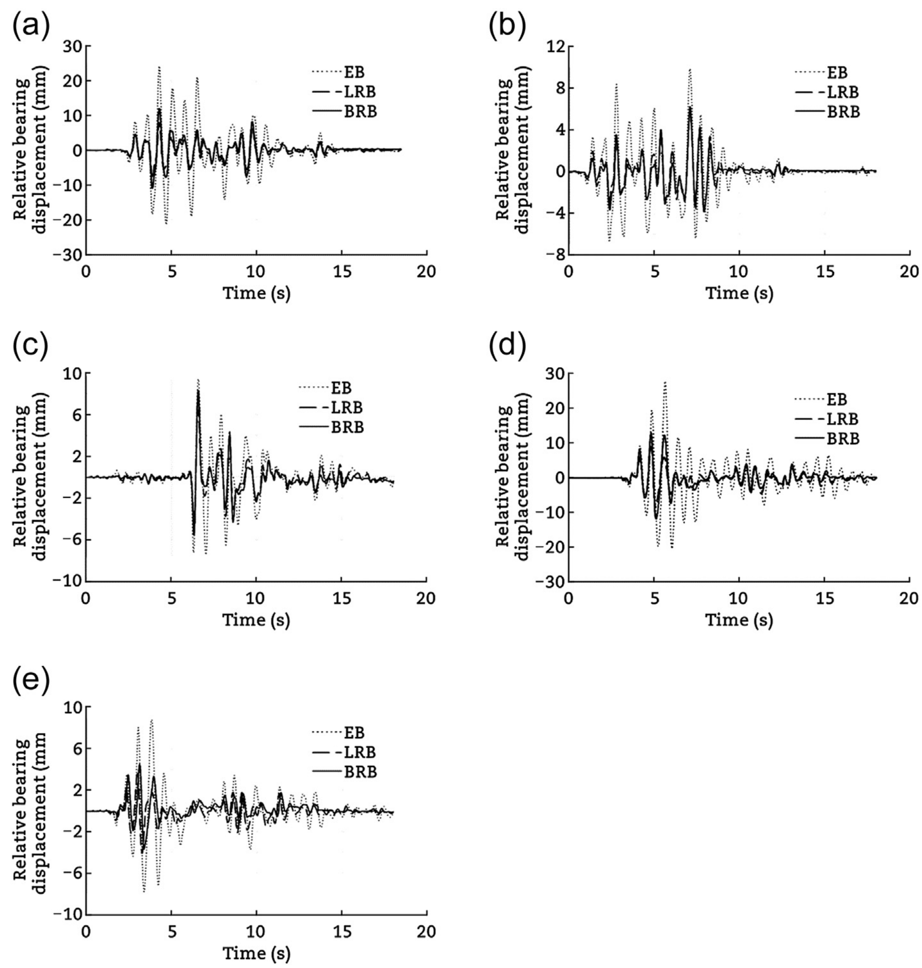

Fig. 14 – Earthquake deck displacement. (a) M1. (b) M2. (c) M3. (d) M4. (e) M5.

Table 5 – Comparison of test results and simplified analytical work.

Support	Peak deck displacement (mm)									
	M1		M2		M3		M4		M5	
	Test	Analytical	Test	Analytical	Test	Analytical	Test	Analytical	Test	Analytical
EB	24.5	22.9	9.9	14.5	9.4	16.1	27.9	27.3	8.8	13.7
LRB	8.1	15.5	6.0	7.9	6.4	14.3	8.9	12.8	4.1	6.8
BRB	12.2	16.3	7.0	7.7	9.2	14.2	14.3	12.0	4.5	6.0

on element level behavior of the three types of elastomeric isolation systems can be found in the PhD theses of Ozkaya (2010), Domanic (2015) and Karimzadeh (2013).

4. Conclusions

The tests of three types of bridge isolation systems, being elastomeric bearing, lead rubber bearing and ball rubber bearing, have clearly indicated the differences in performance due to the stiffness and damping characteristics as well as the characteristics of the earthquake that dominate the control of the deck displacements and accelerations during an earthquake. The tests involved not only individual performance tests but also real time bridge earthquake shake tests. The following conclusions can be drawn from this research:

1. Lead rubber bearings being stiffer compared to the other two resulted in higher deck accelerations at low demand

earthquakes since the bearings stayed around yield stiffness and did not dampen the system. The displacements are low in this case since the lead rubber bearings have higher stiffness compared to others. Therefore, this isolation system is not that effective at low demand earthquake levels.
2. In the case of moderate earthquake demands, the lead rubber bearings and ball rubber bearings dampen the system and resulted in significant reduction in deck accelerations and displacements compared to the ones obtained for the elastomeric bearings. The elastomeric bearings are not as effective as lead rubber or ball rubber bearings in reducing the seismic response under moderate earthquake levels.
3. It has been demonstrated that the ball rubber bearings are as much effective as lead rubber bearings. In all test cases, they can provide a higher reduction in peak deck accelerations compared to the lead rubber bearings, an indication of less substructure design forces. The pounding problem of standard bridges and bridges with skew angles can be controlled by use of isolation systems with high damping and with positive connection to substructure and superstructure.
4. In all the 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.
5. 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 was expected. The individual tests of lead rubber and ball rubber bearings indicated that the damping characteristics of these bearings are about three times as much as those of elastomeric bearings.

Conflicts of interest

The authors do not have any conflict of interest with other entities or researchers.

Acknowledgments

The help by Ali Karimzadeh Naghshineh is gratefully acknowledged. The authors would also like to extend their thanks to Turkish General Directorate of Highways (KGM). This work was supported by TUBITAK through the 110G093 research project and TUBITAK BIDEB 2215 Program.

REFERENCES

AASHTO, 2014. Guide Specifications for Seismic Isolation Design, fourth ed. AASHTO, Washington DC.
Agrawal, A.K., Ghosn, M., Alampalli, S., et al., 2012. Seismic fragility of retrofitted multispan continuous steel bridges in New York. Journal of Bridge Engineering 17 (4), 562–575.
Akansel, V., Ameri, G., Askan, A., et al., 2014. The 23 October 2011 MW 7.0 van (Eastern Turkey) earthquake: interpretations of recorded strong ground motions and post-earthquake conditions of nearby structures. Earthquake Spectra 30 (2), 657–682.
Avsar, O., Ozdemir, G., 2013. Response of seismic-isolated bridges in relation to intensity measures of ordinary and pulselike ground motions. Journal of Bridge Engineering 18 (3), 250–260.
Caner, A., Naghshineh, A.K., Erdal, S., 2015. Performance of ball rubber bearings in low-temperature regions. Journal of Performance of Construction Facilities 29 (2), 10–1061.
Castaldo, P., Lo Priore, R., 2018. Seismic performance assessment of isolated bridges for different limit states. Journal of Civil Structural Health Monitoring 8 (2), 17–32.
Domanic, A., 2015. Seismic Performance of Unbonded Elastomeric Bearings on Bridges: an Experimental and Parametric Study (PhD thesis). Middle East Technical University, Ankara.
Dezfuli, F.H., Alam, S., 2013. Multi-criteria optimization and seismic performance assessment of carbon FRP-based elastomeric isolator. Engineering Structures 49 (2), 525–540.
Karimzadeh, N.A., 2013. Experimental Studies on Fiber-mesh Reinforced Elastomeric Bearings (PhD thesis). Middle East Technical University, Ankara.
Li, Y., Conte, J.P., 2018. Probabilistic performance-based optimum design of seismic isolation for a California high-speed rail prototype bridge. Earthquake Engineering & Structural Dynamics 47 (2), 497–514.
Liu, T., Zordan, T., Briseghella, B., et al., 2014. An improved equivalent linear model of seismic isolation system with bilinear behavior. Engineering Structures 61 (1), 113–126.
Naeim, F., Kelly, J., 1999. Design of seismic isolated structures: from design to practice. Earthquake Spectra 16 (3), 709–710.
Okuyucu, D., Kale, Ö., Erdil, B., et al., 2012. Evaluation of successful seismic bridge design practice in Turkey. Journal of Performance of Constructed Facilities 28 (1), 4–12.
Ozkaya, C., 2010. Development of a New Seismic Isolator Named "Ball Rubber Bearing" (PhD thesis). Middle East Technical University, Ankara.
Ozkaya, C., Akyuz, U., Caner, A., et al., 2011. Development of a new rubber seismic isolator: 'Ball Rubber Bearing (BRB)'. Earthquake Engineering & Structural Dynamics 40 (12), 1337–1352.
Sanchez, J., Masroor, A., Mosqueda, G., et al., 2013. Static and dynamic stability of elastomeric bearings for seismic protection of structures. Journal of Structural Engineering 139 (7), 1149–1159.
Shaban, N., Caner, A., Yakut, A., et al., 2015. Vehicle effects on seismic response of a simple-span bridge during shake tests. Earthquake Engineering & Structural Dynamics 44 (6), 889–905.
Steelman, J.S., Fahnestock, L.A., Filipov, E.T., et al., 2013. Shear and friction response of nonseismic laminated elastomeric bridge bearings subject to seismic demands. Journal of Bridge Engineering 18 (7), 612–623.
TS EN 1337, 2007. Structural Bearings – Part 3: Elastomeric Bearings. Ankara.
TUBITAK, 2014. Guidelines for Developing New Technologies for Design and Construction of Bridges. 110G093. TUBITAK, Ankara.
Vemuru, V.S.M., Nagarajaiah, S., Masroor, A., et al., 2014. Dynamic lateral stability of elastomeric seismic isolation bearings. Journal of Structural Engineering 140 (8), 1–14.
Weisman, J., Warn, G.P., 2012. Stability of elastomeric and lead-rubber seismic isolation bearings. Journal of Structural Engineering 138 (2), 215–223.
Wibowo, H., Smith, D., Buckle, I., et al., 2012. Live load effects on response of bridges during earthquakes. Structures Congress 2012, 591–602.

Yilmaz, S.A., 2014. Reliability Based Evaluation of Seismic Design of Turkish Bridges by Using Load and Resistance Factor Method (Master thesis). Middle East Technical University, Ankara.

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