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Seismic Study of Lead-Rubber Bearing Application in Kutai Kartanegara Steel Arch Bridge

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***Abstract*— The basic concept of the application of base isolation is by extending the natural period of the structure in order to provide lower seismic acceleration. The paper focuses on the investigation of the application of lead-rubber bearings (LRBs) instead of pot bearings in a new Kutai Kartanegara steel arch bridge located in East Kalimantan province. Even though the bridge is known located in Seismic Zone 1 (the zone with the least seismic risk as per SNI 2833-2013), the study was extended for other higher risk seismic zones, namely Seismic Zones 2, 3, and 4. With the aid of Midas software, the analyses of the bridge structures were carried out and it can be concluded that the higher the seismic risk, the more effective the use of LRBs in dissipating the earthquake energy before transmitting to the bridge superstructure. The reductions of seismic base shears obtained from the analyses were between 23.10 and 44.67 percent and 17.07 and 31.47 percent in the longitudinal and transverse directions, respectively. However, the application of LRBs has a consequence of increasing the horizontal displacements of the bridge, which can be solved by introducing either larger expansion joints or passive dampers. In order to validate the seismic responses, the bridge was analyzed using Time History Analysis (THA) by imposing seven earthquake ground motions, which were scaled to a spectral design of Padang as a requirement by the Indonesian code.**

***Keywords*— horizontal displacement; lead rubber bearing; seismic base shear; seismic zone; steel arch bridge.**

I. INTRODUCTION

The seismic isolation system was developed intensively by Kelly [1] in its early days. Since then, it has been rapidly developed and widely implemented in both buildings and bridges to mitigate the impact of vibration, dynamic loads, or earthquakes. The applications of LRBs and low-cost rubber bearings (LCRBs) for building's seismic isolation system have been investigated by many researchers [2]-[12]. In the bridge structures, Turkington et al. [13] investigated the seismic response of a bridge superstructure which was supported by the LRBs. The analyses using the time histories concluded that the presence of LRBs shifted away the natural period of the bridge, and further increased the damping ratio. It was also indicated that the increase of the pier height leads to the decrease of the structural damping of the bridge. Li et al. [14] studied to compare the energies dissipated by the unilateral-, the laminated-, and the lead-rubber bearings under low-frequency cyclic loadings. It was found that the laminated-rubber bearings could deform up to 400 percent of the rubber thickness and the hysteretic curve areas of the LRBs were always more substantial than the those of the laminated rubber bearings. The study of Yi and Li [15] concluded that the seismic damages of the cable-stayed bridges could be simulated by nonlinear numerical models of bridge components such as pylons, decks, girders, bearings, and cables. Another study [16] revealed that the total seismic displacements of a three-span continuous bridge using LRBs were smaller compared with those using a combination of LRB and elastomeric bearing system. The nonlinear time history analysis was conducted for both without-seismically-isolated bridges and with seismically-isolated-bridges to study the effectiveness of the base isolation technique under several earthquake ground motions, [17]. It was found that the properties of the isolated bridge and the ground motion influenced the effectiveness of LRBs as seismic isolation system.

On November 26th, 2011, the Kutai Kartanegara suspension bridge, called as the Indonesian Golden Gate Bridge, collapsed. A through-deck steel truss girder stiffened the bridge. It had a main center span of 270 meters, and two end spans of 100 meters as shown in Fig. 1. It was publicly opened to traffic since 2002. To replace the collapsed bridge that connected the Samarinda and Tenggarong city, a new half-through steel arch bridge was then built, and it had been publicly opened to traffic on December 8th, 2015, while it is still utilizing the strengthened existing foundations. The photograph of the bridge during construction taken shortly prior to its completion can be seen in Fig. 2.

The study focuses on the investigation of the use of Lead Rubber Bearings (LRBs) instead of pot bearings in a new Kutai Kartanegara steel arch bridge located in East Kalimantan province. Although the bridge is known located in Seismic Zone 1 (the zone with the least seismic risk as per SNI 2833:2013), the study was further extended for other higher-risk seismic zones, namely Seismic Zones 2, 3, and 4 to investigate the behavior of the LRBs. Thus, to validate the seismic responses, the bridge was then analyzed using the Time History Analysis (THA) by imposing seven earthquake ground motions, which were scaled to the spectral design of Padang as a requirement by the Indonesian code [18].

Fig. 1 The old Kutai Kartanegara suspension bridge in 2007 before collapsed

Fig. 2 The new Kutai Kartanegara steel arch bridge in 2015 shortly before completing

II. Materials and Method

A. Seismic Isolation System

The isolation system separates the movements of the upper structure from the ground motions (foundations) by inserting base isolation (BI) system between the upper structure and foundation. The BI has lower horizontal stiffness compared to the upper structure and foundation such that the upper structure moves as a rigid body as shown in Fig. 3 [19]. The isolated structures have larger natural period compared to the non-isolated structures. They also provide lower spectral accelerations and thus, its seismic response [13], [20], [21] as shown in Fig. 4. On the contrary, the increase of natural period yields larger horizontal displacements as shown in Fig. 5 [13], [20], [21]. In the bridge structures, larger horizontal displacements can be solved by the introduction of either larger expansion joints or passive dampers. Figures 4 and 5 show that both accelerations and displacements of the structures can be decreased by the increase of the damping which is provided by the base isolation system.

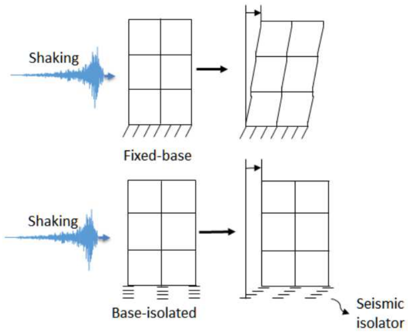


Fig. 3 Effect of seismic (base) isolation on structural response [19]

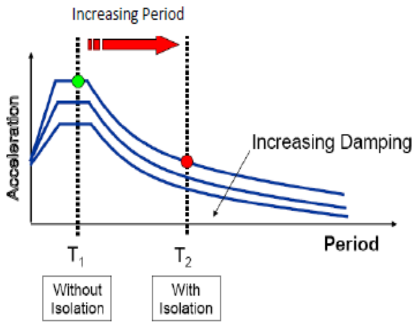


Fig. 4 Relations between acceleration and natural period [13], [20], [21]

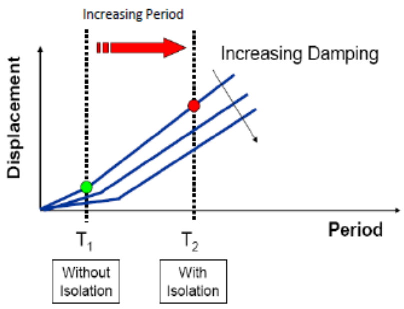
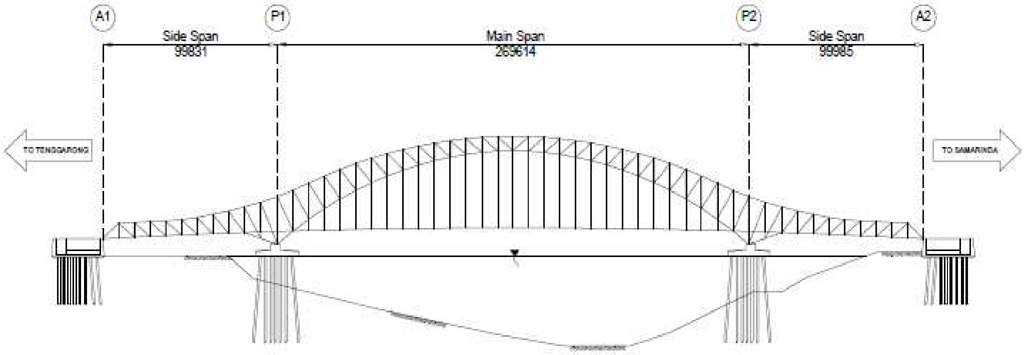


Fig. 5 Relations between displacement and natural period [13], [20], [21]

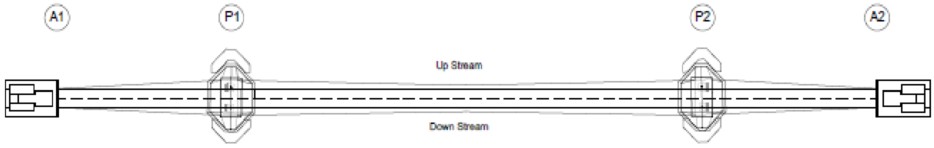
The base isolation types which are frequently used in the isolated structures are shown in Fig. 6, e.g., high damping rubber bearing (HDRB), LRB, and friction pendulum bearing (FPB) [20], [22], [23]. HDRB is a base isolation system which is developed from natural rubber mixed with extra fine carbon block, oil or resin, and other materials, hence the damping ratios increase between 10 and 20 percent, whereas LRB is a base isolation system which has a core made from copper alloy. The core has a function to absorb ground motion energy. Therefore, it can reduce the seismic force transmitted to the bridge superstructure. FPB is also a type of base isolation systems that normally implemented for heavy structures located in very high-risk seismic zone. The largest FPB that has been employed in the bridge structure has a diameter of 3962 mm (13 feet) and lateral displacement capacity of 1346 mm (53 inches) [23]. The use of FPB reduces the dimensions of long span bridge foundation significantly, especially when the bridge is constructed in very high-risk seismic zone.

(a) (b) (c)

Fig. 6 Various types of base isolators [20], [22], [23]: (a). high damping rubber bearing (HDRB); (b). lead rubber bearing (LRB); (c). friction pendulum bearing (FPB)



(a). Elevation



(b). Layout plan

(c). Positioning of pot bearings and number of nodes (Note: arrow signs indicate allowable movement)

Fig. 7 Elevation, layout plan, and pot bearing positionings of the bridge

B. *Descriptions of New Kutai Kartanegara Bridge*

Figure 7a to c shows the elevation and layout plan of the new Kutai Kartanegara bridge as well as the pot bearing positionings, respectively. The bridge data obtained from the design include the geometry, material properties, cross-sections of the main truss, hangers, and bearings as follows:

- Type: half-through steel truss arch
- Span: 99.831 + 269.614 + 99.985 meters
- Rise: 57.84 meter; Rise/Main Span = 1:4.7
- No. of lanes of traffic: 2 + sidewalks of 2 × 1.30 meter
- Width: 10.75 meter; Width/Main Span = 1:25
- Sections of arch truss: box and plate girders; sections of bracings: pipes
- Materials: SM490YA/YB JIS G 3106
- Hangers: steel wire strands with tensile strength of 1570 ~ 1630 MPa
- Original supports: pot bearings of fix-, unidirectional sliding-, and multidirectional- types
- Modified supports: LRBs as replacements for all pot bearings
- Loading code: SNI T-02-2005 [24]

Seismic code: SNI 2833:2013 [18]

C. *Seismic Loading*

Based on SNI 2833:2013 code, the horizontal static seismic load, E_Q, can be calculated using Eq. (1).

$$E_Q = \frac{C_{sm}}{R} \times W_t \tag{1}$$

where:

C_{sm} = coefficient of seismic elastic response at m^{th} mode. It is determined using a probabilistic response spectrum calculated based on the Seismic Map of SNI 2833:2013 for seven-percent probability of being exceeded in 75 years (or 1000 years return period);

R = factor of modified response;

W_t = total weight of the bridge which influences the seismic accelerations, taken into account from dead and superimposed dead loads.

D. Scaling Procedure of Earthquake Ground Motions

The method of least squares which is a scaling technique employed to match the spectral design [25], [2]. With this method, the input acceleration using THA is multiplied by a scale factor (SF) which can be calculated using Eq. (2).

$$SF = \left(\sum_{i=1}^{n} \overline{A}_i A_i \right) \Big/ \left(\sum_{i=1}^{n} A_i A_i \right) \qquad (2)$$

where $\overline{A}_i$ and A_i are the target spectral acceleration and the record's spectral acceleration respectively. The symbol ith represents the spectral period, and n represents the number of periods which ranges between 0.2T1 and 1.5T1, where T1 is the period for a first mode or the fundamental period.

III. Results and Discussion

In modeling LRB using MIDAS software, four parameters were required, namely the lead core strength (F_y), the elastic stiffness (K_e), the ratio of post-yield stiffness to elastic stiffness (r), and the vertical stiffness (K_v). Based on the total weight of the bridge structure of 93,946 kN, the location of the bridge in Seismic Zone 4, and Eq. (1), the dimensions and properties of LRBs can be obtained. They have the diameters of 1000 and 700 mm for piers and abutments (see Table 1), respectively. By using the same method, with the total weights of 77,311, 82,856, and 88,401 kN for Seismic Zones 1, 2, and 3, respectively, the diameters of LRBs obtained are 900 and 600 mm for piers and abutments, respectively.

The seismic base shears resulted from the analyses using LRBs can be found in Table 2. Comparing to the analyses using pot bearings as supports, it can be found that the reductions of seismic base shears obtained from the analyses using LRBs are between 23.10 and 44.67 and 17.07 and 31.47 percent in the transverse and longitudinal directions, respectively. Regarding the use of LRBs, Table 2 also indicates that the higher the seismic risk, the more effective the use of LRBs in dissipating the ground motion energies before transmitting to the bridge superstructure.

TABLE I
Dimensions and properties of LRBs for a bridge located in Padang (seismic zone-4)

Properties	Dimensions	Units
Type-Lasto Mageba Product	LRB700	-
Diameter (D)	700	mm
Lead Core Diameter (D_L)	70	mm
Rubber Layer Thickness (t)	8	mm
Total Rubber Thickness (Tr)	192	mm
Rubber Shear Modulus (G)	0.8	MPa
Lead Effective Yield Stress (σ_L)	20	MPa
Bulk Modulus (K)	2000	MPa
Total Height (H)	374	mm
Designed Seismic Displacement (Δ_{EDE})	162	mm
Designed Bearing Axial Load (P_{EDE})	3450	kN
Yield Stress of Steel Shim Material (F_{yr}) Lead Core Strength (F_y) for Abutment/Pier Elastic Stiffness (K_e) for Abutment/Pier Vertical Stiffness (K_v) for Abutment/Pier Stiffness Ratio (r) for Abutment/Pier	248 77/157 76807/156797 1388504/2970938 0.0207/0.0177	MPa kN kN/m kN/m -

TABLE II
Seismic forces for various zones using pot bearings and LRBs as supports

Seismic Zone	Direction	Seismic base shear (Response Spectrum) (kN)		Difference (%)
		POT Bearing	LRB	
Zone 1 (Samarinda)	longitudinal	2538	1952	23.1
	transversal	2302	1910	17.0
Zone 2 (Palembang)	longitudinal	4616	3199	30.7
	transversal	3811	3150	17.4
Zone 3 (Medan)	longitudinal	7807	5206	33.3
	transversal	5768	4711	18.3
Zone 4 (Padang)	longitudinal	14478	8011	44.7
	transversal	13328	9120	31.6

Table 3 illustrates that the application of LRBs has a consequence of increasing the horizontal displacements of the bridge, which can be solved by introducing either larger expansion joints or passive dampers. In this case, the length of the expansion joint, could reach up to 800 mm. The longitudinal displacements of the bridge using LRBs achieve approximately 12.5 times of those designed using pot bearings. The application of larger dimensions of LRBs in Seismic Zone 4 yields the required length of the expansion joint smaller than that in Seismic Zone 3 (see Table 3). As mentioned above that the application of LRBs aims to provide larger natural period. Table 4 shows that, for all modes, the bridges designed using LRBs experienced more considerable natural periods compared to the bridge designed using pot bearings (excluding the substructure), almost twice for the first mode. The contribution of the substructure and soil stiffness increases the natural period of the bridge approximately 1.27 times (see Table 4). The bridge behaves more flexible when the analysis includes the substructure. From the phenomenon of mode directions, it also indicates that the bridge is moving in the transverse direction firstly, if ground motions occur.

TABLE III
HORIZONTAL DISPLACEMENTS AND REQUIRED LENGTH OF EXPANSION JOINTS

Seismic Zone	Direction	Displacement (m)		Required length of expansion joint (m)
		Pot Bearing	LRB	
Zona 1 (Samarinda)	Longitudinal	0.023	0.290	0.30
	Transversal	0.000	0.000	-
Zona 2 (Palembang)	Longitudinal	0.038	0.476	0.50
	Transversal	0.000	0.000	-
Zona 3 (Medan)	Longitudinal	0.063	0.774	0.80
	Transversal	0.000	0.000	-
Zona 4 (Padang)	Longitudinal	0.100	0.644	0.70
	Transversal	0.000	0.000	-

TABLE IV
NATURAL PERIODS OF THE BRIDGE STRUCTURE

Mode Number	Period (sec)			Movement Direction	
	Pot Bearing		LRB	Pot Bearing	LRB
	Excluding Substructure	Including Substructure	Excluding Substructure	Excluding Substructure	Excluding Substructure
1	2.960	3.784	5.769	Transversal	Transversal
2	1.759	1.560	4.553	Transversal	Longitudinal
3	1.507	1.436	3.617	Longitudinal	Transversal
4	1.210	1.253	2.868	Vertical	Transversal
5	1.017	1.041	2.212	Longitudinal	Transversal
6	0.985	1.000	1.701	Transversal	Vertical
7	0.975	0.943	1.694	Longitudinal	Vertical
8	0.881	0.880	1.607	Transversal	Transversal
9	0.847	0.721	1.635	Longitudinal	Longitudinal
10	0.718	0.670	1.100	Longitudinal	Longitudinal

The pseudo-acceleration spectrums of seven ground motions in X (longitudinal) and Y (transverse) directions were derived using Seismosoft [2], [26] and Eq. (2) to obtain the scalings as shown in Fig. 8. The scale factors that match the spectral design of Padang are listed in Table 5. Seven records with various magnitudes, namely Iran (1978), San Fernando (1971), Northridge (1994), Landers (1992), Morgan Hill (1984), Loma Prieta (1989), and Italy (1980) were then imposed to the bridge structure. The analyses were performed using THA which were multiplied by the scale factors as a requirement by the SNI 2833:2013 [18]. The seismic base shears obtained using both RSA and THA are given in Table 6. From the table, it can be observed that the seismic responses obtained from the THA are always smaller than those obtained from the RSA.

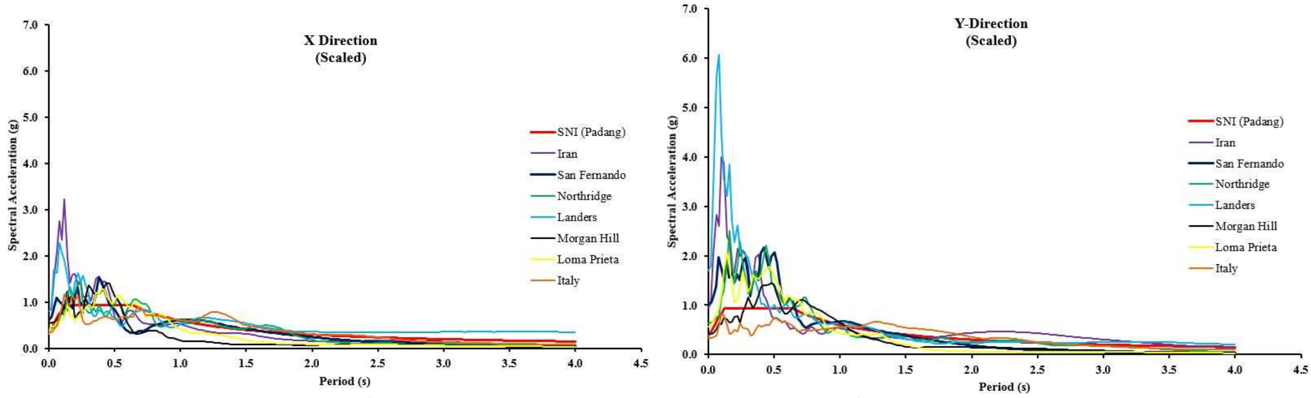


Fig. 8 Scaling of seven ground motion records to match spectral design of Padang based on SNI 2833:2013

TABLE V
SCALE FACTORS OF GROUND MOTIONS TO MATCH SPECTRAL DESIGN OF PADANG

No	Earthquake	Year	Station	Magnitude (R)	Distance	Vs30	PGA	Scaling Factor	
					(km)	(m/s)	(g)	X	Y
1	Tabas, Iran	1978	Tabas	7.4	2.1	767.00	0.85	0.961	1.084
2	San Fernando	1971	Pacoima	6.1	1.81	2016.00	1.12	0.507	0.830
3	Northridge	1994	Alhambra - Fremont School	6.7	35	549.75	0.10	4.259	7.978
4	Landers	1992	Lucerne	7.3	2.19	1369.00	0.72	1.113	2.143
5	Morgan Hill	1984	Anderson Dam (Downstream)	6.2	3.22	488.70	0.40	1.297	1.422
6	Loma Prieta	1989	APEEL 10 - Skyline	6.9	41.7	391.91	0.45	0.679	1.118
7	Italy	1980	Bagnoli Irpinio	6.9	8.14	649.67	0.15	2.653	1.762

TABLE VI
COMPARISON OF SEISMIC BASE SHEARS FOR PADANG SEISMIC ZONE

No	Earthquake	Year	Station	Magnitude (R)	Seismic Base Shear (kN)			
					RS-longitudinal	THA-longitudinal	RS-transversal	THA-transversal
1	Tabas, Iran	1978	Tabas	7.4	14478	13110	13328	12933
2	San Fernando	1971	Pacoima	6.1	14478	13744	13328	11894
3	Northridge	1994	Alhambra - Fremont School	6.7	14478	13452	13328	12594
4	Landers	1992	Lucerne	7.3	14478	13923	13328	12793
5	Morgan Hill	1984	Anderson Dam (Downstream)	6.2	14478	12912	13328	11980
6	Loma Prieta	1989	APEEL 10 - Skyline	6.9	14478	13014	13328	11766
7	Italy	1980	Bagnoli Irpinio	6.9	14478	14072	13328	12382

IV. CONCLUSIONS

The conclusions and recommendations of the current study can be drawn as follows: In general, the application of LRBs in the bridge structure reduced the seismic base shear significantly; The comparisons of the seismic base shears of the bridges designed using the pot bearings and LRBs as bridge supports exhibited considerable difference; The reduction of seismic base shears obtained from the analyses using LRBs from those using pot bearings were between 23.10 and 44.67 and 17.07 and 31.47 percent in the longitudinal and transverse directions, respectively; The application of LRBs has a consequence of increasing the horizontal displacements of the bridge. The longitudinal displacements of the bridge regarding the use of LRBs could reach 12.5 times of the displacement analyzed using the pot bearings. This phenomenon can be solved by the introduction of the expansion joints with a length of up to 800 mm; To validate the seismic responses, it is necessary to analyze the bridge by imposing several scaled ground motions using THA, as required by many bridge codes in the world including the Indonesian bridge code.

As the recommendations in the present study, all the pot bearings were replaced by the LRBs. It is also interesting to investigate the application of LRBs for replacement of only some of the pot bearings. By selected the appropriate positions of the LRBs, it could result in more economical bridge design. Due to the reliable performance of LRBs found in the study in reducing the seismic force up to 44.67 percent, the application of LRBs in bridges constructed in the moderate- risk seismic zone is also recommended.

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